SOME THEORETICAL CONSIDERATIONS 
ON CEMENT ROCK GROUTING

by

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3. SOME THEORETICAL CONSIDERATIONS

3.1 Rheology of the grout mix

Water is a Newtonian body as it has only viscosity accordingly to Figure (3.1), which shows its rheological law.

A stable grout slurry (this means that under normal conditions, water will not separate from cement) behaves as a Bingham body with both cohesion and viscosity (see Figure 3.1). The cohesion (yield point) makes that the behavior of a stable mix is fundamentally different from that of water.

An unstable slurry will separate into water and cement, so that its behavior will be quite unpredictable being alternatively a Newtonian or a Bingham body.

Theoretical investigations show that as soon as internal friction appears in the slurry, the grouting is no more possible. An inferior limit of the W/C-factor exists therefore below which the cement grains will enter in contact to each other and an internal friction will develop. This phenomenon also takes place when during grouting some water is absorbed by the rock or escapes through very thinn joints.

The grout process will then stop immediately.

We therefore may define:
- a lower limit for the W/C-factor below which friction would occur and grouting ceases to be possible and
- an upper limit beyond which the slurry is no more stable and its behavior no more predictable.

In any case the grout mix needs some excess of water in respect to the minimum amount strictly required by the cement to set.
As a rough indication, one can take as limits the two values of \( W/\text{C \ min} = 0.4 \) and \( W/\text{C \ max} = 1.0 \) by weight. These two limits can be influenced to some extend by some admixtures (bentonite, fluidifier a.s.o.).

Figure (3.2) gives the results of the Marsh Flow-time and the sedimentation of a Water-Cement slurry of different \( W/\text{C} \)-factors. It shows the mentioned theoretical range and the value of \( W/\text{C} = 0.6 \), selected for the Paute dam in Ecuador. It may be seen that on the right side of the limit \( W/\text{C} = 1 \) the slurry do not differ too much from that of dirty water.

Theoretical investigations on the grouting process of stable slurries following the law of the Bingham body give the following results.

In grouting a single joint the maximal travel distance is a function only of the final pressure applied, the thickness of the joint and the cohesion of the slurry. The main effect of the cohesion is therefore to limit the extension of the grouted zone and to avoid, at least to some extend, unneccessary high consumptions of grout. (See figure 3.3).

The relationship between grout pressure, thickness of the joint and effective travel distance of the grout is shown for a single case in figure 3.4).

The effective travel distance was computed from the theoretical one using a guessed factor \( k \) of efficiency equal to 0.2. This factor takes into consideration different facts like:

- the joint is never absolutely flat,
- the joint is never completely open so that the grout has to surround some obstacles,
- the thickness of the joint is not absolutely constant so that control sections for the flow exist which produce head losses,
the joint is never absolutely clean so that some debris may disturb the flow, and
the grouting process will always be stopped before its theoretical end.

The factor of efficiency should be checked in the field case by case.
Of course there is a lower limit in using the figure 3.4) because the cement grains cannot enter too thin joints. (Minimum thickness of the joint f.i. 0.2 mm, depending of the type of cement used.)

While the cohesion limits to a finite extend the travel distance and obviously the grout take of a slurry grouted at a constant pressure, the time needed to reach this theoretical distance has still no limit. This means that an asymptotic process takes place. Using a constant pressure a complete stop of the grouting process can thus never be achieved and some tolerance has to be granted in the job-site grouting.
This conclusion differs from the usual thinkings about grouting. (See figure 3.5))

Figure 3.3) shows also that the splitting force is limited by the cohesion of the slurry.
In grouting with water (or with an unstable slurry) the splitting forces could reach any high value, as the cohesion is nil.

The cohesion determines also the minimal pressure needed to put and mantain into movement a grout quantity already introduced in a joint.

