GUIDELINES FOR INJECTION IN UNDERGROUND CONSTRUCTION AND TUNNELLING

Abstract

Underground structures as tunnels, hydroelectric power plants, storage caverns etc are always expensive to build and have a major value to the society, then as infrastructures they are directly responsible for wealth creation and development, justifying thus also their need of better and constant maintenance.

Grouting works are a significant part of these important projects, mainly in:
- Consolidation and strengthening of weak soil during tunnelling excavation
- curtain grouting for concrete and earth dams
- ground settlement control
- waterproofing of existing structures
- preventing spreading of hazardous contaminants
- foundation plate formation
- re-opening of old dams and tunnels

As seen, injection techniques help to solve problems that show up in the construction or during the operative life for the maintenance of such important structures.

Today the range of products and techniques available for injection is quite wide. This guideline is nothing but a humble attempt to order the whole thing in systematic way, helping people during design and application phases to choose easily the best system (material + application method) to be used and thus to solve the specific problems that may occur.

Once the application method is almost independent on the material used for injection we subdivided this paper in two parts. The first one deals with the (often) not easy choice of the injection material and the second part illustrates the most common injection techniques and the necessary equipment.

Historic Background and Definition

In the history of civil engineering, the first injection is considered the one made by the French engineer Charles Bérigny in 1802. Mr. Bérigny prepared a suspension of pozzolanic cement and water to fill cavities in the foundation of a dam. Later on he used this technique also to consolidate bridge foundations. With the years, as knowledge and equipment developed the method was improved and used in Mining (Germany 1864) and Dam Construction (England 1876). The first trial with “synthetic” materials was done in 1926 (Joosten) to consolidate sandy soils, while “modern” (?) injections are considered to start from the early 1930’s with the building of large Dams. After the 1960’s when more and better formulations of resins were made available the use of this kind of material increased too.

Nowadays the concepts of injection and grouting are mixed up frequently, although in our opinion the term grouting should be used for cement based mixes while injection could be intended for resin based materials. Other technicians think exactly the opposite. In any case, following the current practice we refer either to injection or grouting with the same target:

“the introduction with pressure of a material with the objective of waterproofing and consolidate in voids, cracks and porosity.” (Kutzner, Injektionstechnik, 1991)
“the pumping of a stable fluid generally named “injection grout” into rock and soil to fill completely all cavities, voids and cracks, creating a solid sealed mass.” (Volpi, 1998)

For a better comprehension, the concept of “filling” shall be also interpreted as:

“the penetration of the injection grout only by the action of gravity (without pressure).” (Stephan, Inject 99, Essen)

For the good of the clarity and simplicity we can reduce all the things just to three activities that are the purpose of any injection action:

Consolidation  
Waterproofing  
Filling

Part One: The Choice of a Specific Grouting Material

Available Grouting Materials

As a general rule the grouting fluids can be shared in two classes:
- grouts based on cements creating a granular suspension, named Binghamian fluids
- grouts based on chemical products, creating a solutions, named Newtonian fluids.

The Binghamian fluids are subdivided into:
- pure cement mixes, PCM, consisting of cement and water, a non stable mix and as such not applicable as injection grout according to most international standards (AFTES).
- Admixed cement mixes, ACM, composed by cement, water, plasticisers or superplasticisers and eventually an accelerator or thixotropy agent.
- Additived cement mixes, ADCM, composed by an admixed cement mix plus clays [Bentonite] and may contain also other kind of fillers either pozzolanic additives [silica fume, fly ashes etc] or non pozzolanic ones [mineral charges].

When we refer to cement we include also the category of microcements or ultrafine cements, which are chemically equal to “normal” cements, the only difference lies on the fineness of the grains (Blaine grade which ranges from about 3000 cm$^2$/g or 100 m diameter of the largest particles in standard portland cement to about 10,000 cm$^2$/g or 15 m for the finest ground cements). Regarding their chemical behaviour, cement and microcements react in the same way and the admixtures and additives used are exactly the same.

