Ground consolidation using grouting at the new access road to Barajas Airport, Madrid

Consolidation d'un terrain avec l'utilisation d'injections sous une nouvelle route a l'aéroport de Barajas, Madrid

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ABSTRACT: One of the new access roads to Madrid's airport suffered from settlement caused by badly compacted fill upon which the road was founded. A solution was to be designed in such a way as not to disrupt the flow of traffic during the consolidation of the fill. The method adopted consisted of a series of jet grouting and compaction grouting columns undertaken from the hard shoulder of the road within the loose fill, both consolidating it and also causing a certain amount of controlled heave to compensate for the settlements and to restore the road to its original position.

RESUME: Une des nouvelles routes d'accès a l'aéroport de Madrid avait souffert des tassements causés par un remblai mal compacté sur lequel se trouvait fondée cette route. Une solution devait être trouvée de telle façon que la circulation soit affectée le moins possible pendant la consolidation du remblai. La methode adoptée comprenait une serie de colonnes de jet grouting et d'injections de compactation exécutées depuis les bords de la route et dans le reblai, obtenant ainsi une consolidation du terrain et un soulèvement controllé pour compenser les tassements et pour récupérer l'état initial de la route.

1 INTRODUCTION

The dual carriageway A-10 is the access to Barajas airport from the northern area of Madrid, exiting from the M-40 ring road. It was finished in 1992 and almost since has suffered large movements which have given rise to an uneven surface and cracks in the road paving, in some 250 m near the junction with the airport (Chainage: 6,050 to 6,300).

As successive patching of the damages was not sufficient, a solution using ground consolidation beneath the top 2m of the embankment (foundation of the road surface) was considered using grouting from the sides of the road in order to avoid interrupting the flow of traffic.

The solution adopted, based on prior experience in Madrid, includes both jet grouting and compaction grouting, aiming for a technical and economical balance.

The works were undertaken in 1995, starting with a detailed site investigation and a trial area in order to define the final design of the injection holes and the parameters of both types of grouting, as well as to check the results obtained with these ground treatments.

2 DETAILED SITE INVESTIGATION

The preliminary design of the grouting treatment was based on a site investigation including boreholes, laboratory tests from samples taken and dynamic penetration tests, from which the typical ground profile below the road surface was defined (table 1).

Table 1. Typical ground profile

Thickness (m)	Layer	Description
2 to 3	Embankment	Brown, medium to dense silty clayey sand (N 15 to 25)
2 to 12	Fill	Brown and greenish grey, weak to medium silty clayey sand (N 2 to 20)
beneath	Natural ground	Brown and greyish, medium to very dense silty clayey sand and sandy clay (N 20 to 60)

From top to bottom: N = SPT blows, Fines ASTM 200 sieve size. Not plastic to medium plasticity.

The changes in thickness and state of compaction (or consistency) of the fill below the embankment indicated that an additional site investigation was required to obtain a greater degree of precision on the incompetent part of the fill which is the source of the movements of the road surface, particularly with regard to collapse due to the action of water infiltrating from the surface. These changes also were conditioning factors as regards the type of grouting to be used for the improvement as well as the distribution and length of the injection holes to be undertaken. The area chosen for the trial also had to be checked as being representative of the area to be treated as a whole (figure 1).

The site investigation consisted of a mechanical borehole and 42 Borros dynamic penetration tests, located along the edges of the area affected by settlement. The results of the investigation enabled a subdivision in three of the area to be treated (zones A, B and C - figure 1 and table 2), where the differences in the thickness of the fill to be treated and particularly the width of the road were taken into account, giving rise to three types of sections with different combinations of jet grouting and compaction grouting injection holes.

The materials which made up the embankment and the fill were sandy material from the excavation of the natural ground with differing degrees of compaction. It was considered that the fill should be consolidated when its state of compation was weak to very weak: N_B (Borros) below 8 to 10 blows which is equivalent to N (SPT) of 10 to 13 blows.

