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An interpretation of jet grouting effects on the retaining structures of a deep excavation and on adjacent buildings

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ABSTRACT: This paper deals with the effect that an extensive jet grouting treatment produced on pre-existing structures. For the excavation of the new underground station of Conca d'Oro in Rome, adjacent jet grouted columns were created, that connected the two opposite diaphragm walls to provide horizontal contrast, and to reduce the hydraulic flow into the excavation. The jet grouting operations induced significant movements of the diaphragm walls and of the adjacent buildings, that were monitored carefully during the entire construction process. The monitored quantities allowed to establish relationship between the induced structure deformations and some jet grouting parameters, such as the daily production rate and the cumulative number of the jet grouted columns. On the basis of the monitoring results, it was also possible to devise an interpretation of the mechanisms that regulate the jet grouting-induced soil displacements.

1 INTRODUCTION

Displacements induced by deep excavations on the adjacent structures are becoming a basic concerns related to the construction of new underground infrastructures in urban areas.

Vertical displacements at surface points are a result of displacements induced at larger depths, that propagate upwards. Schematically, the main sources of vertical settlements at the ground surface can be thought to be (a) the horizontal displacements of the retaining structures; and (b) the stress-relief-induced heave of the soils located below the bottom of the excavation (Burland *et al*. 1979).

Horizontal wall displacements can only partially be limited by props or anchors, because these constrains can be installed only after the excavation has reached the corresponding elevation. Bottom heave is a direct consequence of the reduction in vertical stress associated with the excavation, and cannot be limited with ordinary support techniques. It is therefore tempting to improve the mechanical properties of deep soil layers within two facing retaining walls in a construction stage that antecedes the commencement of the excavation (pre-strutting), in order to restrict the horizontal wall movements from the earliest excavation stages, and to limit the bottom heave.

Soil improvement at large depths may be achieved with jet grouting, producing secant jet grout column to form a treated layer characterized by increased stiffness and strength. If the jet grouting-treated soil is coarse-grained, the treatment has also the beneficial effect of reducing the soil permeability and hence to minimize any water inflow related to the hydraulic head difference between the external soil and the excavation bottom. This technique was used in a number of projects (Gaba 1990, Sugawara et al. 1996), often involving jet grouting in fine-grained soils.

Jet grouting consists of an erosion of the soil through a very high fluid pressure, with a concurrent injection of grout. Because of the high pressures employed, the soil is not only cut, but also displaced laterally; this effect is more evident in fine-grained soil, and can lead to significant soil movements that can affect the retaining walls and may propagate up to the soil surface (Wong & Poh 2000). The following sections illustrate the ground and structure displacements produced by an extensive jet grouting treatment employed for the pre-strutting of a deep excavation. It is shown that it is possible to relate these detrimental effects to the main characteristics of the grouting and to the specific soil profile encountered.

2 PROJECT DESCRIPTION

The line B of the Rome underground is being extended northwards, (B1 extension) with the addition of three new stations. Figure 1 shows a plan view of the deep excavation needed to accommodate the Conca d'Oro Station: it has an elongated shape, with a length of about 170 m and a width variable between 22 and 35 m. This plan view also shows the location of four boreholes and three CPT verticals, and the position of a portion of the monitoring instruments that is relevant to the data presented in this paper. This instrumentation consists of inclinometer tubes, inserted both into the diaphragm wall and in the soil external to the excavation; and a large number of topographical benchmarks for the precision levelling of six buildings adjacent to the excavation.

Figure 1 also shows a longitudinal and a transversal section through the new subway station. The soil profile consists of a top layer of made ground, with a thickness of 7 to 9 m, overlying a thick alluvial deposit of medium-soft silty clay. The clay fraction of this deposit increases below the depth of 17–18 m and the soil becomes less consistent, with an undrained shear strength of the order of 80-100 kPa, that becomes lower than 50 kPa in the central zone of the excavation. A sandy gravel layer is found below this soft fine-grained deposit, at depths generally larger than 40 m, with the exception of the North-East section of the excavation, where it emerges and is encountered at depths smaller than 30 m.