The Newtonian, also called perfect fluids are subdivided into:
- Silicate Gels, SG, a solution of sodium silicate in aqueous solution with a reagent (hardener), usually either inorganic (sodium bicarbonate or sodium aluminate) or organic (carbonic acid esters, glyoxal), creating a gel (silica snow) with very low mechanical resistance. Although used since the early 1930’s (Joosten), this solution is considered as temporary action.
- Phenolic resins, PH, in aqueous solution are cured with strong acidic or alkaline hardeners, according to the resin type. This kind of material requires a careful operation in jobsite once the reaction catalyst is a very strong acid.
- Acrylics, **AC**, resin and hardener are mixed together and react by polymerisation building up a permanent gel with low adhesive and compressive strength but some formulations show an appreciable tear strength. The reaction can be speeded up by adding an accelerator (in aqueous solution) or slowed down by adding water or changing the ratio between resin and hardener.

- Organomineral resins, **OM**, modified silicate reacts with isocyanate to form a tough material with very high adhesive strength. Some formulations have an intense foaming reaction while others don’t. Although this resin has a fragile behaviour, its elasticity modulus is quite low.

- Polyurethane, **PU**, polyol and isocyanate react forming a high strength adhesive material. The main property of polyurethane is its versatility, it can be found in different formulations having different properties either in liquid or in hardened phase, such as viscosity, thixotropy, foaming reaction (depending on the water being present) and mechanical strength.

- Water reactive polyurethane are, after the optional addition of a catalyst, injected into the ground and cure with the water in the ground yielding a lightweight foam.

- Epoxies, **EP**, resin plus hardener reacts forming a tough non-foaming material but sensitive to moisture (no bonding with water).

The typical properties of both Binghamian and Newtonian fluids can be resumed in the following table:

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Viscosity (mPa.s at 25°C)</th>
<th>Final Set</th>
<th>Modulus</th>
<th>Foaming</th>
<th>Bonding in Moisture</th>
<th>Peculiarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACM</td>
<td>400</td>
<td>12 h</td>
<td>24h</td>
<td>No</td>
<td>Good</td>
<td>Fragile behaviour, Shrinkage</td>
</tr>
<tr>
<td>ADCM</td>
<td>250</td>
<td>10 h</td>
<td>12h</td>
<td>No</td>
<td>Good</td>
<td>Fragile behaviour, Shrinkage</td>
</tr>
<tr>
<td>SG</td>
<td>15</td>
<td>30” to 120’</td>
<td>120’</td>
<td>No</td>
<td>Poor</td>
<td>Soft “creamy” gel</td>
</tr>
<tr>
<td>PF</td>
<td>50 to 1000</td>
<td>30” to 60’</td>
<td>60’</td>
<td>Yes/No*</td>
<td>Good</td>
<td>Fragile Brittle</td>
</tr>
<tr>
<td>AC</td>
<td>10</td>
<td>30” to 30’</td>
<td>30’</td>
<td>No</td>
<td>Good</td>
<td>Soft to Hard Gel</td>
</tr>
<tr>
<td>OM</td>
<td>300</td>
<td>30” to 50’</td>
<td>30’</td>
<td>Yes/No*</td>
<td>Very Good</td>
<td>Fragile behaviour</td>
</tr>
<tr>
<td>PU</td>
<td>50 to 1000</td>
<td>30” to 6h’</td>
<td>30’</td>
<td>Yes/No*</td>
<td>Good</td>
<td>Elastic - Plastic, high energy absorption</td>
</tr>
<tr>
<td>EP</td>
<td>100 to 1000</td>
<td>2’ to 120’</td>
<td>120’</td>
<td>No</td>
<td>Fair</td>
<td>Elastic, low energy absorption</td>
</tr>
</tbody>
</table>

*depending on the type used

**Limits and Advantages**
Generally speaking the main pros and cons for the Binghamian fluids are:

PROS | CONS
--- | ---
- Low priced materials | - Limited penetration capacity
- Easy to apply | - Long setting times
- High E-Modulus | - Fragile Behaviour

On the side of the Newtonian fluids we have:

PROS | CONS
--- | ---
- High penetration capacity | - Non washable (Thixotropic types)
- Fast setting times | - High Price
- High capacity of energy absorption (PU) | - Need of skilled applicator
Selection of most suitable material

In Physical sense, injection is the relationship between the injected fluid and the substrate, which is expressed hydraulically as “relative permeability”. This interaction could be explained through a simplified equation of Dupuit, which for suspensions (Binghamian fluids) is the ratio between the diameter of the particles (grading curve) and the distribution of the pores in the flow path (Filter criterion).