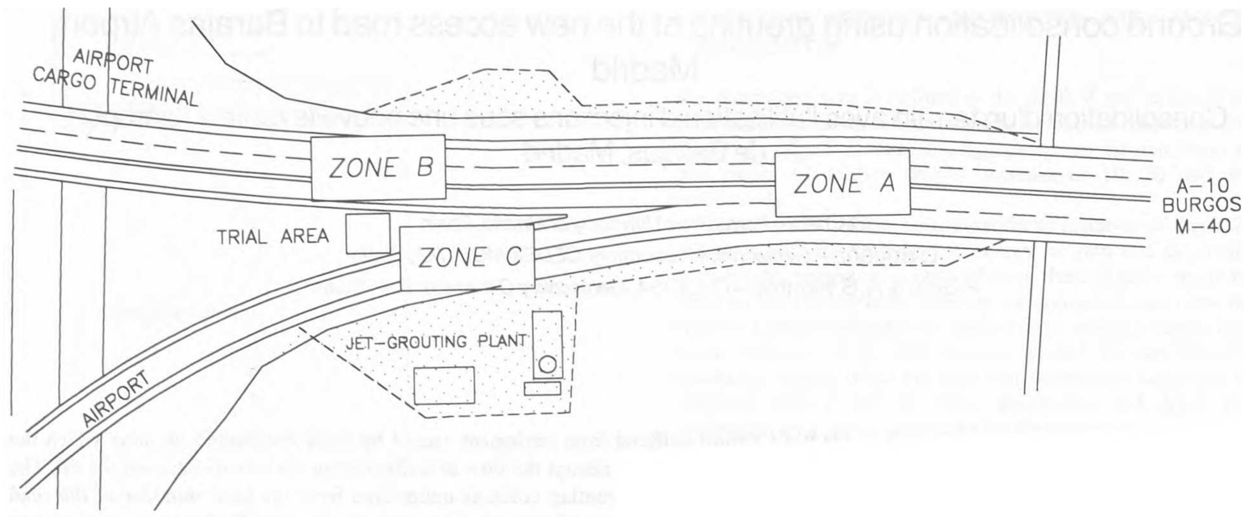

Figure 1. Plan of treatment zones

Table 2. Thickness of embankment and fill to be treated.

Zone	Embankment (m)	Fill to be treated (m)	N_B (blows)
A	2 to 3	6 to 8	2 to 8
B	2 to 3	3 to 8	1 to 9
C	2 to 5	3 to 9	3 to 10

3 TRIAL AREA

The degree of improvement to be obtained with the consolidation treatment was established initially as increasing the degree of compaction of the fill to at least a medium relative density, which should be greater for the top 5 m (average number of SPT blows, N, not less than 15) than at greater depths (average N not less than 10).

In order to check the assumptions on which the preliminary design was based, the execution parameters and the effects induced at ground surface by the two grouting procedures, as well as the results obtained and the controls to be undertaken, it was necessary to undertake a full size trial area in an area without traffic (figure 1), and where the thickness of the fill to be treated was similar to that which exists below the road surface (8 - 9 m).

The tests started with the execution of jet grouting columns using the single jet system, with a cement consumption of between 300 and 500 kg/m, and with inclinations with respect to the horizontal of between 30° and 45°. The objective was to determine the behaviour of the ground, particularly the movements caused at the ground surface.

The results indicated that with 300 kg/m the refusal was very small, and with inclinations of 30° blockages occurred and heave of up to 60 mm was produced very suddenly. However for inclinations of 45° the heave observed was only of 20 mm.

The trials relating to the consolidation as such were undertaken with two different types of treatment, in adjacent areas, with the layout of the injection holes as defined in the sections given in figures 2 and 3. The first of these areas (sections 1 to 3) consisted of a combination of jet grouting and compaction grouting, whilst the second (sections 4 to 6) only included jet grouting. The lengths of the injection holes varied from 4.5 to 10.5 m and the inclinations between 30° and 60° (with respect to the horizontal).

The jet grouting was undertaken using pressures and flow rates of 450 bar and 110 l/min, and cement consumptions of 300 to 500 kg/m with a water/cement ratio (by weight) of 1. The compaction grouting was undertaken using a low consistency mortar (sand, fly ash, cement-bentonite) with pressures of up to 25 bar and consumptions of 300 to 700 l/m.