The excavation has a depth of 24.6 m and is retained by two facing reinforced concrete diaphragm with a thickness of 1.2 m, reaching a

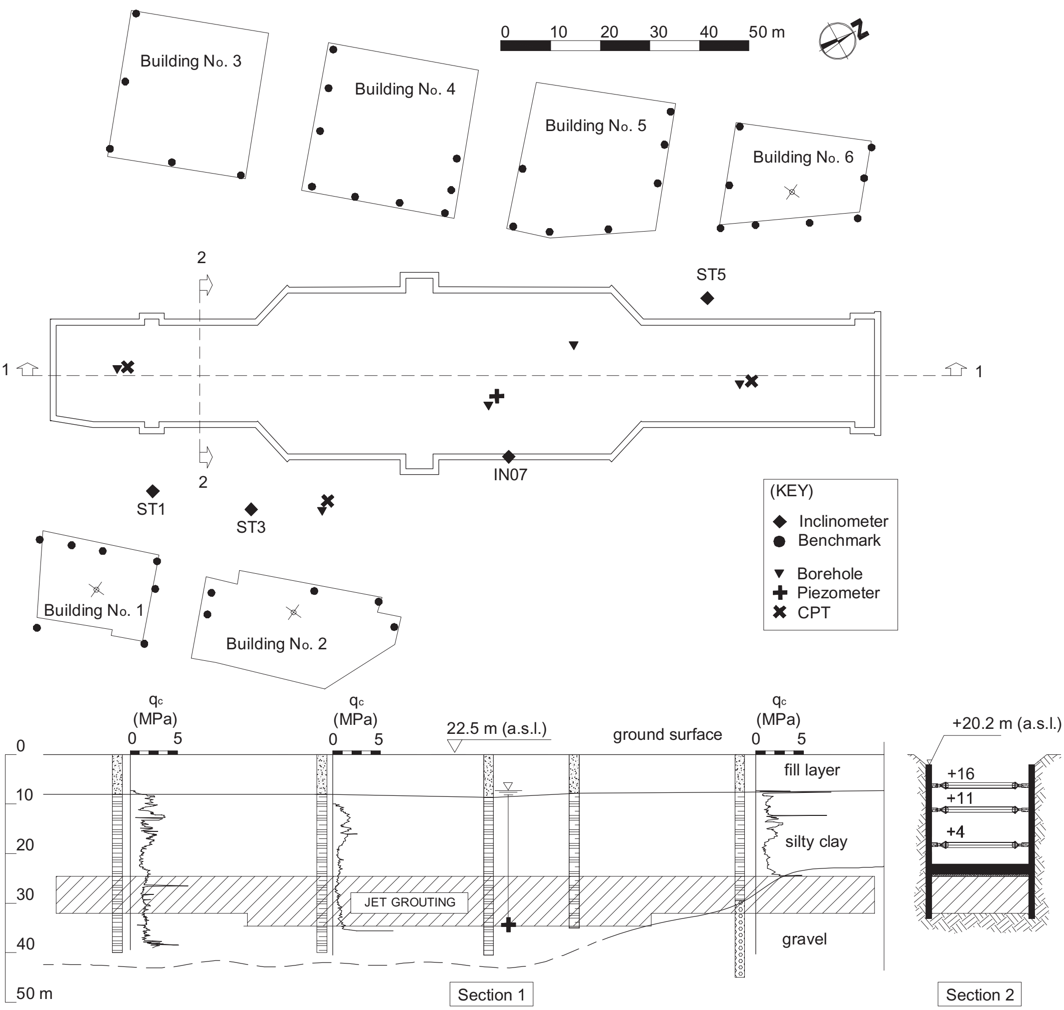

Figure 1. Conca d'Oro subway station in Rome: plan view with an indication of the monitoring instruments mentioned in this paper, and vertical sections with soil profile and jet-grouted levels.

depth of 33.1 m. The excavation was carried out with the bottom-up technique, installing progressively three levels of temporary tubular steel struts, casting a bottom concrete slab, and erecting the internal reinforced concrete structure that gradually replaced the temporary struts.

After a preliminary excavation down to the depth of 2.3 m, a pre-strutting soil treatment was carried out by jet grouting into the soil encountered at a depth interval of 25 to 32–35 m, as indicated in Figure 1. The soil treatment consisted of the formation of secant jet-grouted soil columns, with a diameter of 1.5 m, arranged in a triangular pattern with a spacing of 1.04 m, as shown in Figure 2. The nominal overlapping percentage associated with this pattern is equal to 73%. Figure 1 shows that the treated soil belong mostly to the fine-grained alluvial deposit, with the exception of the North-East section of the station, where the sandy gravels are encountered below the bottom of the excavation.

