Chemical grout injection is a popular method for improving the stability and reducing the permeability of alluvial soils, but it is not always clear if the methodology adopted in a particular application of the practice represents the most efficient or cost-effective option.

It is possible, however, to use simple formulae to aid in the selection of injection parameters and to understand their inter-relationship, as well as to optimise injection spacings and times with respect to injection source dimensions and insitu permeability. A better understanding of these parameters can help when it comes to calculating the real cost of an injection programme and how to modify a scheme in progress to gain the best result.

In recent years “tube á manchette” injection systems have been adopted for grouting in alluvial soils, but a better understanding of the factors involved in grout injection can make simpler – and less expensive – driven rod injection methods equally appropriate in many situations.

The grout injection schemes considered in this paper are applicable to alluvial soils where a two-stage cement/chemical injection programme is usually used.

Alluvial soils – chemical grouting
The theory and practice of grouting have received considerable attention over the years, and a set of simplified criteria have evolved which have, in the main, guided the way in which such injection work is planned.

The process confounds too precise a methodology, since it has to be flexible enough to accept variations in soil conditions, even within an otherwise presupposed set of criteria. However, it is appropriate to attempt a rationalisation to obtain an overall judgement of the economics of the process, and various theoretical models have been proposed as a suitable basis for injection designs, as indicated below. Figure 1 illustrates the terminology of various injection models. check this

Maaga (1938) related injection time (T) to fluid relative viscosity (η), ground porosity (n), ground permeability (k), the injection pressure head (H), injection source radius (R) and grout travel distance (D) as:

\[ T = \frac{\eta n (D^3 - R^3)}{3kHR} \]

Raffe and Greenwood (1961) proposed an expression based on spherical flow theory, thus:

\[ T = \frac{\eta n}{kH} \times \left[ \left( \frac{D^3}{2} - \frac{R^3}{2} \right) - \left( \frac{D^2}{3} - \frac{R^2}{3} \right) \right] \]

This expression can be simplified to Maag’s expression by ignoring the second term in the main bracket. Maag’s expression can be simplified, as shown by Bell (1982), by assuming that, since R is small compared to D, then R^3 can be ignored, thus:

\[ T = \frac{\eta n D^3}{3kHR} \] (Equation 1)

Theoretical results for T derived from the use of the simplified form of Equation 1 show large variations in the early stages of injection compared to the spherical flow theory. However, as injection continues to more realistic radial distances, the differences grow smaller, with the simplified equation deriving time values approximately 5% higher than the more complicated equation.

The simplified equation

\[ Q = 4\pi H R / \eta \] (Equation 2)

derives values approximately 5% lower than those obtained using the Raffe and Greenwood equation. Since these theories both assume idealised spherical flow from an “equivalent area” injection source, the small difference in values obtained using the simplified equation justifies its use for deriving preliminary injection parameters.

In practice, permeability and porosity values are set by the ground conditions – even if they are not always well defined. The fluid viscosity is set by the choice of grout system and, since it is usual in alluvial grouting to inject while the grout is highly fluid, the viscosity is considered to remain constant. The purist may wish to build in varying viscosity as injection continues, but this degree of sophistication is not considered to be practically justified.

Injection time (T), defined as the fastest time that a given quantity of grout can be injected into a soil by permeation flow, will be examined later, together with choice of grout setting time. For injection rod diameter (d) and cell height (b), the injection source radius (R) is generally assumed to be a sphere with a surface area equal to that of the cylindrical injection source, ie:

\[ R = \left( \frac{db}{4} \right)^{1/3} \]

It is normal for small diameter rods of around 45mm to 54mm diameter to be used as driven grout lances with stage cell heights of between 300mm and 1,000mm. With this geometry, R would range from 58mm to 116mm.

For simpler grout injection work, injection rods with a lost point attached to their lower end are driven to the desired full depth and then progressively raised for each injection stage. The void created is the injection cell. A small positive outflow is maintained during rod lifting to limit ground collapse, although the effects are of minor significance to the overall injection. A more positive injection source may be created by using a rod that has perforations over the injection cell length. While this method is thought to ensure a fixed cell geometry, smear effects can be a factor, with partial blockage leading to possible misinterpretation of the injection parameters in the course of the works.

To overcome this, it is better to adopt a perforated or filter type of injection cell, which can be achieved by covering a section of the rod. The entire assembly can be driven to depth with the cell protected and the cover withdrawn over the cell length. During injection the cover assembly is progressively extracted with the injection cell length protruding below it. The cell is afforded protection from smear both by the continual self-cleansing outflow and the marginally larger sleeve diameter tending to hold the soil away from the cell face.