The viscosity on the other side will influence strongly the flow rate of the grout by a given pressure and therefore will determine the time needed to fullfill a grouting process.
Figure 3.6) shows the visco-plastic flow law in a pipe or a joint and summarizes the afore said. To be noted is the stiff kernel of
slurry travelling along the joint. Its dimension decreases with the pressure gradient. At the end of the grouting process the kernel fills up all the joint volume. This is the reason why the flow stops.

To compute and evaluate a grouting process it is necessary to know both viscosity and cohesion of the slurry. The generally used Marsh-cone test gives only a single value the so called "flow time". Figure 3.7) gives the computed relationship "Flow-time T versus cohesion and viscosity" (both related to the density of the slurry). An additional measure is therefore needed to obtain the two mentioned rheological parameters of the slurry. Different methods exist like the use of a viscosimeter or the weighting of the slurry sticking to a rough plate.

3.2 Influencing the properties of the slurry

It is well known that the properties of a water cement slurry may be modified in different ways.
For example the use of bentonite to reduce the decantation (or sedimentation) of the mix is widespread. The use of fluidifiers like (Intraplast) has also been introduced.

As a rule we may note that starting from a given W/C factor:
- adding water will reduce both viscosity and cohesion (and also density) of the slurry.
- adding bentonite will increase strongly the cohesion and also, but to a lesser percentage, the viscosity.
- the fluidifiers will reduce very clearly the viscosity and probably also the cohesion even to a lesser extent.

These admixtures influence of course the strength of the grout set. An example is given in Figure 3.8) where the Marsh flow time is used as the characteristic parameter. Starting from the point A, which represents a 0.67 W/C slurry, Intraplast is added in increasing quantities (Line A-I).
The flow time is reduced from 36 sec to 29.5 sec.
The 28-day strength decreases at the same time from 200 to 100 kg/cm² aprox.

In two other experimental series, bentonite is added. Or better said, the mixes are prepared with water containing 1% (Series B1) or 2% (Series B2) of bentonite.

With the same W/C-factor of 0.67 the flow-time increases strongly to 42 and even to 48 sec.
Increasing now the W/C-factor we get a straight line directed quite exactly to the point W representing water; this both for the flow time and the 28-day strength.

If, for instance, a flow time of 30 sec is required, the strength will be of the order of 10 to 30 kg/cm² with the admixture of bentonite, but can be about 100 kg/cm², that is 3 to 10 times more, in the case Intraplast is used as fluidifier.
This means that Intraplast is able to reduce the viscosity in sacrificing the strength of the set to a much lesser extent as it happens in using bentonite.
These facts show (as the reduction of the strength is never desired as such), that the main reason to use bentonite is to increase the cohesion of the slurry and therefore to limit the travel distance of the grout. (This is just the contrary of the often claimed lubrication effect.)

One has nevertheless to observe that the same limitation of the travel may be obtained quite easily in reducing the grout pressure. The fluidifier allows at the contrary to increase the penetration of the grout even with reduced pressure. (Some cases are reported where bentonite separated from the mix entering the thinnest joint, letting back the cement in the thicker ones.)
The prime use of bentonite seems therefore to be to try to stabilise unstable mixes, that means to limit the decantation of the slurry.
In fact stable mixes are the only ones that warrant a complete filling of the voids after setting, as the excess water do not separate and will not be the cause of future voids and channels.

Comparing stable with unstable mixes the results of recent computations and the practical experience show that stable mixes will:
- limit the travel distance of the grout avoiding unnecessary high consumption of slurry,
- strongly reduce the risk of splitting and heaving the rock mass even if high and very high pressures are used to grout, and
- behave in a more or less predictable way.

The following results can furthermore be achieved with a stable water cement slurry but are completely or partially lost if a thin slurry is made stable with adjuction of bentonite:
- high mechanical strenght,
- good bond to the rock,
- high resistance against leaching out, as a consequence of the former two properties, and
- as thick slurries are generally pressed in with high pressure, any entrapped air bubble will be compressed and its volume strongly reduced.