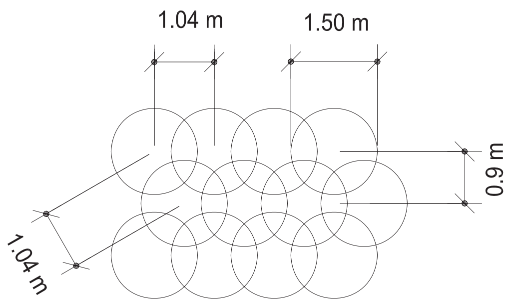

Figure 2. Planimetric arrangement of the jet-grouted columns.

The project area was sub-divided into three sectors: A, B, and C. Table 1 reports the main jet grouting parameters used in the different sectors. In Figure 3, for each sector a temporal bar chart shows the actual daily rate of treatment performed, and, on a separate scale, the cumulative number of columns produced. The grouting operations started in Sector A, with a gross average rate of about 7 columns per day, but with peaks of 22 col./day. The jet grouting was of the double-fluid type, involving a fast rod rotation (12 rpm) and a 45 MPa grout injection pressure.

The jet grouting in Sector C was carried out initially at an average rate of 8.5 col./day for the first 3.5 months, and then proceeded at a very slow

Table 1. Jet grouting parameters.

Operation parameter	Value
Sector A	
Specific energy	57.82 MJ/m
Grout injection pressure	45 MPa
Grout flow rate	0.275 m^3/min
Air pressure	1 to 1.2 MPa
Rod withdrawal rate	0.21 to 0.37 m/min
Rod rotation rate	12 rpm
Water cement ratio	1:1
Sectors B and C	
Specific energy	55.19 MJ/m
Grout injection pressure	41 MPa
Grout flow rate	0.340 m^3/min
Air pressure	1 MPa
Rod withdrawal rate	0.25 to 0.26 m/min
Rod rotation rate	5 rpm
Water cement ratio	1:1

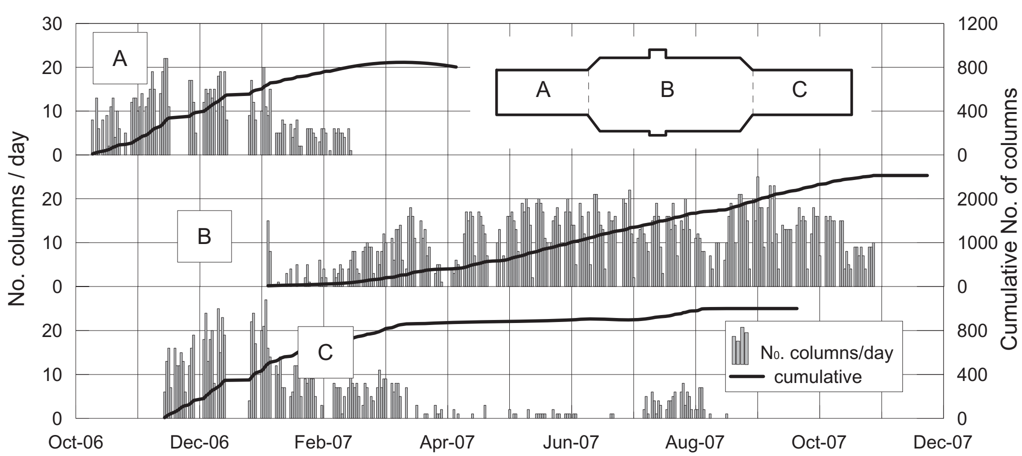

Figure 3. Daily and cumulative production rates of the jet grouted columns.

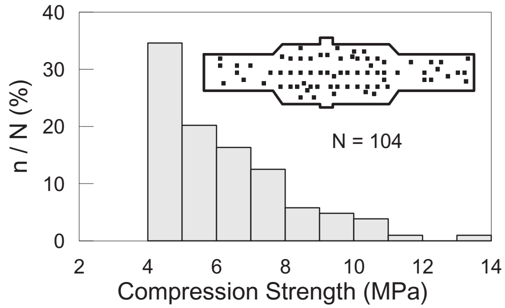

Figure 4. Distribution of the unconfined compression strength measured on core samples retrieved from the jet grouting columns.

rate. Peak rates over the first two months exceeded 25 col./day. In Sector B, after a low initial treatment rate, an average rate of about 11 col./day was maintained, with daily peaks of 20 columns. The jet grouting parameters in the B and C sectors were different, however, involving a much slower rod rotation and a somewhat larger grout flow rate (see Table 1).