The above methods are all variations of the simple driven rod system that can readily be used for the majority of shallow injection cases and afford the most economic solutions.

The tube á manchette (TAM) method is very useful for multiple injections, as the cast in place injection pipe allows multiple injections into any specific soil horizon. TAM is essentially a sleeved
Figure 2: Relationship between factors for a range of soil porosity

Figure 3: Effect of varying injection time

Figure 4: Effect of varying the source radius

The purpose of this type of treatment is to progressively inject grout into soil in which earlier adjacent injections have set. By monitoring injection pressures and flowrates, any “lightening” of the ground can be detected as subsequent passes are made. The grouting-in of the TAM assists shallow injections, as leakage to surface tends to be reduced. The penalty of using this technically superior system is the significantly increased cost due to larger diameter drilling equipment and installation of sleeve grout and TAM pipes. Another disadvantage that is not generally appreciated is that the use of the sleeve grout inherently permeates into the soil in an unknown manner, and can mask the more permeable areas that the driven rod methodology would naturally identify.

Injection pressure head (H) is set by the geometry of the stages and the soil/grout type. It is good practice to define the hydrofracture pressure for the outset of the treatment programme as part of the preliminary permeability testing. A factor of safety may then be applied to a representative hydrofracture pressure to set the safe maximum injection pressure to be used in subsequent work.

The two parameters still to be determined are flowrate (Q) and grout travel distance (D). Flowrate is controlled by the mechanical characteristics of the injection equipment, and grout travel distance is related to the fundamental question of economics.

Figure 2 shows the theoretical relationships between factors when Equations 1 and 2 are used to examine the variation in Q and D for a range of soil permeabilities, assuming the soil has a porosity of 0.25. It assumes that an initial cement-based filler grout has been used to limit the cost of the subsequent chemical injections, and a chemical grout of relative viscosity 1.5 injected in a stage cell of 54mm diameter by 300mm high over an injection time of 15 minutes. It should be noted that, in practice, the viscosity of the grout may rise with time as gelling progresses, and this will tend to reduce flowrate and travel distance.

Figure 2 illustrates that, for typical chemical grouting with pre-treatment permeabilities of the order of 10-5m/sec and safe injection pressures of 2Bar (200kPa), for the parameters as defined, the preliminary basis for economic treatment is a flowrate of 6.4 litres per minute and a hole spacing of 0.45 x 1.8 = 0.8m. Note that the multiplication factor 1.8 is derived from an equivalent plan area consideration of the theoretical spherical grout travel versus the actual hole pattern, i.e. approximately v/n.

Table 1 (below) lists the effects on injection flow rate and grout travel distance of variations in the parameters. It shows that more effective injection can be achieved by reducing grout viscosity and increasing pressure and cell size. However, it is assumed that injection would be made at the maximum safe pressure, as defined earlier. The alternative of injecting for a longer time to give greater travel distance – and hence allow greater injection hole centres (and thus less drilling) – has to be balanced against the cost of possibly longer overall injection time. The inherent variability of the ground tends to point towards closer injection centres for best treatment.

Figure 3 shows the effects of varying the injection time for three typical injection cases, where n = 0.25, η = 1.5 and H = 2Bar, while Figure 4 shows the effects of varying the source radius (R) for similar cases. The conclusion drawn from these results is that, while an increase in injection time is obviously beneficial with respect to an increase in radial distance (at the possible sacrifice of overall economies), there appears to be an effective time cut-off point, as after 15 to 20 minutes the grout travel has reached 60-70% of the distance possible in one hour. In other words, it is subject to the law of diminishing returns.

What is more significant is the obvious advantage of increasing the injection source radius. The possible injection flow rate is increased by »
more than 50% by moving from 45mm to 54mm diameter injection rods and increasing the stage height from 500mm to 1,000mm, as well as a 15% increase in radial grout travel. The disadvantages of increased rod driving energy and ground disturbance are marginal in this context.

So far in this paper, model and graphical representations have essentially dealt with the plan view of the injection process, but the three dimensional effects of the injection pattern must also be examined. Figures 5a and 5b show idealised sections through two typical injection patterns. Figure 5a shows a 54mm diameter injection source with a 300mm stage height, and indicates the theoretical spherical flow boundaries for soils with permeabilities of 10^-4m/sec and 10^-5m/sec. In the former case, the five-minute travel distance is shown and in the latter case the 15-minute travel distance.

