Seismic isolation in existing complex structures

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SUMMARY:
The traditional techniques, based on the increasing of strength and ductility, are not always suitable for the seismic rehabilitation of existing structures. This is certainly true for cultural heritage buildings, designed without accounting for the seismic actions and therefore vulnerable even to moderate events, but also for complex structures, such as the structural aggregates of the Italian historical centre and the old plants at risk of a major accident, such as nuclear power plants and industrial constructions, where large separate buildings or components are connected by complex, vulnerable pipe and lifeline systems. Base isolation could be a suitable solution for the rehabilitation of such kind of structures. It aims to reduce seismic actions, thus avoiding significant damages to the structure and its contents even under strong earthquakes, and presents very low interference with the structure itself. Two new solutions are proposed, which consist in the realization of an isolated platform under the foundations of the building, without touching the building itself, patented by Soles, and ENEA and Politecnico di Torino, respectively.

Keywords: seismic isolation, existing structures, new anti-seismic technologies.

1. INTRODUCTION

The traditional techniques, based on the increasing of strength and ductility, are not always useful in the seismic rehabilitation of complex structures. These are cultural heritage structures, complex aggregates of old masonry buildings, typical of Italian historical centers but also industrial facilities, such as chemical and power production plants, including the nuclear ones, in which separate buildings or components are connected by complex lifelines, pipes and other links.

All the previous cases have some characteristics in common. First of all they are very vulnerable even to moderate earthquakes, because have been designed without accounting for the seismic actions properly and/or are characterized by irregular form both in plan and in elevation, which translates in irregular distribution of masses and stiffness. Furthermore, under earthquakes of high intensity, traditional structures can just guarantee against the collapse, but cannot avoid heavy damages to both structural and non-structural elements. As a result, they are not suitable for the structural types above mentioned. In fact, due to the historical importance and to the daily presence of tourists, in the case of historical buildings, and to the peculiarity of the industrial plants their seismic rehabilitation is quite delicate.

Base isolation could be a suitable solution for the rehabilitation of such complex structures. It aims to reduce seismic actions, thus avoiding significant damages to the structure and its contents even under strong earthquakes, and presents very low interference with the structure itself. In this paper a review of the applications of seismic isolation in existing buildings is first shown, then two innovative solution for the base isolation system are presented.

2. BASE ISOLATION IN THE EXISTING STRUCTURE

As well known seismic isolation is based on a terrific reduction of the seismic actions, which affect the structure, instead of relying on its strength. This result is obtained by increasing the fundamental period of vibration of the building, so that it becomes less vulnerable to earthquakes (Clemente & Buffarini 2008, Clemente & Buffarini 2010). In fact, the superstructure will be loaded by low effects thanks to the filtering of the seismic isolation system. Obviously, the isolation system should be designed so as to reduce the seismic action in the structure to the value that the restored building will be able to support in the elastic range. Usually, and particularly in the Italian technical code, two levels for the seismic actions are considered: i) the highest one is relative to the so-called collapse limit state (*SLC*) and is used for the check of the isolation devices; ii) the lower one is relative to the safeguard limit state (*SLV*) and is used for the check of the superstructure, for which a low structural factor, $q \leq 1.5$ is also allowed.

It is worth noting that both the elastic spectra should be plotted for the damping relative to the isolation devices, $\xi_{is} \geq 10\%$, but for $T < 0.8 \cdot T_{is}$ the damping of the superstructure must be considered, usually $\xi = 5\%$. It is opinion of these authors that, keeping in mind what said about the relevance and the strategic importance of the complex structures object of this study, the seismic event to consider for the *SLC* is that associate to the maximum return period $T_{R,SLC} = 2475$ years. The reasonable corresponding value for the *SLV* should be $T_{R,SLV} = 1215$ years (= $T_{R,SLC}/2.05$). So the first period of vibration of the isolated building is chosen as that one corresponding, in the *SLV* elastic spectrum, to a suitable value of the acceleration. This usually ranges from 0.10 to 0.25 *g*, depending on the seismic vulnerability of the structure. The corresponding period in the *SLV* spectrum is assumed as period T_{is} of the isolated building. Finally the corresponding acceleration and displacements values in the *SLC* spectrum are evaluated (Fig. 2.1).