In conclusion it appears clearly that stable mixes are to be preferred to unstaables ones, and that bentonite should be used only in very special cases to try to stabilise unstable slurry. (Or to bind the excess water of the mix.)

Table 3.1 shows a series of recent jobs where thick water-cement slurries without bentonite (except a very small quantity at El Cajón dam) were used with very good results.
Table 3.1

<table>
<thead>
<tr>
<th>Dam</th>
<th>W/C</th>
<th>Fluidifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paute (Ecuador)</td>
<td>0.6</td>
<td>Intraplast 1.4%</td>
</tr>
<tr>
<td>Alicurá (Argentine)</td>
<td>0.67</td>
<td>Intraplast 1.2%</td>
</tr>
<tr>
<td>El Cajón (Honduras)</td>
<td>0.7</td>
<td>Bentonite 0.2%</td>
</tr>
<tr>
<td>Daule Peripa (Ecuador)</td>
<td>0.6</td>
<td>Intraplast ≈1%</td>
</tr>
<tr>
<td>El Chocón (Argentina) repairs</td>
<td>0.7</td>
<td>Tests going on</td>
</tr>
</tbody>
</table>

Recent thick slurry grouting

3.3 Example

Some computation were carried out, on a single joint grouting, with three slurries used at the Itaipú Dam site. They were obtained using different W/C-factors. The physical properties of these three slurries compared with those of water are presented in figure 3.9). Different joint thicknesses (0.25, 0.5 and 1.0 mm) were investigated supposing a constant grouting pressure of 2 MPa.
Figure 3.10) indicates the grout take versus time as well as the theoretical final take \( V_{\text{max}} \).
This take may vary from 1.10 m\(^3\) for the thick mix in a 0.5 mm joint to 306.8 m\(^3\) for the thin mix in a 1.0 mm joint, to, of course, an unlimited value for water regardless of the thickness of the joint.
It is very impressive to take notice how sensitive the grout take is for changes in the grout thickness and the joint width.

As already said, the theoretical final take is never reached. Nevertheless the figure shows that the practical limit is reach much sooner with thick mixes than with thinner ones.

Figure 3.11) shows the variation of the splitting or uplift forces for the same slurries and the same joints.
It is interesting to take notice how much the forces are different from case to case.
The forces have been obtained by integrating the pressure in the joint from its maximum value at the grout hole to zero at its leading edge of penetration. The enormity of these forces is striking particularly for the thinner mixes.
However one has to consider the already mentioned reduction due to the effective efficiency of the grouting process.

3.4 Some proposals

The mentioned investigations and recent experiences lead to propose some changes in the present practices of rock grouting e.g. in the case of a grout curtain for a dam. These proposal may justify corresponding modifications of the grouting specifications.

a) Rapid grouting

Normally the grouting is supposed to be pursued at constant pressure until it stops. As we have seen, this is theoretically achieved only at an infinite time.
As a rule a small flow rate is therefore arbitrarily selected and the grouting is stopped as soon as the actual flow rate falls below this limit.

Figure 3.12) shows the distance reached by the grout, in a special case, as function of time and grouting pressure. It may be clearly seen that a given distance is reached much faster with a higher pressure than with a lower one. For instance, with a pressure of 2 MPa the grout would reach in just 1.2 hours the final distance that can be arrived at with 1.5 MPa at an infinite time. For 1 MPa the time to obtain the same result would be only 18 minutes and 3 minutes in the case of 0.5 MPa.

On this base we may suggest a rapid grouting procedure as shown at figure 3.13).

The contractor should be allowed to overpass the final prescribed pressure by some percentage to speed up the grouting. After a while the pressure is to be reduced to the theoretical value and it has to be proved that no take occurs any more. In this case a full grouting ("au refus") is really obtained. It is also possible to imagine an automatic device which steers the grouting process and checks from time to time if at the prescribed final pressure any take still occurs and, if no more, ends the grouting.

b) **Allowed maximum take**

It is an usual rule to limit the take of a borehole by a given arbitrary quantity (regardless of the pressure arrived at), combined with the prescription of a maximum pressure.