A total of 104 core samples of jet-grouted soil were retrieved below the final excavation level, and were subjected to unconfined compression tests. The histogram of Figure 4 shows the distribution of the observed unconfined strength. All the tested samples showed a strength larger than the contractual requirement of 4 MPa. The effectiveness and spatial continuity of the treatment was also checked using a cross-hole seismic tomography. The measured shear wave velocities ranged between 900 and 1100 m/s.

3 INTEPRETATION OF THE MONITORING RESULTS

Figure 5 shows the horizontal displacements of the inclinometer tube IN07, measured during the jet grouting operation. This inclinometer was installed into a wall panel, and the horizontal displacement at the tube head was monitored with an independent topographic survey. Figure 5a shows the displacement time history of the inclinometer head, while Figure 5b shows the profiles of the measured horizontal displacements at selected time instants. In July and August 2007 the topographical measurements were temporary suspended: hence, the observations carried out after August 2007 were corrected on the basis of the previous displacement gradient, as shown in Fig. 5a.

The inclinometer IN07 is located in Sector B, and was very sensitive to the soil treatment carried out in this area: the jet grouting operations

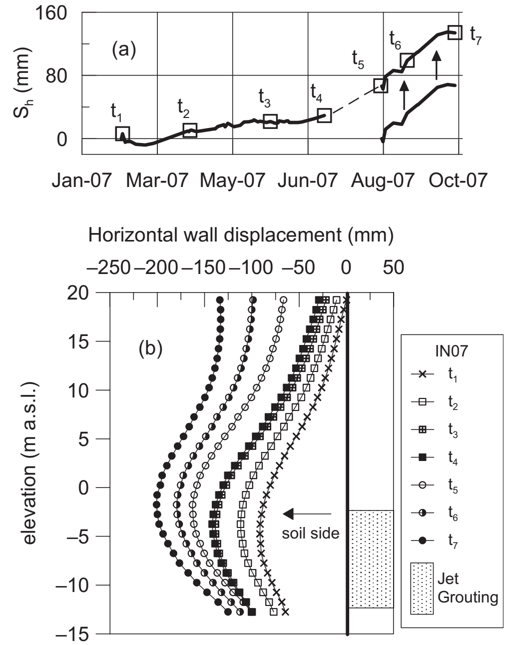

Figure 5. Horizontal displacements induced by the jet grouting, measured at inclinometer IN07, installed in the diaphragm wall.

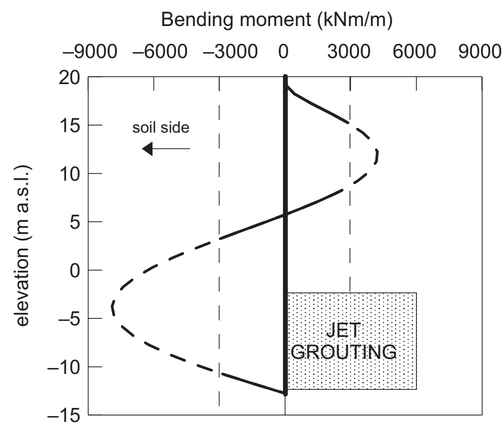

Figure 6. Bending moment profile in diaphragm wall, computed from the measurements shown in Figure 5.

displaced the wall panel away from the prospective excavation by an amount as large as 130 mm. The temporal increase of the horizontal displacements resembles closely that of the cumulative number of columns produced in sector B (see Fig. 3). An estimate of the bending moments in the panel associated with this displacement was obtained through a numerical differentiation of the displacements profile, assuming a nominal bending

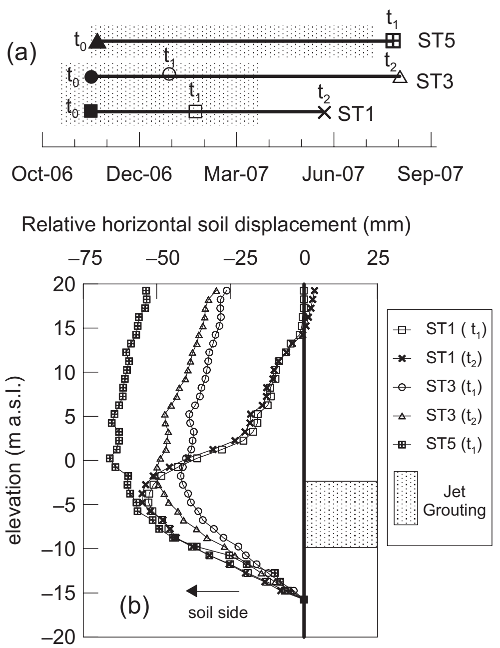

Figure 7. Horizontal displacements induced by the jet grouting at inclinometers ST1 and ST3, installed in the soil, external to the excavation.

