Ground improvement under historical buildings: a case history

Amélioration du sol sous des bâtiments historiques: un cas étude

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ABSTRACT
The soil improvement technique, used to deepen a large excavation in adherence to an historical building into an urbanized area, will be herein presented. The building suffered relevant damagement yet when any excavation activity had still to be started; thus, the excavation's sequence and the retain structure had to be redesigned, because the marked sensitivity of the wet sandy-silt soil did not allow any activity in proximity to the building's foundation.

Test pits assessed that soil improvements may be gained by high pressure injections of fast-settling resins, provided that particular executive details would have been respected.

The monitoring activities which allowed to recognize the building's behavior both before, during and after of the close-by excavation process will be resumed too; furthermore, these observations shall be put in comparison with an FEM simulation, which took into consideration all of the excavation sequences, as well as of the soil improvement simulation.

Attention will be raised on some relevant details regarding the use of these widely diffused fast-settling resins which, usually, are applied with no particular care and specifications: this common practice is not acceptable in instances like the presented case but, on the contrary, these technologies may really solve difficult problems if they are applied under strict control and specifications.

RÉSUMÉ
In ce travail nous décrivons un cas étude, regardant la technique d'amélioration du sol utilisée pour approfondir une grande fouille à proximité d'un bâtiment historique, situé dans une zone bien urbanisée. Le bâtiment présentait des dommages considérables avant le commencement des excavations; donc, on a dû redessiner la séquence de fouilles et la structure retenant, parce que la sensibilité arrêtée du terrain sableux-limon ne permit pas des activités à proximité des fondation du bâtiment.

Préliminaires sondages, prouvaient que on peut obtenir des amélioration du sol par injection à haute pression de résines à rapide sèchement, pourvu que les détails exécutives particulaires soient respectés.

Les activités de surveillance qui ont permis de reconnaître le comportement de la construction avant, pendant et après le processus d'excavation seront également repris; en outre, ces observations devaient être mis en comparaison par a simulation FEM, qui prenne en considération tous les séquences d'excavation et les simulations d'amélioration du sol.

On focalisera l'attention sur des considérables détails concernant l'emploi de ces résines à rapide sèchement, amplement diffuses qui, habituellement, sont utilisées sans aucun soin particulier et spécifications: cette courante pratique n'est pas acceptable dans les circonstances comme le cas présenté mais, au contraire, ces technologies poudraient vraiment résoudre des problèmes difficiles se si elles fussent appliquées sous contrôle strict et spécifications.

Keywords: Soil stabilization, Geophysical investigation, Finite Element Method, Sheet pile wall, Continuous foundation

1 INTRODUCTION

The *Gavotti Palace* is a prestigious building sited within the historical city center of Savona, an important seaport in the northwestern Italian region of Liguria. The Palace has a large entrance hallway, wide stairs, galleries and elegant halls; it was built on the remains of a medieval structure, which was transformed in the late XVIth century after the new Renaissance style, introducing spaces connected each other through a gallery succession. As related on a memorial tablet inserted in the façade, on 1772 the patrician family Gavotti donated the building to the *Opera Pia di Nostra Signora della Misericordia* (Our Lady of Mercy's Congregation), to give hospitality to important people visiting the dedicated Sanctuary in Savona. In the XIXth century several renovation works modified the renaissance structure in accordance to the use of the halls especially when, between 1861 and 1934, the Municipality found its headquarters here. On 1863 a new crossing was opened along its ground level too, thus the entrance hall was transformed into an arcaded public walkway to connect the medieval part of the town to the new districts (see Fig. 1). When the Municipality left it, the Palace maintained the Art Gallery established there from 1868 and the Civic Library was adjoined. After more than a century, the Savona's Art Gallery has its definitive location in Gavotti Palace and is one of the most prestigious galleries in Liguria where, beautiful frescos, paintings and sculptures spanning from mid-1300 icons to masterpieces of Pablo Picasso and Joan Mirò, are on permanent exhibition.