The surface movements were registered using periodical levelling and with five lines of electro-levels for automatic real time readings. The maximum movements were small: 20 mm settlement and 10 mm heave.

The improvement achieved was checked from before and after values of dynamic penetration tests, geophysical test (cross hole and γ-γ testification), as well as from the visual inspection of trial pits.

The differences between the before and after values were similar for both types of treatment: the γ-γ testification results were not very conclusive whilst the dynamic penetration tests were more significant, the blow count passing from 2-8 blows to 6-14 blows. However the results of the cross hole tests were more indicative, giving increases of 43 to 67 % of the pressure waves and of 79 to 97 % for the shear waves. A greater improvement was noticeable at depths of up to 5 m (4 to 37 %). An example of these results can be seen in figure 4.

The grout formations observed in the trial pits were quite different for the jet grouting and the compaction grouting mortar. The first type of treatment, as is know in Madrid, showed a central trunk of soil-cement of an equivalent diameter of approximately 0.2 - 0.4 m with many thin irregular ramifications "reinforcing" the soil between the injection holes. The second gave irregular spherical shapes and subvertical mortar wedges which hardly mixed with the surrounding soil, with thicknesses of between 0.2 and 0.8 m.

With these results and the experience in Madrid of similar ground treatment, the conclusion was drawn that an adequate consolidation had been achieved, and the final design of the treatment below the dual carriageway was undertaken using the same criteria.

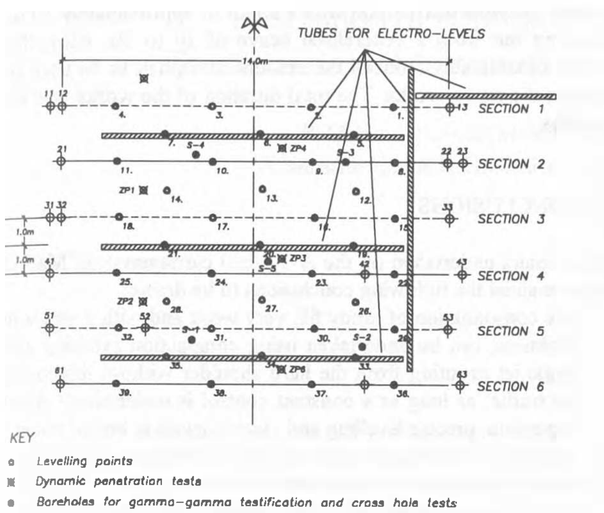

Figure 2. Plan of trial area

4. FINAL DESIGN

The final design showed a combination of compaction and jet grouting for zones A and B (see figures 5 and 6) where the width of the road and the magnitude of the settlement at the surface were greatest, and only using jet grouting in zone C, where the treatment could be undertaken from both sides of the road with jet grouting injection holes inclined at more than 45°. The distance between semi-sections for both types of treatment was taken as 2 m, the same as in the trial area (figure 2).

The sequence of the execution was to be from the outer injection holes towards the centre of the road in order to enclose the treated area, giving priority to the jet grouting injection holes over the compaction grouting ones within a given section. The most characteristic parameters that were specified are given in table 3.

Table 3. Grouting parameters

Single jet grouting	Compaction grouting
Grout w/c = 1	Mortar (G-MFB1-1)
Pump pressure = 450 bar	Pump in injection hole < 25 bar
Flow rate = 100 l/min	Flow rate = 50 - 100 l/min
Rotation = 13 rpm	Rotation = ---
Marsh viscosity = 35 - 42 s	Abrams viscosity = 9 - 13 cm
Consumption = 300 - 500 kg/m	Consumption = 300 - 1200 l/m

The minimum consumption of 300 kg/m during jet grouting was to be increased to a maximum of 500 kg/m if the return was low.

Generally the maximum volumes for compaction grouting corresponded to an equivalent reduction in the porosity of the fill of 5 % below a 5 m depth beneath the road surface, and of 7 to 10 % in the more superficial area. The criteria for stopping the grouting in a particular hole due to heave was set a 10 mm for the grouting phase and 30 mm for the accumulated total.

