MODERN PRE-INJECTIONS IN UNDERGROUND CONSTRUCTION WITH
MICROCEMENTS AND LIQUID COLLOIDAL SILICA FOR WATER INGRESS
REDUCTION AND GROUND IMPROVEMENT

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ABSTRACT

The pre-injection method, or injections ahead of the excavation face in underground construction can in many situations offer significant advantages. This is particularly the case in difficult ground conditions like water ingress or mechanically poor ground or soil, in which pre-injections can contribute to avoid mishaps and serious delays. In sensitive urban environment the need to manage water ingress into tunnels under construction as well as avoiding collapses are crucial factors for the successful completion of a project.

Modern pre-injection technology involves the design of methods adapted to the encountered situation. This includes proper drilling techniques and drilling geometry for the best delivery of the grout into the ground, determination of relevant production criteria during the injection, as well as the employment of state-of-the-art injection products like special microcements and colloidal silica.

Modern cost-effective material technology for pre-injections in underground construction aims to achieve the desired as fast as possible, hence reducing the down time during the excavation as much as possible

In recent years several difficult tasks in tunnelling have been resolved by using modern microcement technology in combination with liquid colloidal silica. Improvement of the technical performance of rapid curing microcements, by using controlled and precise addition of accelerators have made the microcement injection technology far more versatile than before.

Two recent, difficult and significantly different projects are reported and discussed in this paper.

1. INTRODUCTION

Collapses at the tunnel face or unexpected high water inrushes is not a uncommon experience when tunnelling in geologically difficult ground like fault zones in alpine terrain or tunnels with shallow location influenced by weathering or low rock stresses.

Tunnelling in urban areas often involve shallow location of tunnels, proximity to existing underground structures, as well as establishing connections between underground structures. The consequences of a groundwater drawdown or deformations in the ground caused by
instabilities are particularly unacceptable due to the possible impact on buildings with sensitive foundations.

This paper addresses the issue of how pre-injections in a shallow located tunnel strongly can reduce the risk of mishaps.

The state-of-the art technology within rapid hardening microcements and liquid colloidal silica is particularly emphasized. This technology can improve the cost-effectiveness and technical feasibility of tunnelling in sensitive environment in difficult ground significantly.

Three different case studies are reported, all with relevance to shallow location (two of which in sensitive urban environment), showing how serious difficulties were prevented through the cost-effective use of pre-injections.

2. BASIC CONSIDERATIONS

2.1 The pre-injection concept

The basic idea of pre-injection is to treat the ground prior to the excavation by injecting a grout into the ground. Injection in this context means the introduction of a grout into the ground through drillholes or pipes by the pumping with pressure.

Pre-injection basically consists of the following main steps:

1. Drilling of holes or pipes for the injection (placement of the grout by pressure)
2. Injection until the termination criteria are reached
3. Evaluation or control of the injection result: decision regarding repeated injections or to commence excavation through the treated ground

In addition to these three main steps in the actual injection cycle, there is an up front process of determining the main scope and location of the injection works. This includes the following important issues:

- exploratory drillings to determine the initial state of the ground to be treated
- exact location to establish the drillings for the injection
- injection method, main features
- grout types, mix designs

It is important to understand a pre-injection scheme in tunnelling as a sequence of decisions which actively are made at several stages in the injection cycle. Management of the injection works is therefore a crucial factor in order to achieve cost-effectiveness.

2.2 What can be achieved by pre-injections?

Pre-injections can have two main goals
• reduce the permeability of the ground and hence, reduce the flow of water into the tunnel after excavation
• improve the mechanical properties of the ground and hence, provide improved stability of the ground during the excavation and support of the tunnel

In both these cases the chosen injection method will address the issue of achieving the best possible introduction of the grout into the ground. This is a process which aims to optimize the drilling pattern in combination with the eventual use of pipes for injection and specifying the proper characteristics of the grout.

In the case of permeability reduction the main goal will be to fill the water bearing discontinuities with a stable grout that seals off the water flow.

In the case of mechanical improvement of the ground properties, the grout eventually will need to have a certain final mechanical strength.

A combination of these two effects is also desirable in many cases.

2.3 Method considerations

Before the technical details of a pre-injection scheme are designed, one should make overall considerations regarding the method. The layout of the method comprises decisions at a strategic level for the pre-injection works including the fundamental approach as to how to achieve the desired result. The basic framework of the detailed operations in the injection cycle is laid out in this process.

This planning process needs to give the necessary input for the specification of equipment like drilling to desired length and eventual drilling equipment installed on TBMs (Figure 1 below).