stiffness $EI = 5.33$ GNm^2/m. The resulting bending moments are shown in the plot of Figure 6: as the wall bending capacity is close to 3000 kNm/m, it can be seen that the displacements induced by the jet grouting produced an extensive yielding of the diaphragm wall.

Figure 7 shows profiles of the horizontal displacements measured at inclinometer tubes ST1, ST3, and ST5, installed in the soil, midway between the excavation perimeter and Buildings No. 1, 2, and 6, respectively. As no independent measurement of the tube head displacement was carried out, the profiles in this figure represent merely the horizontal displacement relative to the tube toe. The maximum relative displacement induced by the jet grouting along these verticals is similar, reaching 50 to 65 mm, but the shape of the profiles is different: the displacements along the vertical ST1 show much larger gradients at an elevation corresponding roughly to that of the grouted layer, suggesting the occurrence of some grout leakage from the panel joints. The displacement profiles of inclinometers ST3 and ST5 have a gentler slope, that is probably a result of a more uniform displacement of the diaphragm wall away from the excavation.

The horizontal displacements induced by the jet grouting in the wall panels and in the surrounding soil resulted in appreciable movements of the six buildings adjacent to the excavation perimeter. The vertical movements of the topographic benchmarks of Figure 1 were precision-levelled continuously. This paper presents data relative to Buildings No. 1, 2, and 6, that are all founded on bored piles. For a single building, the vertical displacement at a given time instant were least-squares fitted with an interpolating plane. Figure 8 shows, for this three buildings, the vertical displacement w of the reference points shown in Figure 1, read on the interpolating plane, and the slope (α) of the plane in a direction orthogonal to the excavation. Positive values of w denote heave, while positive values of α signify a rotation of the building away from the excavation area (see Figure 8a).

The composite diagram of Figure 8b is relative to Building No. 1, and shows the time histories of w and α, together with that of the horizontal relative displacement of the inclinometer tube ST1 (located between the building and the excavation perimeter) at an elevation of –4 m a.s.l. These time histories are compared with the daily production rate and with the cumulative column production for Sector A. (Note that monitoring of the ST inclinometer tubes was commenced somewhat later than the initiation of the jet grouting.) As a consequence of the jet grouting, the building heaves, reaching a maximum vertical displacement of 7.5 mm, and rotates away from the excavation ($\alpha_{max} = 1.2 \times 10^{-2}$ deg).

A salient feature of Figure 8a is that the horizontal displacements have a temporal trend analogous to that of the cumulative jet grouting production, while the trend of the vertical displacements and rotations of the building is very similar to that of the daily production rate. Any pause in the jet grouting production rate resulted very clearly in a reduction of the building heave and rotation. After the completion of the treatment in Sector A, the horizontal soil displacements remained about constant, while a progressive reduction of the building displacements was observed, down to the somewhat constant residual values of $w = 2$ mm and $\alpha = 3 \times 10^{-3}$ deg.

A possible interpretation of the mechanism at stake for this building is schematically depicted in Figure 9. Because the soil encountered at the jet grouting elevation is fine-grained, it can be expected that the horizontal deformation induced by the formation of the jet-grouted column is, at least partially, undrained. In the short term, the volumetric strains in the soil can only be very small, and any horizontal displacement must be accompanied by a vertical heave, and by a corresponding increase in the pore water pressures (Figure 9a). The nature of the horizontal displacements is largely permanent because the hardened treated columns constitute a rigid inclusion in the soil. After any pause in