Also, in the area which had suffered greatest settlement within sub-zones A and B, a possible second grouting phases was foreseen using intermediate injection holes, in the case where the grouting pressures and the heave were very low during the first phase. The objective of this additional phase was to ensure the improvement in the degree of compaction of the fill, as well as recovering part of the settlement of the road surface with heave produced by the grouting. As this heave was not to deteriorate

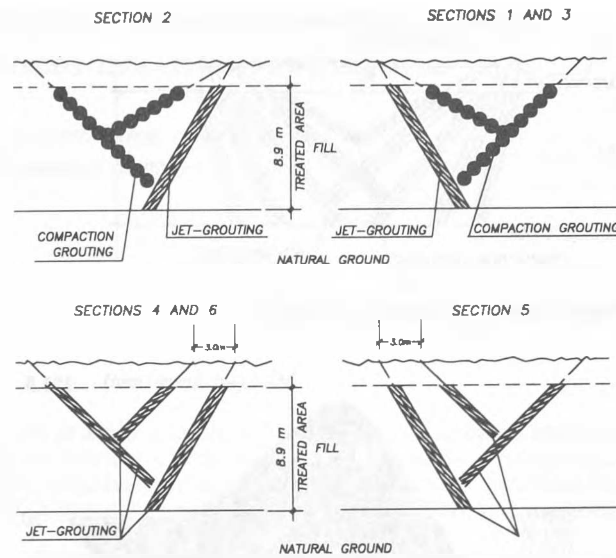

Figure 3. Sections showing details of treatment for trial area

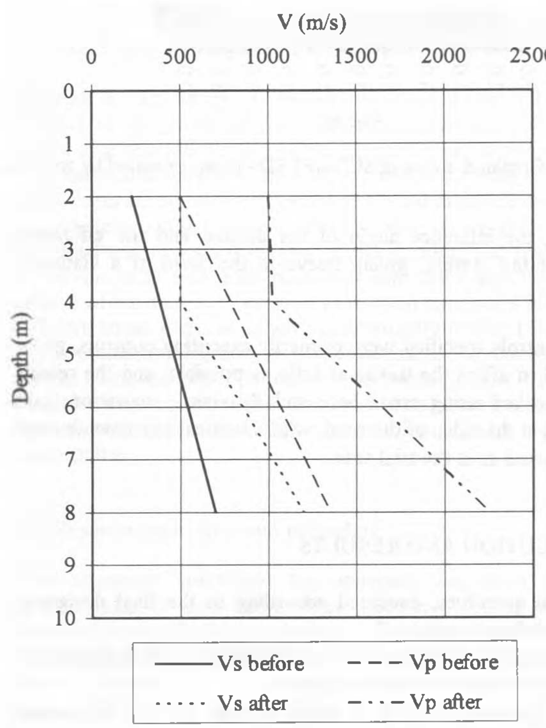

Figure 4. Comparison between values of Vs and Vp in cross hole tests

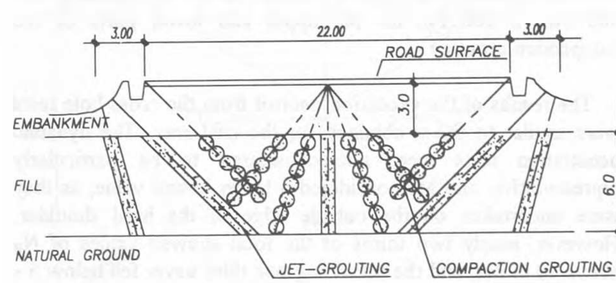

Figure 5. Section of treatment - Zone A

the existing state of the road, the volumes to be used and resulting movements were calculated using the SCOMET 3D programme (figure 7). This programme undertakes a 3 dimensional analysis using as initial data the type and volume of