Figure 1. Drilling for pre-injections ahead of the tunnel face. To the left: injection drilling in conventional drill-and-blast excavation. To the right: drilling equipment for injection installed on a hard rock open TBM (Garshol, 2002)

The main issues to consider in this process are the following:

• ground properties and their capacity to be drilled
• method for the drilling of holes or pipe installation
• packer system to suit the chosen hole diameter or pipe
• grout mix designs to suit the required penetration, early strength and long term material properties
• considerations regarding injection pressures
• termination criteria for the injection process

It is important to understand an injection operation as a complete method in which all the above mentioned issues are always considered during the planning process.

A frequently misunderstood feature is the grouting pressure. Very often maximum permitted grouting pressures are specified at far too low a level. The main reason for this is frequently said to be that a higher grouting pressure might feed a global pressure build-up in the ground, and hence lead to a risk of hydrofracturing or undesired penetration of grout far away from the location of the injection. There however may be good reason for low pressure thresholds in low cover urban tunnel situations.

Barton et al (2004) demonstrates that injection pressures measured at the injection lance (at the collar of the drillhole) do not correspond to the pressure of the grout in the actual ground. There is a significant drop of pressure in the immediate vicinity of the drillhole into the ground, as long as there is a flow of grout.

Another important issue is to always have in mind that an injection operation is a cycle in which decisions are made with regards to specific criteria (pre-defined or subject to adjustment). These decisions are made at each step of the injection cycle. Therefore pre-injection is a type of work which requires experienced hands-on management on a continuous basis during the works.

3. STATE-OF-THE-ART GROUTS FOR PENETRATION IN SOILS AND FINE JOINTS IN ROCK

Injection in difficult ground requires the complete method to be especially adapted in order to achieve penetration in the ground as desired. A very essential detail in this context is the choice and design of the proper grout characteristics with special emphasis on penetrability.

The penetrability of a grout is a difficult parameter to measure or verify directly. Penetrability describes the ability of a grout to penetrate into a medium like a granular soil or fine joints in a rock mass under a certain injection pressure.

The penetrability of a grout for injection purposes in underground construction is mainly influenced by the following three measurable material properties:

• grain size distribution (if the grout is a granular medium)
• viscosity of the grout
• stability of the grout (resistance to separation over time or when exposed to pressure)

The grain size is decisive for the penetrability into fine joints as well as permeating between the grains in a soil. Figure 2 below illustrates graphically the importance of grain size for the penetrability in joints in rock.
The viscosity is important since it will directly influence the shear stresses in a grout when it is flowing through joints or between the grains in a soil.

![Graphical representation of grain sizes of cement grouts and types of penetration.](image)

Figure 2. Left: Graphical representation to scale of grain sizes of cement grouts with respect to a relevant joint aperture for penetration (0.02mm). The largest grain corresponds to the normal cement with a very fine grading, followed by two different microcements, and to the far left silica fume and colloidal silica. Right: Simplified graphical representation of the four main types of penetration of a grout in soils. Pure grout is shown as black. A: replacement, B: compaction, C: hydrofracturing, D: permeation (Holter et al, 1996)

The lower the viscosity, the lower the shear stresses in the grout and hence, the lower the injection pressure which is required to sustain the flow of the grout into the ground.

The stability of the grout is important since it will directly influence the capability of the cement in the grout to penetrate into the fine discontinuities. The process of bleeding, in which the cement grains separate from the grout mix and clog the entrances to the fine joints, does not occur with a stable grout mix.

3.1 Rapid hardening microcements

These microcements offer particular advantages in a tunnelling situation. The main advantages are:

- small grain size
- excellent stability and low viscosity even at relatively low water/cement ratios (like e.g. 1.0)
- excellent penetrability due to the two above mentioned issues
- setting within 1.5 to 2 hours, hence eliminating waiting time for the next step in the injection cycle

3.2 Liquid colloidal silica

This grout type consists of silica grains (SiO₂) in the nanometric scale in a colloidal solution in water. The typical grain size is 0.016 μm. Its viscosity is 5-6 mPas, which is slightly higher than water. This offers particularly good penetration properties, which otherwise only chemical agents like silicates (waterglass) or acrylates can offer.
Colloidal silica, contrary to silicates and acrylates, is a completely non-toxic product, which makes it unique in terms of environmental friendliness and health and safety. Colloidal silica is a mineral grout and designed for permanent long-term purposes, whereas silicates only can have a temporary function.