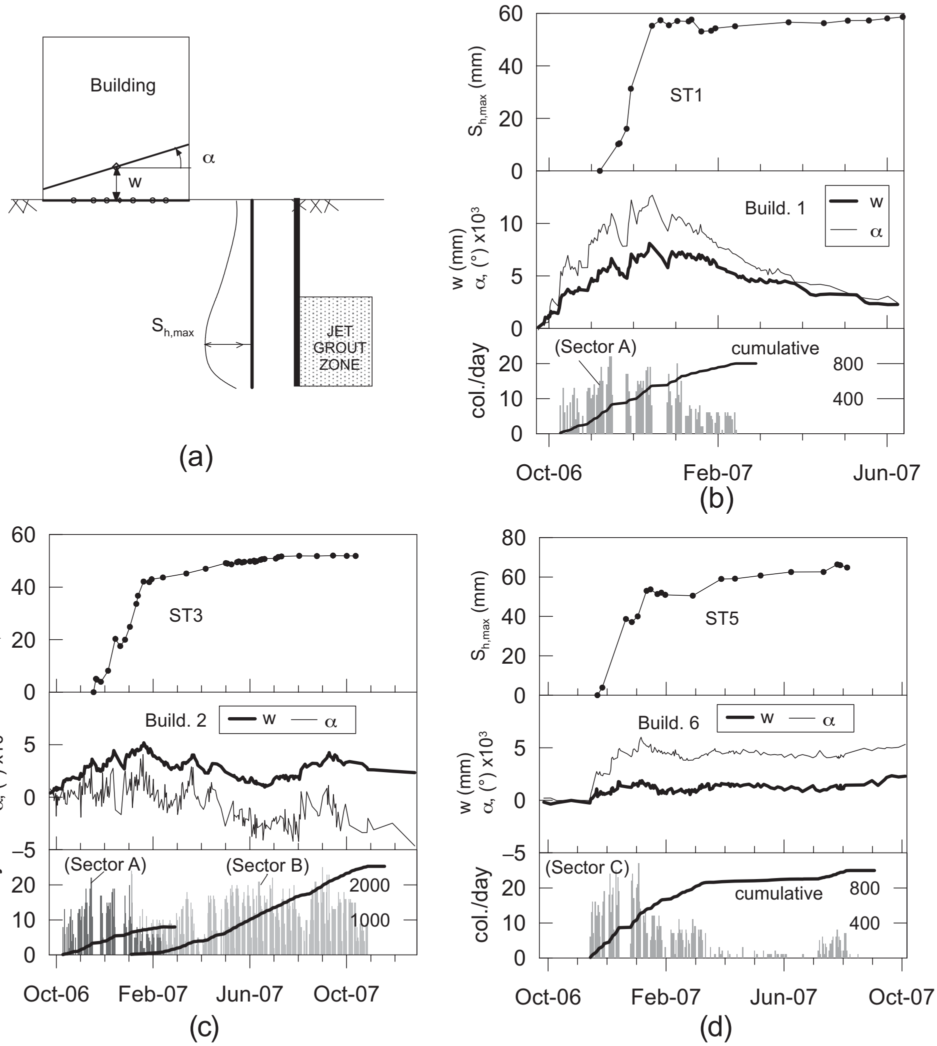

Figure 8. Time histories of horizontal displacements in the inclinometer tubes and vertical displacements of the corresponding buildings, compared to the jet grouting daily and cumulative production rates.

the treatment, and at the end of the jet grouting process, consolidation takes place, involving a reduction of the excess pore water pressures and a recovery of most of the vertical displacements (Figure 9b). Residual vertical displacements may be ascribed to the deviatoric components of the strains induced by the jet grouting, and to some leakage of the grout through the panel joints.

The displacement pattern for Building No. 2 is more complex (Figure 8b), because arguably this building was influenced by the jet grouting carried out in both Sector A and Sector B. However, the overall behaviour is quite similar to that outlined for Building No. 1: jet grouting caused an horizontal permanent displacement of the soil located between the building and the excavation area, as indicated by inclinometer ST3. The building heaved (w_{max} = 5 mm) and showed a very slight rotation, initially away from the excavation, and subsequently in the opposite direction. Once again, vertical displacements are very sensitive to the daily treatment rate, and are partially recovered as a consequence of any pause in the treatment. Between February and July 2007, jet grouting was carried out predominantly in the North-East portion of Sector B, and therefore interested only marginally the building, that recovered a significant portion of the previous heave. Subsequent jet