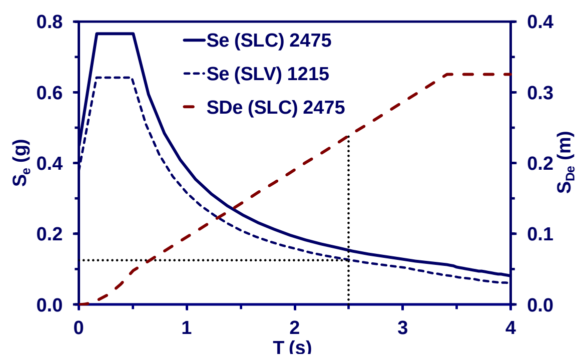


Figure 2.1 Elastic and design spectra

The chosen value of T_{is} must also guarantee a suitable decoupling between the motion of the building and the motion of the soil. As well known, in fact, the period of vibration of the isolated building should be much higher than the period of vibration of the superstructure, supposed fixed at its base. In practice the ratio between the two should be not lower than three. Besides, especially when using new anti-seismic technologies, the analysis of the local seismic response is necessary to find out the presence of any seismic amplifications in specific ranges of frequency at the specific site.

3. SEISMIC RETROFIT BY MEANS OF SEISMIC ISOLATION

3.1. Applications in reinforced concrete buildings

The first Italian building to be retrofitted with seismic isolation was the *Rione Traiano Polyfunctional Centre* in Naples, a large asymmetric, 4-storey reinforced concrete building with pile foundations. It had been erected in the ‘70s, before the classification of Naples as seismic zone, but left incomplete due to lack of funds. The insertion of the isolation devices was realized by means of the cut of pillars and walls at the foundation level. Approximately 600 HDRBs were installed, the pillars were reinforced and a steel beams floor was added just above the isolators to provide the stiffness necessary to allow for the correct transmission of the horizontal forces to the isolators themselves and the superstructure (Fig. 3.1). The works were completed in 2004.

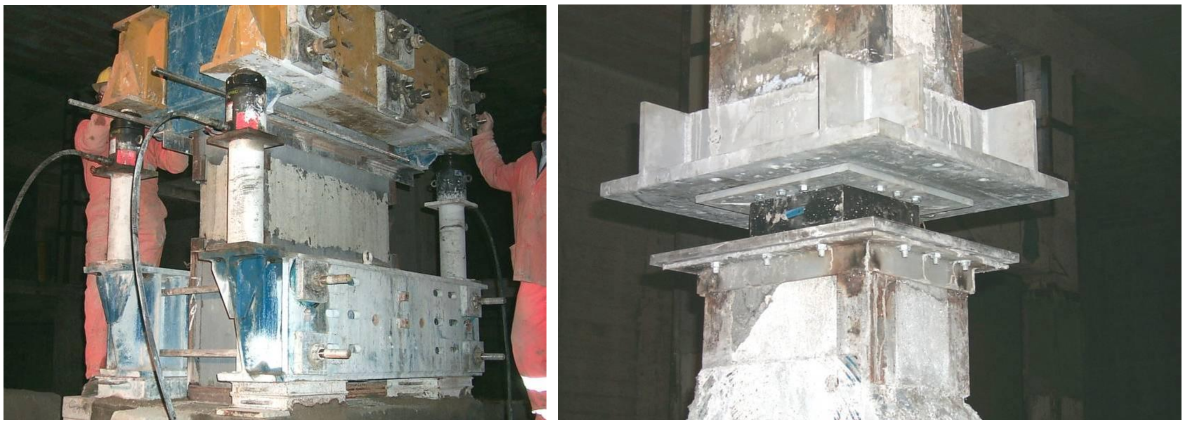


Figure 3.1. One column of the building in Rione Traiano (a) before the cut and (b) after the installation of the isolator (courtesy by R. Sparacio)