The neighboring property planned recently to demolish his old and nowadays unused picture-theater *Astor*, standing adjacent to Gavotti Palace, in order to develop in its place a new residential-commercial complex, named the new *Astor Gallery*, which was planned to have a three-levels underground garage.

The Astor demolition caused minimal troubles to the Palace, even if a large amount of its masonry wall was practically side-adjoined to the old theater structure. Then the new Astor Gallery development proceeded and, as planned, the casting of contiguous large diameter bored piles (diam. 900 mm) started to form the curtain wall which, when finished and propped-up, would have had to retain the excavation facings.

But, as the piles' execution approached the Gavotti Palace's masonry wall, this begun to settle markedly, rousing up safety issues.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2399

Figure 1. Main façade of the Gavotti Palace, with the exit of its arcaded walkway and, at left, the neighboring erecting yard.

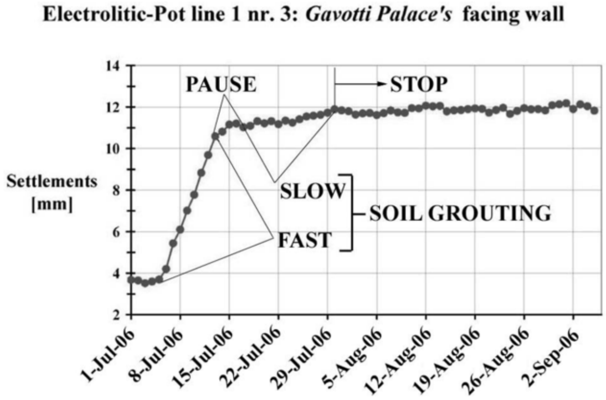

Figure 2. The sudden rise and evolutions of the Palace's settlements, retrieved during the soil grouting sequences applied, by a water-cement mix injections, underneath its foundation's level.

2 THE PALACE DAMAGEMENT

The Gavotti Palace situation, whose elevation went through complex structural modifications during a period of almost seven centuries and, being sited as is on a wet sandy-silt stratum ~ 8 meters deep, arouse in advance the nearby developers' attention to apply special care. In fact, before of starting any of the planned activity, a complex monitoring array was made up by installing piezometrs, inclinometers, long base extensometers, crack-propagation detectors and, most important in the following scrutiny, a set of electrolytic-pots on the Palace's facing wall to observe directly, in real time and continuously, its eventual settlements.

The original layout plan intended that the closing-by retaining-piles' row had to approach the Palace's wall, then to run on a straight line flanking it for circa 15 meters holding a mere half meter of maximum clearance.

It was also planned that a soil improvement beneath the existing foundation had to precede the execution of this piles' alignment, get done by grouting a simple water-cement mix through 15 equally spaced small diameter perforated pipes, each equipped with a one-way valve per foot-length (*rubber-sleeved liners* or *tubes a manchettes*); these had to be placed from the outer edge of the Palace's wall, slanted forward 10° to deepen 10 meters under it and to reach an overconsolidated clay level, resting about 7 ÷ 9 meters below ground level of the overall downtown district area.

Consequently, when one of the piles' execution was made at 1.6 meter from the Palace, its masonry wall settling was retrieved by the leveling system to mark a dangerous local value of 3 mm; this evidence alerted that time had come to stop immediately the nearby piles' borings and to start applying the soil improvement activity, as intended.

The groutings were to be applied in alternated sequence and selective time-delayed repetitions, both in plan and depth, using double-packer injectors and caring of the liners' accessibility, by internal flushing.

At this point the timing record of events is particularly relevant, because what happened was surprising and barely predictable.

The grouting-liners were installed on the first week of July 2006 then, after one week from the injections' start (July the 5^{th}), four of them were completed. On the 13^{th} of July the soil grouting was interrupted, because the leveling system showed a steep gradient of the Palace's settling which, as remarked in the following figure 2, gained a dangerous 7 mm increment.

Having at the moment no alternatives and observing that after a five days suspension the settling faded, a lesser aggressive grouting phase was restarted, hence, other nine liners were injected up to a mean 60% of their completion.

The Palace's settlement arouse again, even if slower than before, without help of using a much more cautious grouting approach so, at the end of July, any neighboring activity was unconditionally interrupted.

