Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-68367-8

Design control and monitoring of a jet grouted excavation bottom plug

N. Eramo & G. Modoni
University of Cassino, Cassino, Italy

M. Arroyo Alvarez de Toledo
Universidad Politécnica de Catalunya, Barcelona, Spain

ABSTRACT: Jet grouting is adopted in different geotechnical conditions to ensure provisional earth retaining and waterproofing functions in excavations. Despite careful theoretical models available to predict the mechanical response of these structures, design is often carried out without adequate control, i.e. by assuming ideal effectiveness of ground improvement. On the contrary, adverse effects have been documented by past experiences which can be traced back to erroneous prediction of treatments effects, inaccurate control of the execution or to unexpected responses of the surrounding environment. All these uncertainties, which are critical when working in urban areas, can be minimized by detailed preliminary field trials, accurate treatment execution control and a prompt monitoring of the surrounding area. The present paper illustrates these issues with a description of the design and execution of a massive jet grouting bottom plug forming the base of a large excavation for a tube station. The results of preliminary field trials are summarized to directly compare the effectiveness of different injection systems and introduced in statistical design analyses of the jet grouted structure. A detailed investigation of the surface movements induced by injections is also reported. To this aim, the evolution of displacements recorded around trial columns and on the area surrounding the excavation is mapped to evaluate the effects of the different adopted injection techniques.

1 INTRODUCTION

Jet grouting is adopted in a variety of geometrical configurations to ensure provisional or final earth retaining and waterproofing functions at the bottom and walls of excavations (e.g. Balossi Restelli et al., 1986; Santoro & Bianco, 1995; Sondermann & Toth, 2001; Miyasaka et al., 1992). The basic solution consists in a continuous impervious barrier formed with assemblies of overlapped columns. Another important requirement is the resistance against buoyancy, usually provided by self weight and/or internal strength of the foundation system. This function can be satisfied by creating massive cemented soil portions (plugs) of overlapped columns.

Regardless the analysis method applied, the successful performance of these structures is strongly influenced by the cemented soil geometry and materials properties. In particular, since waterproofing is due to the interpenetration of adjacent columns (Croce et al., 2006), discontinuous barriers may result from perforation deviations or by overestimation of columns diameter. Also prediction of the resistance against uplift forces becomes worthless if inexact determination is made of unit weight or shear strength of cemented soil.

All these properties, dependent on the interaction between injected fluids and original soil, cannot be precisely controlled by simply tuning the injection parameters and thus represent the most significant source of uncertainty in the calculation. Different approaches are promoted by different standards to govern uncertainty in the design and to properly define a treatment. The Japanese code (JJGA, 2005) deterministically provides diameter, unit weight and strength of columns for different jet grouting systems (double or triple fluid) and undisturbed soil properties (N_{SPT} values); uncertainty is then managed with global safety factors fixed for various types of structures. On the contrary European standard (ENV 12716, 2001) and US guidelines (G.I. ASCE, 2009) do not suggest typical values for jet grouting properties but stress on the role of preliminary field trials and Quality Control—Quality Assurance tests for their quantification. In particular the ENV 12716 standard insists on the assessment of variability of jet grouting properties and on its influence on the performance of structures. Following this second approach a procedure for the design of jet grouted bottom plugs is herein applied to the excavation of a railway station near Barcelona. Properties of columns determined by field trial investigations are statistically analyzed and introduced in the assessment of the continuity and resistance against buoyancy forces of the bottom plug. Results of field trial experiments and monitoring of the effects on the surrounding environment are also discussed in relation with different adopted injection techniques.

2 THE CASE STUDY

The excavation considered in the present study (Fig. 1) is aimed to host a station along a new subway line in Barcelona.