In 2005 the retrofit of a reinforced concrete building with seismic isolation by means of the realization of a sub-foundation was completed (Fig. 3.2). It had suffered severe but non-structural damage during the 1997-98 Umbria-Marche earthquake. 56 HDRBs of two sizes were used, of 400 *mm* and 450 *mm* diameter, respectively. The construction phases consisted in: i) the realization of the ground retaining wall around the building; ii) the excavation under the existing basement level at the side of the original foundation piles; iii) the injection of the new foundation piles (4 for each previous couple) around the base of the original ones; iv) the realization of the basement of the new underground floor. The isolators were then inserted, superposed to flat jacks, in which epoxy resins was injected to put in action the isolators and finally cut the old piles.

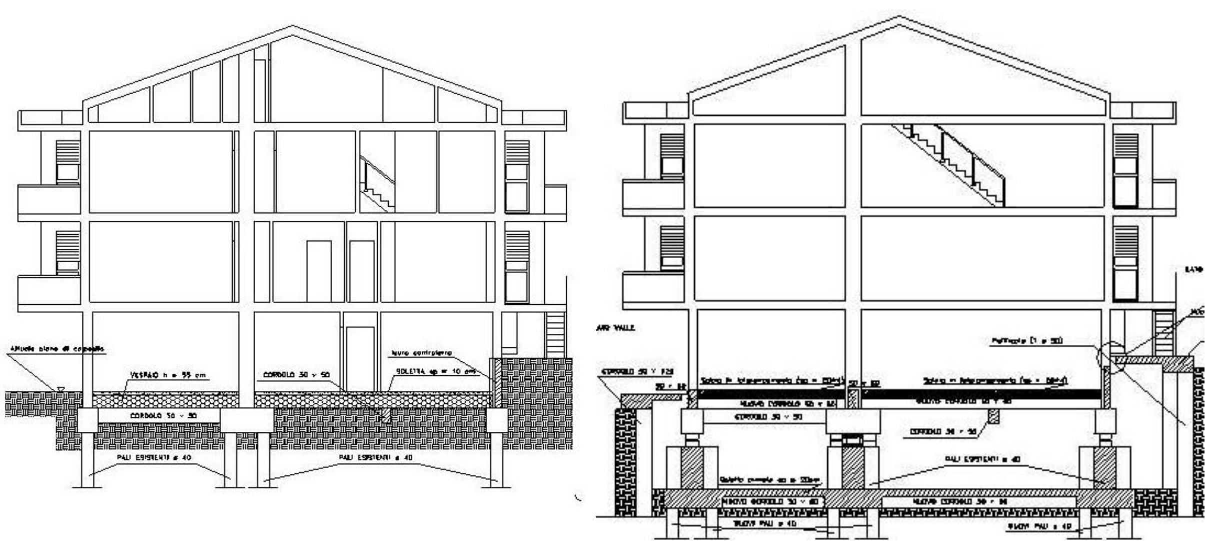


Figure 3.2. The building in Fabriano (a) before and (b) after the retrofit (courtesy by G. Mancinelli)

3.2. Applications in masonry buildings

The Saint Francisco City Hall, built after the collapse of the previous structure during the 1906 earthquake, has sizes in plan of 94 and 124 *m*, a very heavy dome with a diameter of 27 *m* and a height of more than 90 *m* (Fig. 3.3) The building has five levels, a steel carrying structure and masonry walls, which contribute to support the horizontal actions. The building suffered heavy damages due to the 1989 Loma Prieta earthquake. The retrofit was done by means of the insertion of an isolation system and the realization of concrete shear walls. The construction phase were the following. The foundations were first reinforced with new beams and a new deck was realized above the isolation interface. Then, the structural elements were shored up and the foundations were cut at their top. Hydraulic jacks were used as temporary supports for steel columns and brick walls to install the lead rubber bearings under each column. The isolation system was completed in 1998.