In fact, having the local settlement now reached well over than one centimeter, Gavotti Palace suffered a damagement which spread widely, as happens in structures such alike, diffusing from the perimetrical masonry wall to the inner ones, passing through a multitude of arch ribs and slabs, of barrel and groined vaults (see Fig. 3).

(a) (b)

Figure 3. Some examples of the cracks' propagation on Gavotti Palace: along the masonry wall which borders the erecting yard (a), over one of the inner court's façades (b).

The Municipality, highly worried about both of the public safety and of its property damagement, solicited the developers to activate an immediate confrontation with appointed Consultants to analyze the emerging situation and, if possible, to find with them acceptable solutions in order to obtain a Works' Continuation release.

Even if these activities implied some months of yard inactivity, the neighboring Property assumed a cooperative approach dedicating, above all, particular care and attentions to Gavotti Palace's safety issues.

Also the attitude enlisted by the Savona's Municipality honors the judgment of having been a very wise one; indeed, with respect to issuing a *Building Concession Full Annulment* and an immediate *Sue for Property Damages*, on a short term the erecting works did restart, as will be referred in the following, avoiding to leave a dangerous situation unattended for an unpredictable number of years and, moreover, allowing to complete an important and most wanted of the city center district's re-urbanization.

3 THE ALTERNATIVE SOIL IMPROVEMENT

This situation denoted that, clearly, the masonry structure of Gavotti Palace was extremely vulnerable and that its overall safety margin had been pushed close to a dangerous level.

Its shallow foundation is placed 2 meters below G:L. over a 5 to 7 meters deep alluvial-colluvial deposit. This loose stratum holds the water table, which ranges seasonally in between 2.8 to 3.8 meters from G.L., is formed by clayey-silts (mean distribution presence at 55%) with fine sands (≤ 35%) and is rendered locally more colluvial by sparse gravels (< 10%); it overburdens a typical tertiary deposit (*Pliocene*) of silty-clays, which are much more consistent as being slightly overconsolidated (OCR ≈ 1.8).

The loose soils, whose finer strata (no gravels) SPT results covered values from N = 9 @ -2.6 to N = 12 @ -6.5, were exhibiting a great sensitivity to any stress increment or disturbance, even the slightest ones, if exerted in proximity to Gavotti Palace, showing that its soil-foundation system was close to the bearing capacity.

What happened during the attempted grouting is, most probably, due to a combination of effects. On the Author's opinion, the main issue is here connected to the long setting time of a Portland cement based grout; accelerators may be added in this case, such as calcium chloride, soluble carbonates, silicates or triethanolamine, to reduce sensibly the setting time but, at most, it never falls below than some hours, because lubricants are always mixed in to improve the grout pumpability and these substances, in the classes of fly ashes or rock flours, act also as retarders (U.S.A. – D.o.D. 2004).

When the injection pressure (here applied from 0.4 up to 5 MPa) is released, at the end of a staged grouting, an expanded and stressed cavity is left in place, just filled by the injected volume; but, this local pressure let gradually go as a consequence of the grout seepage through these soils, thus allowing the shrinkage (or the eventual collapse) of a "deflating" soil cavity where, in effect, is a mix which will stay in a liquid state for hours.

Anyhow, a grouting approach still seemed the most appropriate methodology to improve the mechanical properties of the soil in place; in fact, a conventional underpinning technique was to be excluded, because of the observed behavior and of the Palace's actual damagement.

Chemical grouts' use began seriously some twenty years ago, with the employ of only few types as silicates, acrylamide, epoxy and some fatty acid derivates; since then, the kinds of grouts have proliferated with some of the originals still there, others dropping out entirely and still others changing in type.

Today the polyurethane grouts are confidently used, among other applications, in soil stabilizing; the two component systems in this class can have high expansive properties, with many of them capable of curing to a foam density of up to 0.9 KN/m^3 (6 lb/cu ft). Unlike the *hydrophilic* or *hydrophobic* systems, they do not require water as catalyst because the reaction is started when Part A comes into contact with Part B in a static mixing/injecting tube. They are generally faster reacting systems and can reach up to 25 times expansion in as little as 7 to 10 seconds (Magill & Berry 2007). These resins are injected using pressures which can reach up to 20 MPa and can substantially increase the soil's compressive strength.