It extends over a sub rectangular plan arrangement having a total length of 107.4 m, a width ranging from 17.2 m (in the middle part) to 29.1 m (in the left part), and a maximum depth of 18.7 m below the ground level, this latter positioned 4.7 m a.s.l. In order to minimise the disturbance at the upper road level, the excavation has been performed with a cut and cover method, briefly summarised in the following steps:

- Excavation for about 2.5 m depth below the ground surface and execution, all along the side of station and descending ramps, of reinforced concrete diaphragm walls (1.2 m thick and 20 m deep);
- Execution of a jet grouting bottom plug (with thickness variable between 8 and 10 m) extended for about 3 m out of the side walls in order to anchor their foot and to increase resistance against buoyancy;
- Excavation by TBM of a 8.43 m large tunnel throughout the station;
- Cast of beams and slabs on the roof of the station, cover with soil and excavation down to the lower level (3.3 m b.s.l.);
- Cast of beams and slabs, excavation to the next level (11.47 m b.s.l.) and demolition of the tunnel shield;
- Cast of the lowest slab and fill by concrete of the gap from the jet grouted plug.

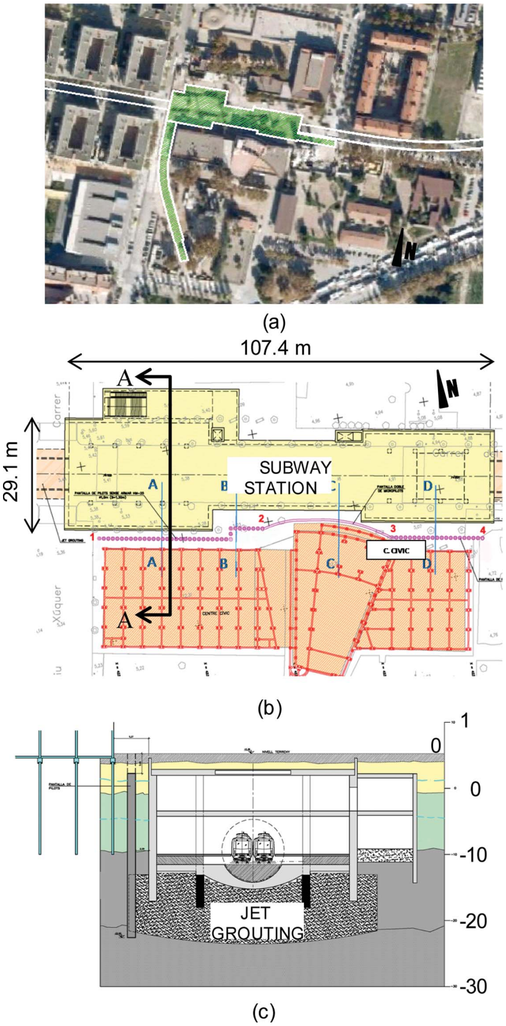

Figure 1. Location of the station and nearby buildings in the urban texture (a), plan map (b) and cross section A-A (c).

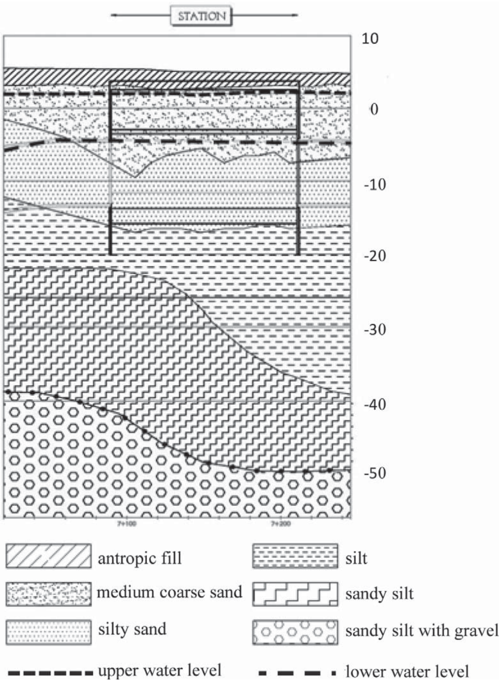

Figure 2. Schematic subsoil profile around the station.

Walls of piles and micropiles, extending at depths larger than the jet grouting plug, were created in the southern part of the station to prevent settlements induced by excavation on the nearby building.

The composition and the geotechnical characteristics of the subsoil have been obtained from two different experimental campaigns carried out at different design stages. The combination of both investigation results gives the profile reported in Figure 2, showing an alternation of different alluvial soil layers.

Two different water bearing strata, separated by silty materials, have been identified by piezometers located at different plan positions and depths. Figure 1 shows the waterproofing and the uplift resisting functions of the jet grouting plug, whose depth was limited to avoid influence on the water circulation of the upper acquifer.