Also the City Hall of Oakland was seriously damaged by the Loma Prieta earthquake in 1989. It had been completed in 1914 and has a height of 99 *m*. From the podium, composed by the first three levels with size in plan of 38 and 56 *m*, the Office Tower of ten levels rises up and from this the Clock Tower of about 27 *m*. The carrying structure is composed by steel frames and masonry walls with the original foundation in reinforced concrete. The structural analysis pointed out that traditional interventions would not suitable to improve the seismic behaviour, so seismic isolation was considered in order to make regular the dynamic response of the structure. 112 devices were installed and the superstructure was strengthened by means of reinforced concrete shear walls. Structural details were studied to protect the structure from earthquakes during the works, and the construction phases guaranteed the symmetry. The work were completed in 1995.

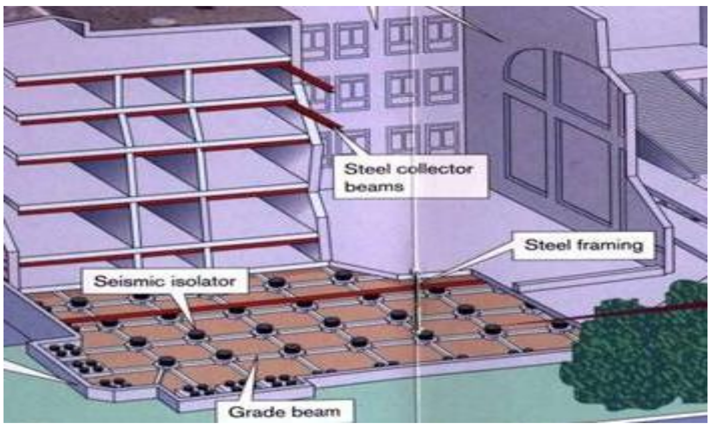


Figure 3.3. The Isolation system in the City Hall in St. Francisco

A very interesting intervention was done on the school in Vanadzor, Armenia. It was designed by Melkumyan after the 1988 earthquake. The location of isolators devices are shown in Fig. 3.4, and the construction phases were:

- realization of windows in the masonry walls at the isolation device positions. The window should be high enough to contain a lower and a upper beams and the isolator device;
- construction of the portion of the lower concrete beam, with the overlap steel bar between the beam portion of the considered window and the next ones;
- installation of the isolation device;
- realization of the portion of the upper concrete beam, with the overlap steel bar between the adjacent windows;

- realization of the sandwich beams above and below the isolators;
- cutting of masonry between the windows.