This relationship is additionally complicated by the variations of the flow path during the injection works due to hydraulic surcharges caused by the injection itself or external factor as water streaming in underground (mainly in granular terrain).

A safe basis of starting is indeed a geologic survey to know as good as possible the substrate that is going to be injected. With concrete information concerning the geometry and distribution of particles, together with the data of the grout (viscosity, grading curve of the particles and the so called “rheogram”) to be injected is possible to determinate with a certain accuracy the Pressfiltration limit of the injection. Machon recommends that the diameter of the biggest particle within the fluid shall not be more than 1/3 to 1/5 of the crack width or porosity diameter.

What normally happens at the site is that the grading curve of the ground is known well only in the decimeter range, only global permeability tests as e.g. the Lugeon test are done (without data regarding vertical conductivity) and vague information about “medium” to “compact” ground does not furnish enough parameters for the choice of the injection technique and the appropriate grout. Additionally nothing or very little is known about the capacity of the suspension (always the cheapest materials) to penetrate a certain porosity or to achieve a certain grouting radius.

As guide for a good research campaign we recommend the use of the new (pre)European Standard prEN 12715 or the German Standard DIN 4093. Some guidelines are also given in the report of the Commission on Rock Grouting of the international Society for Rock Mechanics (1996).

The same is valid also for Newtonian fluids with the advantage that at least the injection grout can be well defined and constant, since it is a perfect fluid without solids.

Fissures down to 0,05mm can be perfectly sealed using such materials even in wet conditions, assuring a complete bonding of the particles (or fissure walls) within it. In any case, trials to choose the best setting times are also recommended, since resin based materials are very sensitive to temperature, causing changes in some important properties as viscosity and setting times.

Criteria for selection

As seen, the different materials have properties that make them suitable in some cases but completely wrong in other situations. Our goal is to establish parameters to help the decision that can be the difference between a successful job and an applicational disaster.
The main choice parameters to be taken in consideration before using a product are:

a) Permeability of the soil (or granulometric distribution) or width of cracks (or the porosity) of the rock mass.

The following table is a résumé from different sources that indicates the practical degree of penetration in different soil/rock types of different materials.

<table>
<thead>
<tr>
<th>Grouting Material</th>
<th>Minimum Practical Injectable Limit</th>
<th>Rock/Ground Permeability K (m/s)</th>
<th>Grain Diameter $D_{15***}$ (µm)</th>
<th>Crack Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admixed Cement Mix</td>
<td></td>
<td>$3.10^{-2}$</td>
<td>2000</td>
<td>1</td>
</tr>
<tr>
<td>Additived Cement Mix</td>
<td></td>
<td>$3.10^{-3}$</td>
<td>1500</td>
<td>1</td>
</tr>
<tr>
<td>AD Microfine Cement Mix*</td>
<td></td>
<td>$1.10^{-3}$</td>
<td>1000</td>
<td>.5</td>
</tr>
<tr>
<td>AD Ultrafine Cement Mix**</td>
<td></td>
<td>$3.10^{-4}$</td>
<td>600</td>
<td>.5</td>
</tr>
<tr>
<td>Silicate Gel</td>
<td></td>
<td>$2.10^{-4}$</td>
<td>500</td>
<td>.5</td>
</tr>
<tr>
<td>PU and OM Resins</td>
<td></td>
<td>$2.10^{-5}$</td>
<td>50 to 100</td>
<td>.05</td>
</tr>
<tr>
<td>Acrylic Resins</td>
<td></td>
<td>$1.10^{-6}$</td>
<td>1 to 10</td>
<td>.01</td>
</tr>
</tbody>
</table>

*Blaine 8000 **Blaine 10000 ***15% of the soil mass is finer than the diameter given.

b) The presence (or not) of water

Since it seems logical that flowing water has an evident impact on the results of the injection, we made the following distinction to evaluate the importance of the water flow:

**Moist (M)**: the structure (or ground or rock mass) shows signs of moisture (dark spots). At this stage, the water has no appreciable influence in the injection. To verify the presence of moisture, dry hands keep dry after touching a moist surface.

**Wet (W)**: the structure is saturated with water but it is not in movement, the influence on the injection is minimal. Dry hands get wet after touching wet surfaces.