The penetrability of colloidal silica in jointed rock and soils is illustrated graphically in figure 2. above.

Note the size of a grain of colloidal silica to the far left. In a soil injection situation, colloidal silica can offer permeation (D) in soils down to the coarse silt fraction (0.01 mm) with the proper injection method.

4. CASE EXAMPLE A: TBM BREAKTHROUGH INTO A VENTILATION SHAFT, CTRL CONTRACT 220 CORSICA STREET, UK, 2002

4.1 The project

The construction of the Channel Tunnel Rail Link (CTRL) in the UK, contract 220, involved several difficult situations with complex geometries of tunnels, cross-passages and ventilation shafts which had to be excavated in sandy silts. Mostly these situations were dealt with by dewatering the sand through vacuum drainage.
At the ventilation shaft at Corsica St a shielded TBM was to break through into the already constructed shaft. The ground conditions were loose sands and silts below ground water table. Grain size tests of the sands showed that the 80% of the grains were in the range of 0.1 to 1 mm, with approximately 10% uniformly distributed on each side of this range.

4.2 The challenge

In this particular case it was evident prior to the construction, that the dewatering of the sands was not sufficient for achieving the required stability of the sands for a safe and controlled breakthrough of the advancing TBM into the shaft. An injection campaign for stabilisation of the loose sands was therefore necessary.

4.3 The technical solution

The main contractor undertook a full scale in-situ trial with injections of liquid colloidal silica into the sands in order to determine the possible achievable effect of such an injection campaign.

The trial injections were done in the main shaft floor during construction using sleeve port pipes (tube a manchettes). The trial showed thorough permeation of colloidal silica to radial distances of 0.5 to 0.7 m around the sleeved pipes. A significant improvement of the mechanical strength was observed, however no measurements of the UCS were done at this stage. The results were convincing and an injection campaign with colloidal silica was decided.

During construction, a fan of sleeved pipes was drilled from the shaft into the sands at the location of the breakthrough of the TBM. The fan of pipes was laid out in order to cover the ground around the whole perimeter of the TBM, as well as completely covering the intersection between the shaft wall and the TBM excavated tunnel. The configuration of this situation is shown in figure 3 above.

Holes with tubes-a-manchettes pipes with lengths 4-6 m and 1.2 – 1.5 m spacing were drilled covering the entire perimeter of the advancing TBM. A total of approximately 60 tonnes colloidal silica was injected.

5. CASE EXAMPLE B: MANERI BHALI HYDROPOWER PROJECT, HEADRACE TUNNEL, INDIA 2005-2006

5.1 The project

The headrace tunnel for the Maneri Bhali hydroelectric power project phase 2 (Uttaranchal Province) underpasses a valley with low rock cover. The tunnel was excavated by drill-and-blast and supported by steel sets and lagging with concrete backfill. During the last phase of the construction wet-mix steel fibre reinforced sprayed concrete was also used for rock support in the most adverse rock conditions. The situation with valley underpass and main geological formations is shown in figure 4 below.
The valley corresponds to a weakness zone which intersected approximately 300 m length of the tunnel. The weakness zone exhibited densely jointed and partially crushed mica-quartzite schist. In-situ fine grained crushed material in the silt fraction occurred as joint fillings. The entire weakness zone was highly permeable; hence high water inflows were encountered.

The valley had been underpassed with serious difficulty several years earlier. No pre-injections were carried out at this stage. Hence, large water inflows in combination with a very irregular tunnel contour resulting from cave-ins were the result. In this phase, the earlier excavated tunnel portion through the weakness zone was bypassed, in order to create feasible conditions for the support and waterproofing of the headrace tunnel.

5.2 The challenge

The highly jointed and crushed rock combined with the low overburden of only 20-25 m (of which only ca 5 m rock) at the shallowest imposed a critical point in the headrace tunnel. The maximum water pressure in the tunnel during the operation of the power plant would be 10 bars. This would create a potential risk of hydrofracturing and leakages out of the headrace tunnel.
tunnel. There would also be a risk of charging of water in the surrounding ground resulting in a danger of landslides.

A technical solution with the following main goals had to be laid out:

- stabilization and permeability reduction of the ground in the weak zone to facilitate the establishment of a sufficient rock support as well as the structural and waterproofing lining of the tunnel
- facilitate safe conditions for excavation and immediate support of the tunnel

5.3 The technical solution

Previously pre-injections with locally manufactured ordinary portland cement had been attempted, but with very limited penetration into the ground. In order to address the difficult ground conditions, a two-stage pre-injection scheme with two different grout types was undertaken.