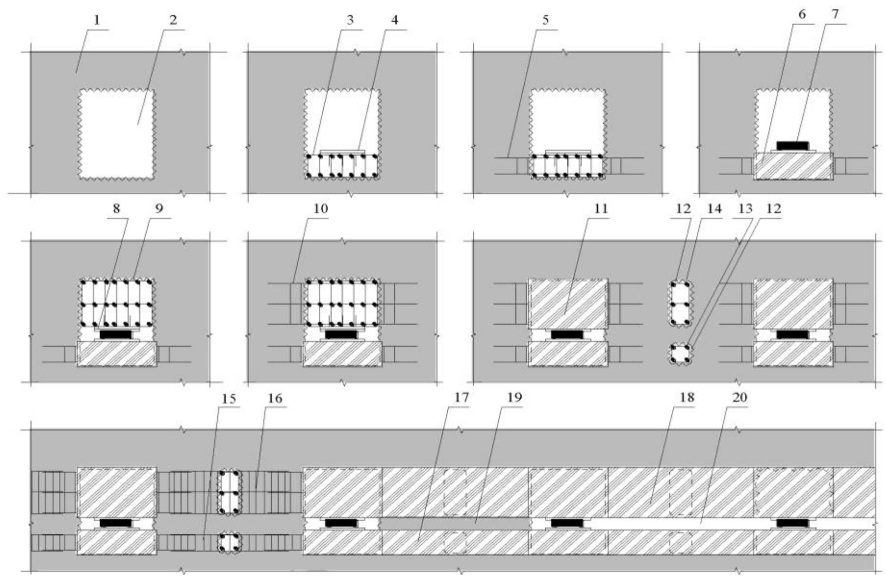


Figure 3.4. Application of base isolation in the school in Vanadzor: construction phases (courtesy by M. Melkumyan)

Among the proposals with this procedure, not realized at the moment, it is worth reminding the seismic retrofit of the Iran Bastan Museum in Tehran (Santini et al. 2007, Clemente et al. 2009) and the seismic retrofit of a residential building in Belluno, Italy (Forni & Clemente, 2006).

4. NEW SOLUTIONS FOR BASE ISOLATION IN EXISTING BUILDINGS

In all the previously mentioned cases the insertion of base isolation is made by means of traditional works and is not very expensive, but presents the disadvantages of requiring the modification of the ground or underground level and of the foundations. Besides, it is not reversible, and so not always applicable in practice for historical constructions. In the following two new solutions are proposed.

4.1. Insertion of the seismic devices in existing buildings

The Soles company developed a new technology for the application of seismic isolation to existing buildings. It is based on the lifting by means of the application of methods that represent the technological development of the systems used and developed by Soles in the last forty years (Fig. 4.1).

The technology is based on the construction of a new reinforced concrete foundation plate placed on the ground and a second reinforced concrete plate laying on the first one but connected to the existing foundations of the building. The first plate could also be substituted by a set of Soles piles, the choice depending on the mechanical properties of the soil.

Besides, jacks are positioned on devices included in the upper foundation plate. By means of them and pushing against the lower plate, the upper plate is lifted together with the existing structure. Finally, the seismic isolation devices are placed between the two reinforced concrete plates.

(a) existing building

(b) First mat foundation not linked to the building and Soles® piles

(c) Second foundation linked to the structure

(d) Positioning of hydraulic jacks and lifting of the building

(e) insertion of the isolators

(f) Disassembly of the jacks

Figure 4.1. Construction phases for the "Insertion of the seismic devices in existing buildings"

The raising of the structure is carried out in a safe and "simple" way. In fact, due to the low values of speed and movement, the structure is never considered under dynamic actions. Besides, it is always possible to stop the raising whenever necessary in order to allow inspections, monitoring, calibration and modification of the electric or hydraulic machinery. In this way, the risks that could arise from the cut of the existing structural elements are eliminated as well as the necessity to create joints in the stairs, in the elevator shafts and in the partition walls. The two foundation plates are provided with manholes and wells, so allowing the inspection, the maintenance and the replacement of the seismic isolators.

Recently, this type of intervention has been used for the seismic retrofit of a building, whose structure that suffered very few damages during the 2009 L'Aquila earthquake was actually not able to support significant seismic actions and has also been proposed for the seismic rehabilitation of Palazzo Margherita, the City Hall in L'Aquila (Fig. 4.2).