Given their high expansion rates and extremely fast reaction times, they have the potential to move structures and require extreme care when using.

This type of chemicals seemed to meet the Gavotti Palace needs, taking also into consideration the fact that their grouting is made by the least invasive technique among any other; in fact, they are forced through small pipes (outer diameter < 20 mm) driven into the soil, with no pre-boring, by handheld electric hammers.

In Italy is quite a common practice to assess the efficiency of these groutings by monitoring, with laser-leveling systems on real-time, the heaving start of the structure under which the grouting is in progress. When a formal check is asked to demonstrate the obtained improvement, this is usually provided by taking SPT readings both before and after of the treatment.

Such empirical and subsequent procedures didn't seem acceptable in this particularly delicate case, hence, a first test pit was set up inside of the erecting yard, not far from Gavotti Palace; additionally, it was judged more appropriate to add at the usual SPT soundings the values of Cross-Hole (CH) shear waves velocity V_S, at different depths and through the whole soil volume of the test pit, before and after the grouting.

From the test pit it came out that the grouting could reach depths of no more than 4 meters below GL, because its fast-setting time clogged the tubing on the go.

The sub-Contractor studied a specific ratio of the two components, to augment slightly the curing time; then, on a second test pit it was demonstrated that the specifically mixed resin could be grouted down to 9 meters below GL, allowing to reach the embedded clay as was imposed.

Furthermore, the CH readings made through both of the test pits pointed out that the final V_S values had a gain, after grouting, which could confidently reach 1.5 times; hence, taking into account of the well known relationship as in (1) which, multiplied by the soil density ρ, relates this parameter to the dynamic shear modulus G_d:

$$G_d = \rho \cdot V_S^2 \tag{1}$$

the soil stiffness was expected to increase more than 2 times.

A soil improvement project was immediately planned, to be applied under the Gavotti Palace's foundation by following the operative procedures just established in the second test pit. In the sake of an extreme synthesis, it consisted in forming two vertically grouted screens down to the clay, made along two alignments flanking the Palace's wall on either the yard and the arcaded walkway sides; the screens shall have to confine the subsequent groutings, slant-diffused directly below the existing foundation to improve the mechanical behavior of all its loose-soil bedding. Nine CH borings were set up along the full contour of the Palace's foundation and, by them, the chemical grouting would have to be checked.

In addition, it was planned to modify the original layout of the sheet-piles, by deviating its bordering line farther from the Palace's wall and, just to stay on a safer side, the casings had also to be left in place.

4 NUMERICAL SIMULATION AND COMPARISON

The original project of the excavation's sequence, during which the emerging pile-wall have to be propped, needed a critical analysis and an eventual revision, to verify if the Palace's structure would have sustained the consequent, unavoidable and further deformations induced from the restarting yard activities.

A Finite Element Analysis seemed the appropriate tool to choose and, particularly, an implementation which would consent to take into full account of the soil non linearity, plasticity, anisotropy, heterogeneity and of a staged construction.

A commercially available code was selected and, given the on-site contour conditions, its plain-strain/stress version was judged proper, with a 15-node triangle as default to simulate the soil elements (Vermeer et al. 2002); this specific type of element provides a fourth-order interpolation for displacements and the numerical stress integration involves twelve Gauss points.

Without considering here the pure structural objects, to gain a realistic computation it was needed to implement a geometry model formed by five *material layers* (upper cover, sandy-silts, clayey-silts, lower-transition, bottom OC clay), further subdivided into a proper number of *clusters*, in order to activate/deactivate them at need to simulate the different *stages* of construction/excavation. The full mesh was formed by (circa) 3’450 elements, with an average size of 0.7 meters, linked by 28’500 nodes and giving a grand total which equals to 41’500 stress points. Thirteen computation phases were worth to analyze the complex of works’ progression and alternations (grouting, excavation, struts prop / release, concreting …).