The main feature of the injection method was to inject through grouted steel pipes with a length of 2.5 m. The high degree of jointing and crushing of the rock mass severely limited the drilling operation. Each of the steel pipes was therefore used for repeated drilling and injection. The first drilling and injection step through the steel pipes reached 6 m in front of the tunnel face. The second step reached 8-11 m, and the third and final step reached 13 m in front of the tunnel face.

The first stage consisted of injection of rapid hardening microfine cement. The rapid hardening of this cement allowed for a continuous operation with drilling, injections and the subsequent re-drilling to larger depth through the same steel pipes without damaging the result of the previously injected volume.

![Figure 5. Layout of the injection method (longitudinal vertical section), principally showing the target areas for the two stages of the pre-injections. The outer dark area in front of the tunnel face represents the volume which was treated in injection stage1 with rapid setting microcements. The lighter area in front of the tunnel face represents the volume which was treated subsequently in injection stage 2, employing liquid colloidal silica. After this treatment the tunnel was excavated a length of approximately 8 m before the injection cycle was repeated. (Bahadur et. al, 2007)
The second main stage was the injection of liquid colloidal silica. Featuring extremely low viscosity and grain size in the nanometric scale, the finest joints as well as joints with fillings were grouted. A very satisfactory result in terms of water ingress reduction and ground improvement was achieved.

The second stage was geometrically laid out in a way that it would be enveloped by the grouted rock mass from the first stage. In this way the injection of the low viscous grout would entirely take place where the microfine cement already had been injected, thus only utilizing the colloidal silica for the fine joints.

5.4 Experiences during injection

During injection it was necessary to limit the maximum injection pressure to approximately 60 bars. The reasons for this were occurrence of backflow of grout into the tunnel and sliding of the packers in the steel pipes.

The first stage injections with rapid hardening microcement showed a relatively limited grout take of only 100-150 kg per m drillhole when the termination pressure of 60 bars was reached. Bearing in mind the seepage which was encountered in the drillholes one would expect a higher grout take.

The reason for the relatively low grout take was joint fillings which consisted of the silt and clay particles, which in turn limited the penetration of the grout created by filtration. The first stage injection fan with microcement was always completed in the full circumference of the tunnel before the secondary fan was attempted. The reason for this was that the first stage injection provided penetration of grout into the joints with the largest apertures.

Figure 6. To the right: Photo taken at the tunnel face showing injection through steel pipes, first stage, with rapid hardening microfine cement. To the left: The tunnel face towards the end of the difficult zone. A stable and literally dry contour and tunnel face was achieved by the pre-injections, allowing for the installation of the temporary rock support without difficulty. (Bhadur et al. 2007)
The second injection stage with an extremely low viscous grout could therefore be targeted for the finer joints and the joints which were partially filled with clay and silt. The secondary fan was drilled and injected with liquid colloidal silica with a termination pressure of 25 bars, or approximately 100 kg per m drillhole length.

Injection beyond a pressure of 25 bars with liquid colloidal silica usually showed signs of hydrofracturing. The control of the achieved result was done in two ways. Firstly, the water seepage situation after the injection of the two stages was controlled in drillholes. Secondly, the result was observed in the tunnel contour after the excavation of the first round starting from the injection location. In this way the detailed criteria for termination of the injection were fine tuned and continuously adjusted. The result was a literally dry and stable tunnel contour. No excessive breakouts of rock or cave-ins occurred during excavation through the weakness zone.

6. CONCLUSIONS

The proactive approach demonstrated in both these mentioned cases, by pre-injecting the difficult ground ahead of the excavation face resulted in safe, cost-effective an predictable conditions during the actual excavation. In the Maneri Bhali case, the effects could be directly compared to the poor conditions and heavy water flows observed in the adjacent tunnel where pre-injections were not used. A direct comparison of the effectiveness of microfine cements and liquid colloidal silica grout versus ordinary Portland cement was also clearly evident.

The experiences from Maneri Bhali also show that a proactive approach to drilling and grouting with a clearly defined method statement and utilizing materials with the proper penetration, viscosity and rapid hardening characteristics can significantly reduce the construction time through such highly faulted and unstable zones (6 months in by-pass tunnel versus 18 months in original tunnel). The low cost of pre-injection in comparison with post-injection techniques can also be clearly seen. The cost for materials on this project came to a material cost of approximately Euro 1,200/m versus a similar condition in another tunnel in India where polyurethane post-injections were utilized at a cost of approximately Euro 12,000/m and currently almost 2 years behind schedule.

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