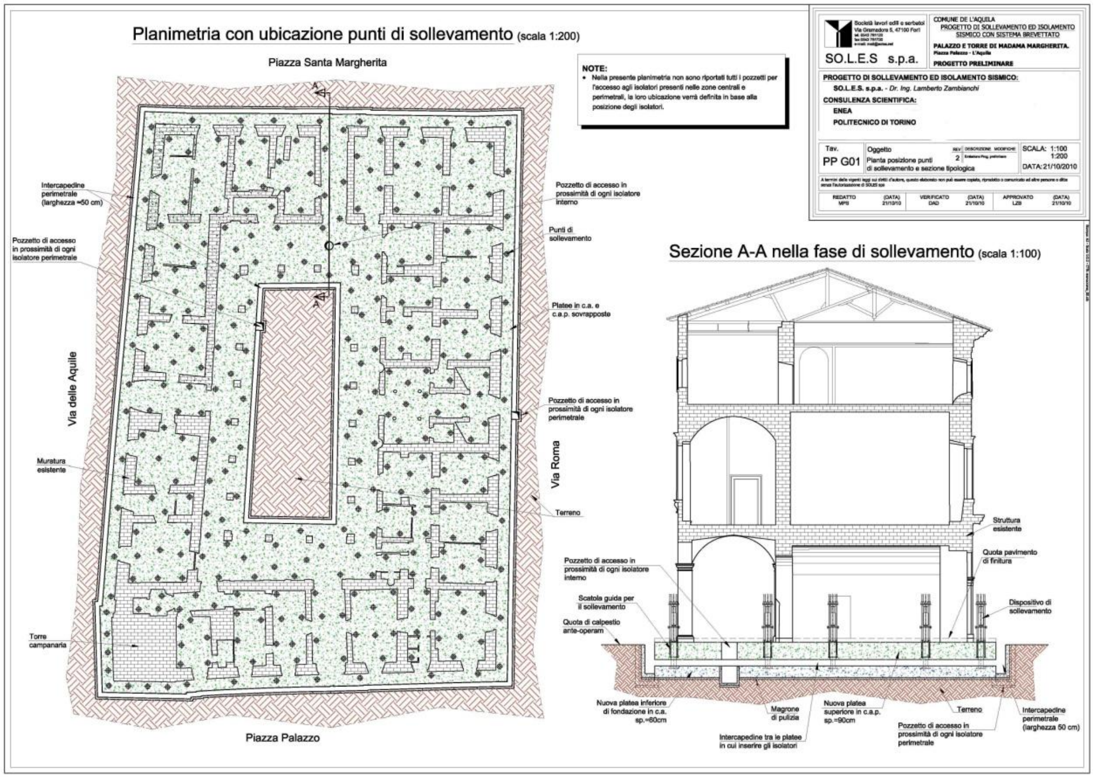


Figure 4.2. The proposed Soles system for Palazzo Margherita in L'Aquila

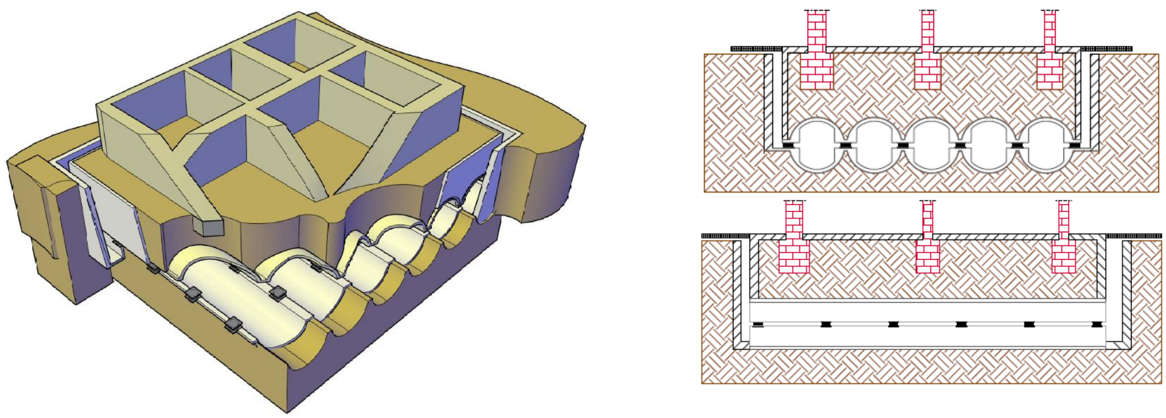
4.2. Seismic Isolation Structure for Existing Buildings

The Seismic Isolation Structure for Existing Buildings (SISEB) consists in the realization of an isolated platform under the foundations of the building, without touching the building itself (Fig. 4.3). A discontinuity between the foundations and the soil is created by means of the insertion of horizontal pipes and the positioning of isolation devices at the horizontal diametric plane. The pieces of pipe should have a particular shape and are composed by two portions, the lower and the upper sectors, respectively, which are connected by means of removable elements. Then the building is separated from the surrounding soil in order to allow the horizontal displacements required by the isolation system. So the structure is seismically isolated but not interested by interventions that could modify its architectural characteristics, which is very important for historical buildings.