In figure 3.14) a different grouting scheme is proposed. The grout take should be limited by a quantity related to the pressure arrived at.
The solid line in the figure 3.14), an hyperbolic function, gives the relationship if a constant travel, that is a constant thickness of the grout curtain, is desired indipendently of the unknown thickness of the joints to be filled up.

The grouting rule is thus defined by a number $N$ which is the product of the pressure time the take. (In the example $N = 0.6 \text{ MPa} \cdot \text{m}^3/\text{m}^1$).

One of the dotted lines is to be respected in the case a danger of heaving the rock mass would exist. Some time a combination of both line types is to be selected.

Of course the expression "constant" we just used is to be intended as "of the same order of magnitude", because the rock mass is obviously a complex structure.

In any case a rule of such a kind would solve many of the problems encountered during the grouting avoiding at the same time unnecessary high takes. It is clearly understood that under special conditions, like f.i. karstic rocks, special prescriptions are to be edicted.

c) Improved sequences
Taking into account that, accordingly with figure 3.4), the travel is longer in thicker joints at higher pressure than in thinner joints at lower pressure, it is possible to improve somewhat the grouting scheme for the curtain. The splitting method of the borehole distance should be kept as it proved to be a very good one.

However the grout pressure should be increased from borehole series to borehole series.

The distance between adjacent boreholes are no more constant but will be somewhat changed in such a way to have the distance proportionally increased with the sum of the pressure to be used in the two adjacent holes.
Figure 3.15) refers to a proposed scheme of this type. It shows also, in the case of a homogeniously jointed rock, which joints and how far they are grouted from each of the boreholes.

The distribution shown is valid in the plane of the grout curtain itself. Laterally of it, the relative importance of the secondary and further series increases in respect to the first one.

Combining the second proposal with this one, the maximum pressures indicated at figure 3.15) are to be replaced with a serie of increasing numbers N accordingly with figure 3.14). Operating in this way it should be possible to obtain a more homogenious grout curtain at lesser cost with lesser problems.

3.5 Conclusions

The studies carried on recently and various practical experiences have shown the following:
- as a general rule, stable slurries are to be preferred to unstabiles ones,
- as a rule, bentonite should not be used to thicken up thin slurries. It is better to reduce the water content of the water-cement mixes,
- to ease the penetration a fluidifier can be used which reduces the strenght of the grout set much less than the use of bentonite,
- the grouting process may be speeded up by using of a variable grout pressure,
- the grouting of a grout curtain can be improved and made more economical in using a grouting number N (pressure times grout take) instead of a limiting fix take and a limiting maximum pressure, and
the splitting method for a grout curtain can be improved in increasing the maximum pressure (better the number N) from borehole series to borehole series, and in varying somewhat the distance between the boreholes.

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Giovanni Lombardi Ph.D.
Rheological laws

1: \( \tau = \eta \frac{dv}{dx} \)

2: \( \tau = C + \eta \frac{dv}{dx} \)

1: Newton (e.g. water)

2: Bingham (e.g. stable slurry)

\( \tau \) = shear stress

\( \frac{dv}{dx} \) = velocity gradient

\( \eta \) = viscosity

\( C \) = cohesion
Fig. 3.2

Blaine = 3527 cm²/gr.

Paute dam Ecuador
Theoretical range and used value of W/C factor
Grouting a Joint

\[ R_{\text{max}} = \frac{P_{\text{max}} \cdot t}{C} = h \cdot \frac{t}{Cr} \]
where: \( Cr = \frac{C}{\delta} \)

\[ h = \frac{P}{\delta} \]

\[ P_{\text{need.}} = \frac{R \cdot C}{t} = \frac{2 \cdot C}{2 \cdot t_{\text{min.}}} \cdot R \]

\[ V_{\text{max}} = \frac{2 \pi \cdot P_{\text{max}}^2 \cdot t^3}{C^2} = 2 \pi \cdot h^2 \cdot \frac{t^3}{Cr^2} \]

\[ F_{\text{max}} = \frac{V_{\text{max}} \cdot P_{\text{max}}}{6 \cdot t_{\text{min.}}} = \frac{V_{\text{max}}^{2/3} \cdot P_{\text{max}}^{5/3}}{C^{2/3}} \]

\[ R_{\text{eff.}} = R_{\text{max}} \cdot k \]