Figure 5b shows the comparable flow boundaries for a similar diameter injection source with a 1,000mm stage height. These diagrams illustrate two points. First, it is undesirable to have a grout boundary extending significantly further than the stage height, as considerable overlap occurs. The adjacent soil may have been previously injected, so the fresh injection would tend to be diverted. It also leads to non-applicability of the theory being used. Premature grout breakage to the surface, via the drill rod/soil interface, is also more likely to occur, particularly in less shallow stages of injection.

This argument is tempered to some extent by the greater horizontal to vertical permeability normally found in naturally deposited alluvial formations. A simple examination based on comparing an equivalent injection volume per stage with the spherical volume anticipated indicates that D should equal 0.75h. However, it is suggested that the stage height should be approximately equal to the anticipated radial distance of grout travel. The second point to be drawn from Figures 5(a) and 5(b) is that there is a decrease in radial grout travel distance over time with a decrease in soil permeability. The previous discussion still applies, and it is therefore considered good practice to reduce the stage height with decreasing soil permeability, and vice versa, to create optimum injection flow patterns.

Figure 6 is based on the same injection model as used earlier (soil permeability of 10^-4m/sec to 10^-5m/sec). The two broad bands indicate the injection distances, with time, for 45mm and 54mm cell diameters and stage height equal to the planned grout travel distance, D.

This suggests the following general rule: for lower permeability soils, use a shorter stage length with a longer injection time. In the examples above, it would therefore be best to base injection in the higher permeability soil on a 10-15 minute injection time with a cell height of the order of 1m, leading to injection holes on a 2m grid. In the lower permeability soil, the optimum is to use a 15-20 minute injection with a cell height of the order of 500mm and injection holes at 1m grid spacing.

In the above examples of simple injection methods, potential increases in injection flow rate of 50% and increases in grout travel/hole centres of the order of 15% can be achieved, the latter leading to an overall reduction of approximately 30% in the number of injection holes required. When combined with a potential 50% reduction in the number of injection stages per hole, a significant reduction in overall stage numbers could be possible. However, there has to be a limit to this argument since the theoretical conclusion is to go on increasing the injection source size and reap greater and greater benefit. At this point, science meets art and art
wins, since driving larger diameter rods becomes more expensive and ground disturbance significant.

When considering the economics of the process there are essentially three categories of cost: mobilisation and demobilisation, supervision; drilling; and materials, mixing and injection. Since any saving in overall time is unlikely to affect mobilisation/demobilisation, the only saving in the first category would be by reducing supervision time. Drilling rates vary with the geometry of the project and drilling methods adopted, but it is here that the largest financial savings are potentially significant. The economics of drilling are clear, since the quantity of work varies with the hole or stage, pressures or injection quantities. This is compounded when working in poor conditions in which record keeping becomes difficult. Problems can be reduced by using electronic data acquisition by means of real time pressure transducers and flow meters that can be operated at the pumping station with the injection reference entered via a keyboard. This will assist the instant and historical review and appreciation of how the injection programme evolves. Data can be analysed using simple programs with built-in warnings to highlight where further treatment is needed.

**Conclusions**

Approximate formulae can be used as a suitable basis for preliminary designs of schemes for chemical injection in alluvial soils, while optimising parameters can lead to cost savings through improvements in injection flow rate, fewer stages and an overall reduction in injection hole numbers. However, it is important to remember that the simplified theory of spherical flow can only be used as a guide, as non-uniform soil conditions – particularly differences between vertical and horizontal permeabilities – control the real form of grout boundary achieved.

While the use of tube à manchette methods has been noted, this paper has concentrated on the more simple driven injection rod methods in which the selection of stage heights and hole centres can be rationalised to suit a particular project. As a general rule it is suggested that stage height should be approximately equal to the anticipated radial grout travel distance. Also, with lower permeability soils, relatively short stage heights should be adopted with longer injection times and vice versa for higher permeability soils.

Minor changes to these criteria can be seen to have a small effect on overall project economics, leading to the conclusion that an approximate selection of injection parameters can be used throughout an injection programme or small on-going modifications can lead to improvements in the treatment without significant financial escalation.

It is important that the personnel responsible for executing this type of work plan effective on-site data collation and control methods that enable the effectiveness of the treatment to be evaluated, using either manually produced records and graphical representations or automatic data recording linked to computer data storage and analysis.

The theory behind injection work has to bend to the art, as the ground is not an idealised material, and ongoing examination and probable revision to the injection design is the hallmark of a job well done.