Even underground level are not modified but can be part of the seismically protected building. In more details the construction phases are the following:

- a trench is first excavated of at one side of the building and pipes are inserted by means of auger boring or micro-tunnelling technique; the diameter of pipes should be ≥ 2 *m*, in order to allow the inspection of the isolation system;

- the connection elements placed in correspondence of the isolation devices are removed and each pipe is joined with the two adjacent ones, for example by means of a reinforced concrete elements;
- the isolation devices are positioned and the upper adjacent sectors are connected in correspondence of the isolators;
- successively also the other connection elements are removed, so the lower and upper sectors are definitely separated;
- finally vertical walls are built along the four sides of the building and a rigid connection, a concrete slab or other, is realized between the building and the isolation system.



(a) (b)

Figure 4.3. The new isolation system: (a) view; (b) Longitudinal and transversal cross-sections

The system allows also the realization of a tunnel for pedestrian or vehicles. The size of the pipes must guarantee the accessibility and the possibility to substitute the devices. It is worth reminding that the solution presents the advantages that the building and its architectural aspect are not changed and so are the underground levels; this is a very important requirement for historical and monumental structures but also for complex and aggregated structures in general.

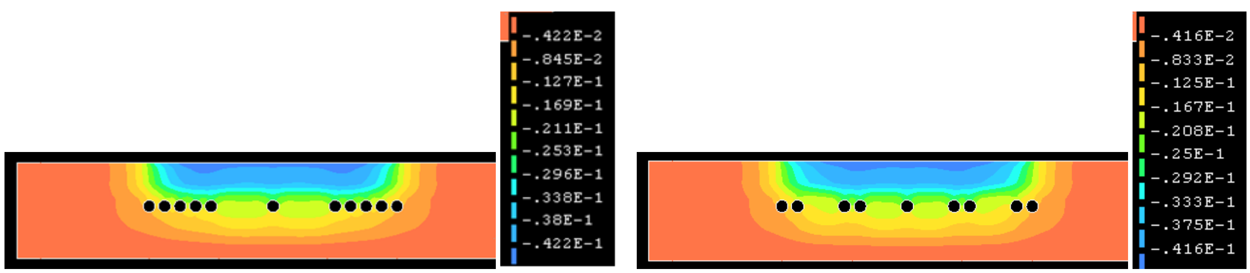
Two issues can be studied in detail, which could arise during the micro-tunnelling operations: the soil settlement and the vibrations induced at the surface level. According to previous experiences, relative to large tunnelling works or vertical boreholes, actually not strictly pertinent, vibrations induced by micro-tunnelling are not very dangerous, but theoretical and experimental deeper studies are needed. Instead, serious problems can arise by settlements (Barla and Camusso 2011, Barla and Viggiani 2002, Miliziano et al. 2002).

To analyze the issues in details we referred to a specific case study, Palazzo Margherita in L'Aquila, for the rehabilitation of which SISEB has been proposed also (Clemente and De Stefano 2011). First of all an experimental campaign has been carried out in order to find out the dynamic characteristics of the structure (Buffarini et al. 2011). Then a seismic improvement intervention has been defined, which allows the structure to be able to support minimum horizontal actions. On the basis of the effective earthquake resistance of the restored structure, the base isolation system were designed.