Some formulas to the grouting of a single joint

- \( p \) = pressure
- \( q \) = flow
- \( R \) = reach (travel)
- \( 2t \) = thickness of the joint
- \( C \) = cohesion
- \( \delta \) = density
- \( V \) = Volume (take)
- \( F \) = Splitting force
- \( k \) = efficiency
Fig. 3.4

\[ \frac{C}{\delta} = C_y = 0.2 \text{ mm, } \delta = 17 \text{ k N/m}^3, \ k = 0.2, \ S = 2t \]

**Travel of grout (Example)**

- C = cohesion
- \(\delta\) = density
- S = 2t = joint thickness
- k = efficiency


<table>
<thead>
<tr>
<th>( p = \text{const.} )</th>
<th>( V \lim. )</th>
<th>( V = \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t \lim. )</td>
<td>grouting &quot;au refus&quot;</td>
<td>( \times \times )</td>
</tr>
<tr>
<td>( t = \infty )</td>
<td>Reality</td>
<td>Computations Cambefort</td>
</tr>
</tbody>
</table>

**Thinkings about Grouting**

Take vs Time with \( p = \) constant for stable slurry
Flow Law in a Pipe or Joint for a Bingham body

Q = Flow rate  
J = pressure gradient  
Jo = minimum for flow

\[ e/r = J_o/J \]

Radius of the stiff kernel \( e \)

\[ J_o = 2 \cdot C/\delta \cdot r \]
Flow time vs. Viscosity and Cohesion

(Marsh Funnel Eur.)
28-day Strength VS Mash Funnel Flow Time (Am)
<table>
<thead>
<tr>
<th>Properties</th>
<th>dimens. (MKS)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slurry type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>related cohesion $C/\gamma$</td>
<td>mm</td>
<td>1.25</td>
<td>1.05</td>
<td>0.75</td>
<td>0.20</td>
<td>0</td>
</tr>
<tr>
<td>related viscosity $\eta/\gamma$</td>
<td>$10^{-6}$ ms</td>
<td>2.30</td>
<td>1.85</td>
<td>1.30</td>
<td>0.68</td>
<td>0.13</td>
</tr>
<tr>
<td>specific weight $\gamma$</td>
<td>kN/m$^3$</td>
<td>19.0</td>
<td>18.0</td>
<td>17.0</td>
<td>16.0</td>
<td>9.81</td>
</tr>
<tr>
<td>flow time (Marsh Am.)</td>
<td>sec.</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>27.5</td>
</tr>
</tbody>
</table>

Physical properties

of 4 Slurries and Water (Slurries B, C and D used at ITAIPU)
Take $V$ vs time

for ITAIPU - Slurries and Water
Uplift force / vs time

for ITAIPU - Slurries and Water
Grout travel vs time

Fig. 3.12

$P = 3.0 \text{ MPa}$

$P = 2.5 \text{ MPa}$

$R_{\text{max}} \quad P = 2.0 \text{ MPa} \quad t = \infty$

$P = 2 \text{ MPa}$

$P = 1.5 \text{ MPa}$

$P = 1.0 \text{ MPa}$

$P = 0.5 \text{ MPa}$

1 mm - Single Joint • Slurry A ITAIPÚ
a) pressure vs time
b) grout take vs time
G = grouting, T = test

Two grouting procedures

1 usual  2 rapid
**Example grouting rule**

Allowed pressure vs grout take or maximum take vs pressure arrived at.
Grout - Curtain. A proposed scheme