3 FIELD TRIAL INVESTIGATION

Before execution of treatments different field trials were performed with the following purposes:

- Recognition, from a comparison of different systems and sets of injection parameters, of the most effective solution to ensure the required characteristics of columns;
- Definition of quality control/assurance and monitoring plan to be implemented in the construction process;
- Check of possible undesired effects produced by the execution of treatments.

With reference to the first goal, the properties of cemented soil columns listed in Table 1 were established by the designer to satisfy functionality of the plug. Moreover continuity had to be warranted by overlapping of columns. All these standards formed a benchmark for the experimental activities carried out before and during the construction of the plug.

In the preliminary stage, verification of these requirements was accomplished by injecting several triplets of columns with different systems (double and triple fluid), injection parameters and procedures, and monitor nozzle configuration (Fig. 3.a). In particular three sets of columns (groups A, C and D) were injected with double fluid systems, one (G) with triple fluid system and the other three (B, E and F) with Sanella method (Sanella, 2007). This latter procedure, described in Fig. 3.b consists in the injection of the upper column section (1/3 of columns length in group B and E, 2/3 in group F) with water and of the lower section (2/3 of columns length in group B and E, 1/3 in group F) with grout. This procedure is aimed to fill the upper part of columns with returning spoil (Fig. 3.b). The columns axes, located at the corner of a triangle, were distanced accordingly with the

	Double fluid			Sanella method			Triple fluid
Parameter	A	C	D	B	E	F	G
Nozzles diameter, d (mm)	4.5	6	Upper=3.8 Lower=5	4.5	Upper=5 Lower=3.8	4.5	
Number of nozzles	2	1	2	2	2	2	
Grout pressure (bar)	350	400	375	350	400	380	150
Air pressure (bar)	10	10	10	10	10	10	>8
Water pressure (bar)	-	-	-	350	300	380	575
Uplift speed (sec/cm)	28"/ 6cm	33"/ 4cm	55.5"/ 6cm	32"/ 6cm	55.5"/ 6cm	60"/ 6cm	60"/ 6cm
Water cement ratio by weight W/C	1.1/1	1/1	1/1	1.1/1	1/1	1/1	1/1
Expected column diameter (m)	2.0	2.5	2.5	2.0	2.5	3.0	4.3
Columns mesh (m x m)	1.58x1.38	2.05 x 1.78	2.05 x 1.78	1.58 x 1.38	2.05 x 1.78	2.46 x 2.13	3 x 3.5

(a)

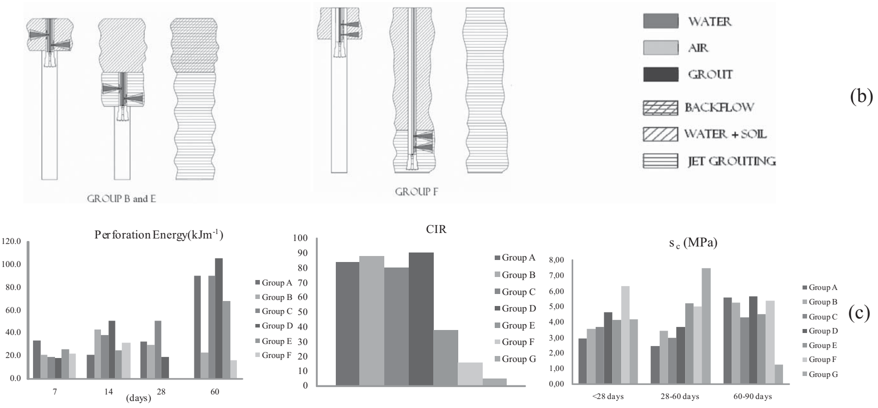

Figure 3. Selected results from jet grouting field trial (a) list of adopted injection parameters and techniques; (b) Sanella method injection procedures; (c) measured parameters.

expected diameter in order to produce overlapping of columns. The best solution was then chosen based on a comparative analysis of the following tests results (Fig. 3.c):

- Instrumented drilling performed in the centre of each triplet at different time after injection;
- Continuous rotary boring in the centre of triplets and at different distances from columns centre with evaluation of core improvement rate (Yoshitake et al., 2003);
- Laboratory tests (uniaxial compression, density, Young's modulus, permeability) on samples cored from columns.