Thanks to a previous experimental dynamic characterization of the near site, it was possible to model the mechanical properties of the ground with accuracy, by means of a FE 2-D model was set up and then exploited in *Diana 2* environment. The vertical edges of the model were kept far enough from the perturbed zone, in order to minimize their influence. The nodes belonging to those edges were restrained by means of spring and dampers able to cut-off the wave reflection.

In the model the soil was described as a layered continuum indefinitely extended, supported by the bedrock at 17 *m* depth. Each layer was 1.0 *m* thick and its elastic dynamic tangential modulus was coherent with the measured wave propagation velocities. The mass density was assumed equal to 2090 kg/m^3. and the building imposes a load of 3000 *kN/m* uniformly distributed along its base width, which induces a local settlement. Eight node quadrangular elements were used, with aspect ratio near to one and regular shape. The plane deformation condition was imposed and the boundary nodes respected the following restraining conditions: vertical displacements were inhibited at the nodes belonging to the lower horizontal edge; horizontal displacements were inhibited at the nodes belonging to both the lateral vertical edges.

Then micro-tunnels, later named simply "pipes", are included in the model, following two different alternative strategies: i) one central pipe first, then the two most external ones and all the other filling the layer from the external pipes to the centre; ii) one central pipe first, then the two most external ones; other pipes are then inserted in intermediate positions, regularly spaced, filling gradually the layer. The advances following the two strategies are shown in Fig. 4.4, respectively, where the settlement is also represented. The boreholes induce an additional settlement, which we are interested to estimate. The problem being non-linear, the settlement due to insertion of pipes, originated by a stress release process, is computed as difference between the settlement due to the weight of the building and the insertion of the pipes and the settlement due to the weight of the building alone. The stress release during micro-tunnelling is a three-dimensional mechanism that shall be described by a plane-strain two-dimensional model, as previously stated. It is possible to reach that goal through a conventional hole-boundary force reduction approach known as "β-value method" or convergence-confinement method proposed by Panet and Guenot (1982) using the stress-release factor λ, varying in the range 0÷1 (Barla and Camusso, 2011). Analyses are then based on the decrement of a fictitious internal pressure at the boundary of the holes in agreement with the β-value method. To apply that method inside the FE model, simply supporting elastic restrains are distributed along the hole boundaries, with operating direction orthogonal to them. By modifying the stiffness of the elastic supports it is possible to simulate the stress release. A null stiffness of the elastic support gives λ=1. For the actual case study we assume λ=0.4 and *H/D* =3.5, where *H* is the depth of the pipe axis and *D* is the diameter of the pipe.



a) strategy 1 b) strategy 2

Figure 4.4. Filling the layer of pipes

The strategy 1 is easier to apply, but the effect on soil adaptation is not so smooth and regular. The final computed value of the settlement is about 6.8 *mm*. The strategy 2 leads to more regular advancement and allows a slight settlement reduction to about 5.6 *mm*. Increasing the stress release factor λ to 0.6 the settlement values increase of about 20%. Besides, the case low depth with *H/D* = 2 and λ=0.4 showed an increment of the maximum displacement of about 27% with reference to the case of *H/D* = 3 and λ=0.4. It is worth noting that in this case some uplift, of very low values, were pointed out around the hole. A larger *H/D* ratio reduces the problem but increases the cost of the trenches. Technologies to contrast the settlements exist and are consolidated but, of course, they push the cost up.

5. CONCLUSIONS

The application of seismic isolation to existing complex structures represent one of the most interesting challenges of the next future. On one hand, it is the only useful strategy in some cases, on the other, it a correct use and application of seismic isolation is required to guarantee its proper working. The new proposal here shown are characterized by the realization of a isolated platform under the building foundation without any intervention on the building itself. The first one is very suitable for single buildings, the second one can be also used for complex structure, typical of Italian historical centers, and in any situation in which separate buildings or components are connected by complex lifelines, pipes and other links. Such condition is usual, for instance, in chemical and power production plants, including the nuclear ones.

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