Special *interface elements* were introduced to consider accurately of the soil-structure interactions, allowing friction with no-tension contacts.

The non-linear stress-strain behavior have been taken into account by the elastic, perfectly-plastic Mohr-Coulomb model, which requires five basic input parameters: a Young’s modulus, a Poisson’s ratio, a cohesion, a friction angle and a dilatancy angle; the last being relevant to account for irreversible increase in volume and to eventually mobilize the confining increase at contact interfaces.

To account for both the non-linearity and the plasticity, each stage of construction simulation proceed by *computation steps* up to the eventual (not granted) *phase convergence*: in the worst case of the many analyses here executed, 268 were required.

The Finite Element Model (FEM) permitted to discretize the loose-soils block resting below the Palace’s foundation in two *clusters* of elements and, during the *staged* analysis, their geotechnical parameters were updated to simulate the effects of the chemical grouting; this was substantially achieved by changing the soil elements’ shear resistances and moduli of deformability, respectively estimated from the after-grouting SPT and CH soundings. It’s worth to be pointed out that the values of the Young’s Moduli were deducted by (1) using, initially, the elastic relationship:

$$E_d = 2 \cdot (1 - \nu) \cdot G_d \tag{2}$$

then, the dynamic values obtained by (2) at very small strains were further modified, to render them appropriate to a static analysis as suggested in literature (Seed 1969 – Swiger 1974).

FEM analyses allowed to identify and correct some issues, among whose the most relevant had been: the depth at which the first stage of excavation must stop and the struts’ pre-stressing values, to be applied at both the planned levels, before of the deepening restarts.

Figure 4. The two levels of struts and the excavation at full depth.

The vertical settlements of the Palace’s foundation are shown in figure 5, both the computed and the measured ones, as they evolved during the staged construction; the comparison show a good agreement, even if the FEM simulation overestimated on the first stages: most probably, the chemical groutings had been better than expected.

It musty be finally observed that the full-front excavation, down to 9 meters below GL, caused a settlement of no more than 6 millimeters and, on the contrary, with the suspended first tentative of grouting alone 7 millimeters where surmounted.

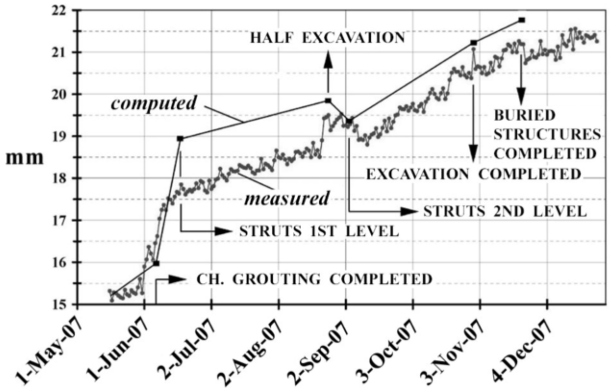

Figure 5. Gavotti Palace’s vertical settlements comparisons, as measured on-site by the leveling system (jagged lines) and as computed by the FEM analysis (straight lines).

5 CONCLUSION

This experience had proved that the expansive, fast-setting chemical grouts may really solve delicate problems but, forward testing, severe controls and firm specifications must be applied, during any stage of an intervention in order to reach a successful conclusion.

As a final remark, cooperativeness and well disposition of people is always welcome, being much more productive than any other attitude.

ACKNOWLEDGEMENTS

Many persons had a role to analyze and solve this problem as a whole, because of the multidisciplinary aspects which were involved. Among them, a mention is due to the Developer’s Technical Staff and, in particular, to Engineer A. Molfino (*M&L Engineering* – Genoa), Geologist G.B. Vezzolla (*SGG – Savona*) and Surveyor T. Cerutti for their full availability and cooperation.

Thanks are also due to Professors F. Lagomaggiore and S. Lagomarsino (*DICAT – University of Genoa*) who, acting as Consultants with the Author on the side of Savona’s Municipality, made the structural analyses and assessments on the complex elevation of Gavotti Palace.

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