These indexes have been also adopted as a routine control to check the effectiveness of jet grouting during the execution of treatments. Based on these results the set of injection parameters listed with letter D in Figure 3.a has been selected as the most effective for the bottom plug injection.

For this column type, the frequency distributions reported in Figure 4.a and 4.b have been obtained for the unit weight γ and the uniaxial compressive strength σ_c of cemented soil. A Gaussian function can be fitted to both plots: the median values and the standard deviations are respectively 16.0 kN/m^3 and 1.21 kN/m^3 for the unit weight, 6.481 MPa and 3.37 MPa for the uniaxial compressive strength. Note that his variability includes that due to the variation of soil types within the treated volume.

Another field trial test consisted in the measurement of the perforation deviations. Inclinations measured on 44 columns provide the frequency distributions reported in Figure 5 for the α and β angles quantifying the deviation from verticality.

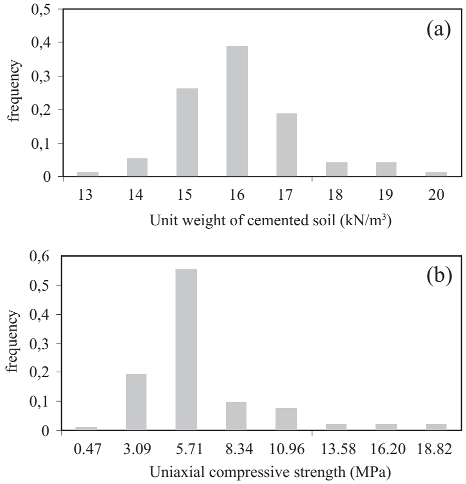

Figure 4. Frequency distributions of unit weight γ and uniaxial compressive strength σ_c of cemented soil.

Table 1. Required properties of cemented soil.

Property	Unit	Accepted value
Uniaxial compressive strength	MPa	>3,5
Traction resistance	MPa	>0,6
Young's modulus	GPa	1 < E < 4
Density	kN/m^3	>16
Permeability	cm/s	10^{-7}

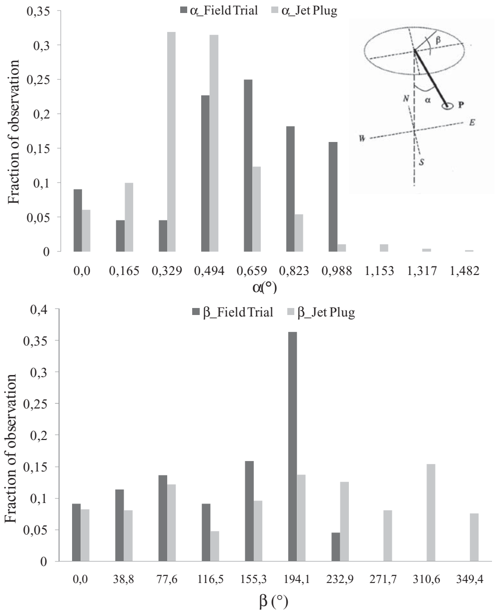

Figure 5. Statistical deviation of columns axes from vertical direction during field trial and routine quality control tests.

These plots show relatively small angles α (indicating the deviation from the ideal vertical direction), with a median value of 0.37° and a standard deviation of 0,16° and an almost flat distribution of the azimuth angle β. Similar distributions have been also retrieved by tests performed during routine control of the production columns.

4 PROBABILISTIC ANALYSES

The continuity and the resistance of the bottom plug are here evaluated with probabilistic calculations based on statistic derived from the results previously shown. With regard to the imperviousness of the barrier, a check has been made on the probability that continuous holes could cross the whole plug. To this aim the geometry of several columns triplets is simulated with a Monte Carlo technique by assigning a normal distribution to the angle α, and a uniform distribution to β. Mean and variance of α are taken from the previous statistical analyses (Fig. 5). The columns diameters D at different depths have been calculated by assuming a normal distribution with mean value equal to the design assumption (2500 mm). It is worth recalling that column diameters cannot be measured at such big depth and that this assumption is based on the continuity of drilling energy profile measured during tests. The coefficients of variation have been assumed between 0.05 and 0.2 (direct measurement performed in a site close to this station provided a value of 0.13).