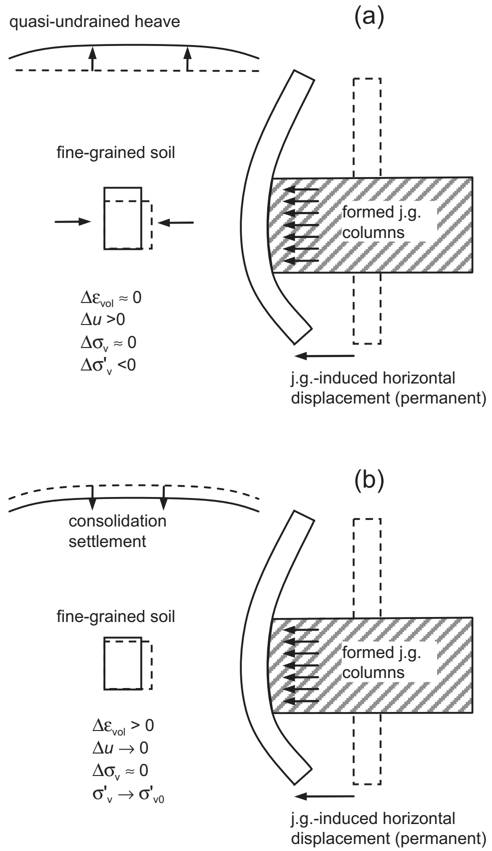

Figure 9. Interpretation of the observed horizontal and vertical displacements induced by the jet grouting.

grouting in the portions of Sector B closer to the building produced an additional heave, that was partially recovered after the completion of the jet grouting works.

Building No. 6 was affected by the jet grouting activities carried out in Sector C. Inspection of Figure 8d showed that for the present building a somewhat different behaviour was observed. The movements of the soil between the building and the excavation (inclinometer ST5) showed the usual trend: a permanent horizontal displacement comparable with that of other areas, with a temporal trend strongly related to the cumulative number of treated columns. Conversely, the building showed very small vertical displacements ($w < 1$ mm) and rotations, that were only marginally sensitive to the daily production rate, but rather increased progressively with the cumulative number of treated columns.

This atypical behaviour is to be related to the local soil profile: Figure 1 shows that Building No. 6 is situated in the North-East area, where a coarse grained gravel deposit is found at the jet grouting elevation. It can then be argued that the horizontal strains imposed by the jet grouting in this layer occurred in a drained manner, producing volumetric compression strains in the gravelly soil and little or no vertical displacements. The sensitivity to the treatment rate that is still perceptible in the plot of Figure 8d was probably due to the fine grained upper deposit, that were deformed in undrained conditions, but were only marginally interested by the displacements resulting from the jet grouting treatment.

4 CONCLUSIONS

The formation of a jet-grouted layer between facing diaphragm walls at the Conca d'Oro station produced large horizontal displacements in both the walls and the surrounding soil. The distortions in the reinforced concrete walls were significant, reaching in some cases the structure's bending capacity.

One of the reasons that prompted the use of a pre-strutting technique for this excavation was the need to minimize any effect of the excavation on the existing buildings located next to the excavation. However, the jet grouting itself produced, together with horizontal soil movements, vertical displacements and some distortion of these buildings.

A comparison between the temporal variations of several quantities, including the production details of the jet grouted columns and the displacements of the soil and the buildings, provided some insight into the mechanics of the jet grouting-induced displacements. Specifically, the vertical heave associated to jet grouting was seen to depend strongly on the local soil profile.

Jet grouting can be thought to create an inclusion between the two facing diaphragm walls that progressively expands, displacing the walls, but also hardens, making the horizontal displacements irreversible. If this expansion process were drained, it would cause only marginal vertical heaves, because the pore water pressures would remain stationary, and the total vertical stresses cannot vary for equilibrium. If the displaced soil is fine-grained, it is forced by its low permeability to deform at quasi-constant volume. Therefore, excess pore water pressures are generated, that cause a decrease in the effective vertical stresses and substantial vertical strains. This effect is mostly temporary, because the excess pore water pressures are dissipated during consolidation, and in the long term the vertical effective stresses recover their initial value.

It follows form this discussion that the vertical heave produced by jet grouting can be somewhat mitigated by performing the treatment with a low production rate, while the horizontal displacements of the walls cannot, being directly related to the geometry of the planned treatment, e.g. the amount of column overlapping and the planimetric extension of the treated area.

Admittedly, the present interpretation is partially speculative, since it is based on the measurement of integral quantities only, such as the horizontal and the vertical displacements at selected points. To be further substantiated, it would benefit of additional measurements of local quantities, and particularly of the observation of the variation of pore water pressures in fine-grained soils, with appropriate quick-responding piezometric cells.

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