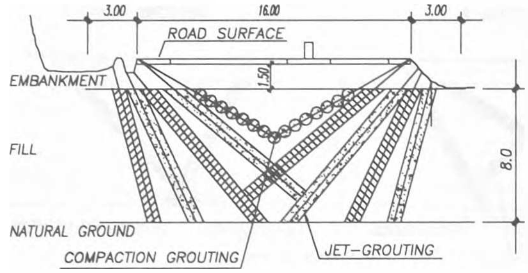

Figure 6. Section of treatment - Zone B

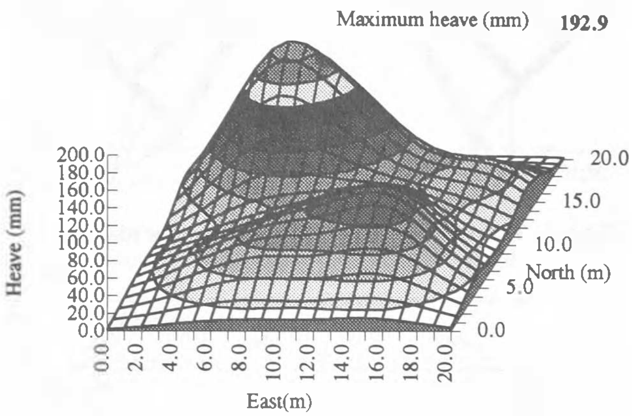

Figure 7. Graphical output of SCOMET 3D - Heave produced by grouting

the mix, the influence angle of the ground and the efficiency factor of the system, giving heave in the form of a Gaussian surface.

The controls specified were primarily execution controls, given the need to affect the traffic as little as possible, and the results were checked using cross hole and dynamic penetration tests (Borros) at the sides of the road, where vertical movements were also checked as in the trial area.

5. EXECUTION AND RESULTS

The total quantities, executed according to the final design as described above, were:
- for compaction grouting: 2045 m of drilling, 1226 m of grouted column and 776 m^3 of mortar grouted.
- for jet grouting: 1229 m of sterile drilling, 3929 m of grouted column and 1493 t of cement grouted.

The average consumptions were approximately what was expected: around 400 kg/m of cement for the jet grouting, and 900 l/m to 300 l/m for the upper and lower parts of the compaction grouting.

The results of the execution control from the cross hole tests were similar to those obtained for the trial area. The dynamic penetration tests were not considered to be particularly representative, and are considered a lower bound value, as they were undertaken on the outside edge of the hard shoulder. However, nearly two thirds of the total showed values of N_B above 10 blows, and the remaining one third never fell below 5 - 10 blows in stretched of less than 1 m which corresponds to 8 - 13 SPT blows.

The influence of the road surface itself was important as regards the compaction grouting though not so for the jet grouting. The cracks increased and produced heave of up to 190 mm with a typical gaussian distribution with a width of approximately 10 m, standing out from a generalised heave of 20 to 50. Also, this heave considerably reduced the amount of asphalt to be used to finalise the repair works. The total duration of the works was six months.

6. CONCLUSIONS

The repairs undertaken on the A-10 dual carriageway in Madrid have enabled the following conclusions to be drawn:
- The consolidation of sandy fill, very weak and with 3 and 9 m thickness, can be undertaken using compaction grouting and single jet grouting from the hard shoulder without disrupting the traffic, as long as a constant control is undertaken: visual inspection, precise levelling and electro-levels in buried pipes.
- The type of treatment which is considered most appropriate and economical is a combination of both types of grouting, which depending on the width of the road, should include compaction grouting injection holes in the centre and jet grouting injection holes on the edges. A trial area should be undertaken to check the initial design assumptions.
- The single jet grouting columns should not be inclined a less than 45°. The compaction grouting columns did not show any specific problems for inclination of up to 30° with respect to the horizontal. The spacing of the grid of columns should be between 2 to 4 m, the closer spacing being for the weaker areas.
- The average consumptions were around 400 kg/m of cement for the single jet grouting, while the compaction grouting took 900 l/m in the top 5m and around 300 l/m at greater depths.
- The results obtained have been checked in the trial area and at the edges of the road, dynamic penetration tests and also cross hole tests being the most reliable of the methods used. According to these results, a medium degree of compaction was obtained, with values in the top 5 m as specified in the design. Also, the compaction grouting enabled a generalised recovery of 20 - 50 mm of settlement of the road surface, with maximums of up to 190 mm in areas of greater initial settlement.

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