By repeating this numerical experiment for one thousand triplets of columns, a frequency distribution of the minimum holes dimensions can be derived. The values correspondent to a cumulated probability of 5%, reported in Figure 6 as functions of the columns axes distance at ground level, shows that gap dimension reduces with variability of columns diameter CV(D), and that is nil for the assigned axis span at ground level (2.0 m).

The functionality of the plug has been verified by a numerical simulation of the construction process using a two dimensional FEM code (Brinkgrave & Vermeer, 2000). The properties of original soil layers have been calculated from the results of in situ and laboratory tests, the stiffness of cemented soil has been estimated by laboratory tests under the assumption of a linear elastic perfectly plastic behaviour (Mohr Coulomb constitutive model). If the experimentally determined average unit weight (16 kN/m^3) is assigned to the whole jet grouted plug, the ratio between the self weight of the structure and the resultant buoyancy force becomes equal to 1.91.

To evaluate failure likelihood, the maximum tangential stress τ_{max} and the correspondent normal stress σ have been computed from the stress tensor in all calculation points of the plug and compared with failure envelopes obtained from laboratory tests (Fig. 7). For simplicity a purely cohesive resistance has been assigned to the cemented soil with limit tangential stress calculated as half of the uniaxial compressive strength σ_c. Variability of this latter (Fig. 4.b) is considered by adopting a normal distribution and by reporting in Figure 7 the envelope correspondent to an accepted probability of failure equal to 5%. The plot shows that only two τ_{max} values are located above the assumed envelope, while all other points fall in the safe region. It must however highlighted that this result becomes fully satisfactory when considering the positive effect of confining stress on the cemented soil resistance, which has been neglected in this analysis.

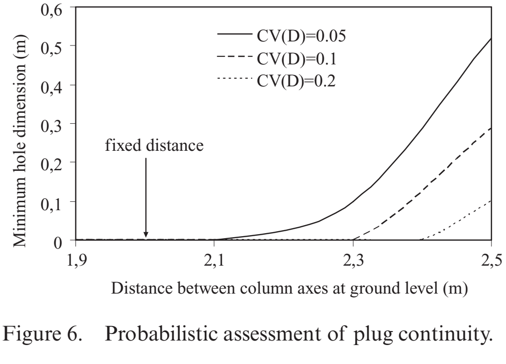

Figure 6. Probabilistic assessment of plug continuity.

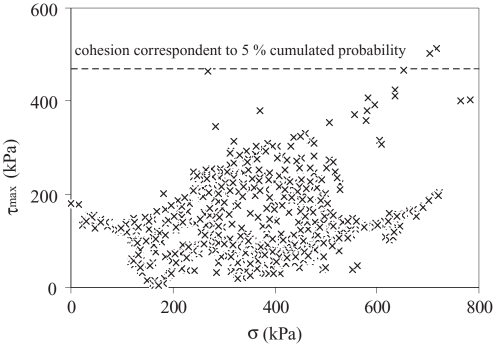

Figure 7. Stress state tolerability of the bottom plug.

5 GROUND SURFACE MOVEMENTS

Both the execution of a massive jet grouting treatment and the subsequent excavation were expected to produce movements of the nearby ground. Concerning jet grouting, significant uplifts have been recorded by previous studies (e.g. Russo and Modoni, 2005) when repeated injections are performed close to each other. To deal with these effects, a detailed monitoring plan was implemented in the present case. Settlements induced by columns injection were initially observed in field trial experiments using four benchmarks at different distances from the centre of columns triplets; a topographic observation network was subsequently installed on the ground and buildings surrounding the station to observe the effects produced by current operations.