After this point hands always get wet and we leave the realm of Hydrostatics and enter the water in movement range that is classified according to the basic concepts of Hydrodynamics.

In 1883 the Irish engineer Osborne Reynolds showed the existence of two types of viscous flows in pipes. At low velocities the fluid particles follow the streamlines (laminar flow) and results match the analytical predictions. At higher velocities the flow breaks up into a fluctuating velocity pattern or eddies (turbulent flow) in a form that cannot be fully predicted even today. Reynolds also established that the transition from laminar to turbulent flow was a function of a single parameter that has since become known as the Reynolds number (Re):

\[ Re = \left( \frac{v d}{\nu} \right) \]

Where,

- \(v\) is the velocity in m/s
- \(\nu\) is the kinematic viscosity in m²/s
- \(\sigma\) is the density of the fluid in kg/m³
- \(d\) is the pipe diameter in m
- \(\eta\) is the dynamic viscosity in Pa·s

If \(Re\) is less than 2000, the flow in pipes will always be laminar; for \(Re\) higher than 4000 the flow will be turbulent. Intermediate values show a transition phase from laminar to turbulent.
Water Flow (WF): water running with Re less than 2000 (laminar flow)
Strong Water Flow (SWF): water running with Re greater than 4000 (turbulent flow)
Very Strong Water Flow (VSWF): Re>4000 associated with high pressure.

c) Water Pressure (or hydraulic gradient), from 2 bar until 7 bar should be classified as high pressure, above 7 bar the pressure is considered very high.

Other Parameters
Even if not crucial for the injectability, these additional parameters are necessary to identify the right material to be used:
d) Compressive Strength needed for the pure injection grout, low compressive strength is intended when less than 10 MPa, medium compressive strength is between 10 and until 35MPa while higher values identify high strength.
e) Adhesion required to the surface (especially in case of crack sealing): Low (less than 1 MPa) or High (more than 1MPa)
f) Void filling (expansion) needed, just yes or no.
g) Speed of reaction (hardening), depends strongly from parameter b) and c) and can be subdivided roughly in Slow (>24h), Normal (>6h), Accelerated (>15'), Fast (>1') and Very Fast (<1').

Selection Menu
The following pages present 4 different flow diagrams for different starting conditions (Crack width or Permeability or Grain Diameter) and should guide in the choice of the most suitable material for injection depending on the environmental conditions.
The first Chart is for permeability (K) superior to $10^{-2}$ m/s, which is equivalent to coarse gravel.
The second Chart is made for permeability superior to $10^{-4}$ m/s, which is equivalent to coarse sands.
The third Chart is made for K> $10^{-5}$ m/s, covering middle size sands.
The fourth finally covers lose materials from clay, throughout silt and fine sands.
When a choice is done for a certain injection material, for example ADCM, the additional conditions such as Adhesive strength, Setting time Compressive Strength etc., shall be used to fine tune the final mix. In case of resins this fine tuning is made by choosing among different formulations proposed by the producers according to the same required additional conditions.
Crack Width, $w > 1.5 \text{mm}$
Permeability, $K > 10^{-2} \text{ m/s}$
Grain Size, $D_{15} > 2000 \mu\text{m}$

Flow? $Re > 0$
Pressure? $P > 2 \text{ bar}$
Void Filling? Yes

OM or PU
PU or PH
ADCM or PU
ADCM
SG or PH
PU
PU
OM or PU
### Permeability K (m/s)

<table>
<thead>
<tr>
<th>Realm of Soil</th>
<th>Gravel</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10^-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10^-2</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10^-3</td>
<td></td>
<td></td>
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<tr>
<td>10^-4</td>
<td></td>
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<tr>
<td>10^-5</td>
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<tr>
<td>10^-6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10^-7</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

### D15 (µm)

<table>
<thead>
<tr>
<th>ACM</th>
<th>ADCM</th>
<th>ADmCM</th>
<th>ADuCM</th>
<th>SG / OM</th>
<th>PU / PH / EP</th>
<th>AC</th>
</tr>
</thead>
</table>

### Diametre D<sub>15</sub> (µm)

| 100.000      | 2.000  | 500   | 250   | 75      | 5            |

### Crack Width w (mm)

| 10           | 5      | 1     | 0.5   | 0.1     | 0.05         |
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