The movements induced by the different injection systems described in Figure 3 on a benchmark located at 3.75 m distance from the centre of column triplets are reported in Figure 8.a. The plot shows

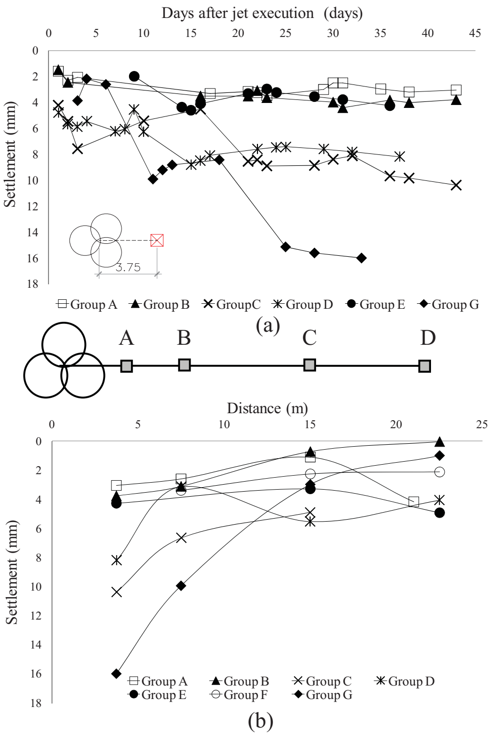

Figure 8. Ground settlements induced by different injection systems (a) instrumentation's setup; (b) settlements profile; (c) time evolution.

a progressive increase of downward settlements for all cases, beginning soon after injection and proceeding with a faster rate in a period of about two weeks. The comparison among the different results leads to the following considerations:

- Settlements induced with triple fluid are from two to six times larger than those produced by double fluid systems;
- With regard to double fluid, larger final settlements (8–10 mm) are obtained near columns injected with C and D systems, these latter presenting a rod lifting speed lower than adopted for system A (it is worth noting that grout in systems B, E and F is injected only in a portion of column length).

The profiles of maximum settlements recorded on the benchmarks located at different distances (Fig. 8.b) show a common concave shape attenuating with distances and reaching a maximum near the centre of columns triplets. Based on these results it is not possible to give a conclusive assertion about the mechanisms involved in the movements. However, it is interesting to observe the relation existing between maximum measured settlements and total amount of injected cement among the different columns triplets (Fig. 9). This result suggests as possible explanation the lack of support given by fresh grout-soil mix on the surrounding soil (C, D and G are arguably the larger columns) and/or the consolidation induced by the considerable heat developed during the cement hydration process.

Settlements induced by the injection of the excavation plug have been continuously monitored with high precision optical levelling on a grid of 35 benchmarks located all around the station (Fig. 10).

By interpolating these data with a geostatistical technique (Kriging), two settlement maps have been created describing the situation before and after the execution of the jet grouting treatments. From these two maps (Fig. 10.a and 10.b) it is seen that the most subsiding area (the largest settlements at the end treatments are about 55 mm) is located near the south west border of the station, close to the ramp accessing to the construction site. In particular, by observing the time evolution on different benchmarks (Fig. 10.c) it is seen that less than 20 mm are induced by the construction of diaphragm walls, built for the accessing ramp and the station, while the remaining part (about 35 mm) has occurred during and after the execution of jet grouting treatments. It is also worth observing that triple fluid injections (with the set of parameters indicated with G in Fig. 3) were attempted in this area to increase the speed of operations and that this system was discarded after observing the sudden increase of settlement rates on closer benchmarks (point 1 in Fig. 10.a and corresponding curve in Fig. 10.c).

It can be concluded that, up to the end of the process, when the subsidence rate becomes negligible, jet grouting operations have produced overall downward settlements of about 40 mm near the south-east border of the station, where a larger part of treatments performed with double and

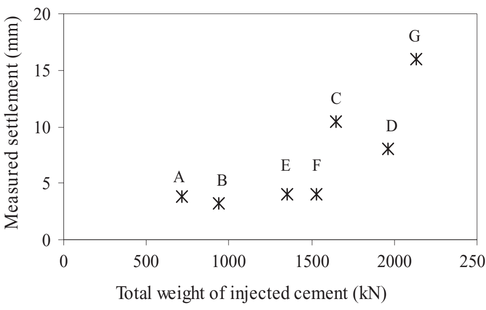

Figure 9. Relation between measured settlements and injected amount of cement.

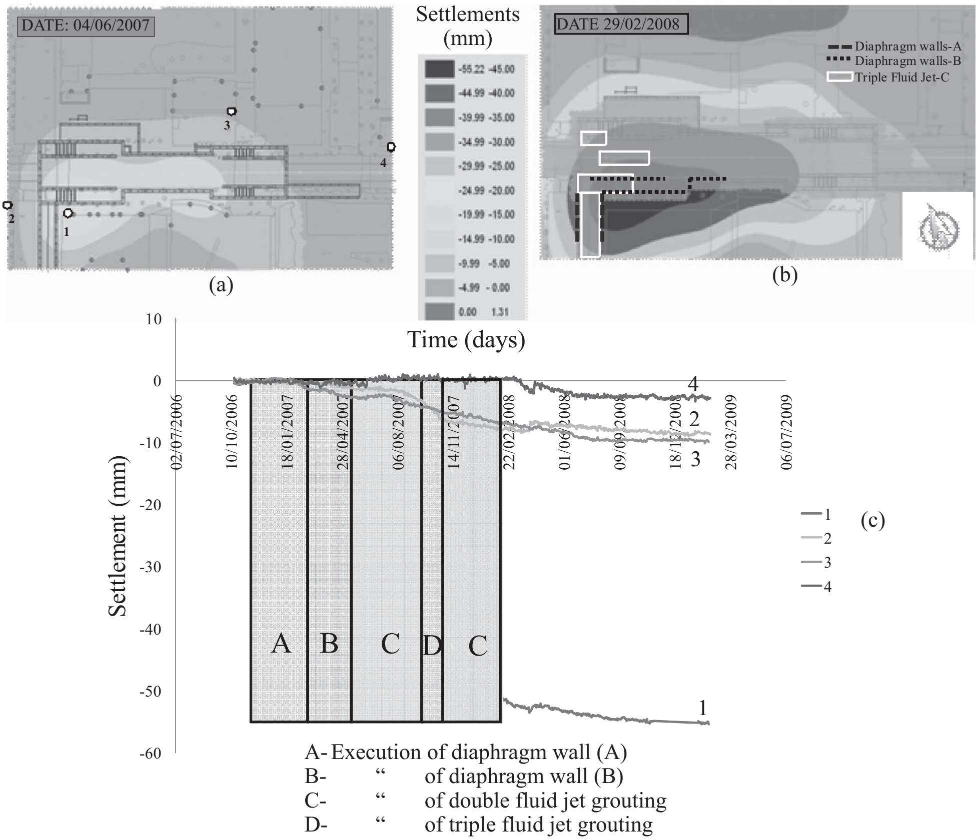

Figure 10. Contour of settlements before (a) at after (b) jet grouting treatments and settlement evolution on different benchmarks (c).

triple fluid are concentrated. Displacements in the outer zones are in the range of few millimetres.

6 CONCLUSIONS

The procedure described by the European Standard ENV12716 (2001) "Execution of special geotechnical works: jet grouting" has been herein illustrated with the analysis of an excavation bottom plug created with jet grouting. In particular, the Standard recommends to prove by preliminary field experiments the effectiveness of the adopted injection system, to verify the execution of treatments with an accurate control plan and to monitor possible undesired effects on the surrounding environment. With reference to the former aspect a comparison has been established among different injection systems. The selection of the optimum injection technique was based on different tests (drilling energy per unit length, sample recovery index; uniaxial compressive strength) all providing satisfactory results for the chosen system. The results obtained by preliminary field tests were then used to perform a probabilistic prediction of the functionality of the jet grouting plug (continuity and stress compatibility). With reference to the effects on the surrounding environment, particular attention has been paid to the movements induced at road level by execution of treatments, initially observed during field trial investigations and monitored during construction of the plug. Contrarily with former studies, the results obtained in the present case have shown a non negligible pattern of downward settlements induced by injections. Movements become particularly relevant for those systems injecting a big amount of cement. The importance of field measurements and their introduction in the design have been clearly demonstrated in this work both to optimise the solution (a reduction of the amount and the quality of cement could be assumed) and to minimise the undesired effects (by considering injection techniques providing lower settlements).

Too often essential operational details of jet grouting treatments are left to the criteria of operators. The advantage of applying an objective procedure for the design and the control of jet grouting treatments are clear. On the one hand it will support design decisions with data specifically obtained in the same conditions of the final work, on the other hand it provides a rational frame to advance towards more effective treatments. This article illustrates how this procedure can be established.

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