ARTIFICIAL GROUND FREEZING (AGF) VERSUS GROUTING

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ABSTRACT

Temporary works have a substantial impact on a project. Applying a risk assessment and value analysis should be an important part of the evaluation process in order to rank various geotechnical processes in relation to a specific job. Although Artificial Ground Freezing (AGF) has long been established as a reliable technique for the stabilization of weak and/or water bearing strata, as an aid to excavation for shafts and tunnels, many engineers still regard it as a high-cost solution of last resort. This paper attempts to identify some of the salient factors which influence the cost effectiveness of the AGF process versus the use of grouting.

KEYWORDS

Artificial Ground freezing (AGF), Grouting, Groundwater ingress control, Ground stability control

INTRODUCTION

This paper will initially look at the site investigation data which is required to determine whether the ground is water-bearing, stable (self-standing when excavated) rock, in which case the choice to be made is whether the groundwater in the excavation can be handled by pumping or does it need to be reduced first by grouting or AGF. If the ground is unstable sands, silts and clays when excavated, is it possible to grout it to achieve the required groundwater ingress prevention and ground stability control during excavation or will it need freezing. The paper will follow this with a discussion on risk and review methods of risk and value assessment in relation to the various geotechnical processes. Final summary comments complete the paper.

OVERALL REQUIREMENTS

The first step is to identify what type the ground is and what are its characteristics. Soils normally come under the classifications of sands, silts, clays and gravels. Rocks encompass sandstones, limestones including vuggy forms, siltstones and mudstones with fractured variations. The direction of excavation could be horizontally for a tunnel or vertically for a shaft. Maintaining ground stability during excavation is of fundamental importance, whether it be a tunnel or a shaft, and therefore the ground strength needs to be known as well as the ground deformation characteristics under load for deformation control purposes. The method of excavation can also be an important factor. For shallow shafts and tunnels, constructed using civil engineering methods in depths up to about 100m from the surface, mechanical excavators and tunnelling machines will normally be adopted. In the case of deeper mine shafts, excavation is generally by the drill and blast method but modern trends are adopting mechanical excavation using sinking machines. It is important in these cases for the method of ground treatment, be it grouting or AGF, to be compatible with mechanical excavation. Sinking machines are geared up for continuous excavation at faster rates than with the drill and blast method. AGF is more suited to this type of operation as all water inflow is precluded from the shaft and sinking can progress unhindered whereas forward probe drilling and grouting is a start and stop operation restricting continuous machine use. The latter imposes a time penalty on the operation whereas AGF does not once the ground is frozen ahead of the operation. Estimates of groundwater inflows into tunnels and shafts during excavation are required to determine whether it is feasible to handle the inflow volumes by pumping or whether the inflow volumes need to be reduced to an amount which can be pumped. If the estimated amount is greater than a volume which can be handled practically, then grouting may be a solution to reduce the volume, otherwise AGF may be used. The use of grouting depends upon the permeability of the ground and the limits on permeability define whether the ground can be grouted using normal cements, or whether for lower permeabilities fine cements can be injected or chemical grouts are necessary. When using grouts, cognizance must be taken of what can be used bearing in mind Health and Safety requirements. Finally, a Risk Assessment and Value Analysis should be carried out to evaluate the viability of any project on a time and cost basis.

Site Investigation Requirements

Shallow Shafts and Tunnels (Generally civil engineering works in depths up to about 100m)

This again generally encompasses work in soils such as sands, silts clays and gravels. Groundwater inflow prevention and ground stability control are the key essentials to cater for in this case. For groundwater inflow prevention using grouting, it is necessary to predetermine the ground permeability and the resulting injectable capability of the ground. Borehole pumping or slug tests are carried out to determine the ground permeability in situ. Estimates of the expected groundwater inflows can then be made and decisions on the method of ground treatment to be adopted decided upon. As a general rule, ground with permeabilities greater than 10^{-4}cm/sec can be injected with normal Portland cements. Permeabilities of less than 10^{-4}cm/sec require injection with microfine cements or chemical grouts. If the level of groundwater inflow can be lowered to the required handleable amount by grouting, it can be adopted. A suggested level is a maximum amount of 10gpm (45.5litres/min.). Otherwise AGF will be necessary. Careful consideration should be made on whether to use grouting in lieu of AGF, as past experience has shown that in some cases when ground has been considered injectable by grout, it has not achieved the required reduction in groundwater inflow and AGF has eventually been required with an additional time and cost penalty. In some cases, AGF requires less drilling than grouting and it is noted that the drilling is the most significant component of the costs.

For ground stability control, the soil strength and deformation under load properties must be investigated prior to excavation. It is possible to use a grout which will enhance the strength of a soil to some degree. AGF increases the soil strength when frozen and frozen sand will be stronger than frozen silt and clay. It is therefore important to determine the Unconfined Compression Strength (UCS) value of the soil, after it is treated by either grouting or AGF, by testing samples in a laboratory for excavation stability design purposes. Frozen soil deforms with time under load and frozen soil laboratory creep tests are required to determine its deformation characteristics.

Deep Mine Shafts (Depths greater than 100m)

These projects generally encompass work in rocks such as sandstones, limestones including vuggy forms, siltstones and mudstones with fractured variations. In these cases, it is normally just water inflow prevention which is needed, although there are some situations at deep level which require AGF for ground stability control requiring a knowledge of the soil deformation characteristics. Down the borehole Pressure Recovery Tests by water injection are used to determine the permeability of the rocks to enable estimations to be made of the expected groundwater inflows into the shaft excavations. A decision can then be made as to whether the expected groundwater inflow amount can be handled just by pumping, or can be reduced to an acceptable amount by grouting or whether AGF is required. In relation to an acceptable reduced amount by grouting, 50gpm (227.3litres/min.) is suggested but the lower limit of 10gpm (45.5litres/min.) could be more appropriate if it can be achieved. However, A lot of time and money could be expended in trying to reduce the groundwater inflow to an unrealistic amount.

Value, Risk and Cost effectiveness in AGF and Grouting Works

The following sections of this paper are a based on The British Ground Freezing Society's Artificial Ground Freezing Technical Memorandum TM5 prepared on the subject by S. J. Harvey of the British Drilling & Freezing Co. Ltd. and Dr. A. J. Wills of Trafalgar House Technology Ltd.

Risk

Prior identification of likely problems, the RISKS, and the EFFECTS if they materialize, are the basis of Risk assessment. Comparison of alternative methods of ground treatment will provide a guide to cost effectiveness and value.

RISK is defined as *an uncertain event which may have a detrimental (or beneficial) effect* and Risk Factor as *the likelihood that the perceived Risk will materialize, combined with the comparative impact such would have on any aspect (s) of the Works.*

HAZARD is *an uncertain event whose consequence is detrimental having the potential for damage to the works or the environment, or injury to people.*

OPPORTUNITY is *an uncertain event whose consequence is beneficial, usually in cost or time savings*.

UNCERTAINTY is *an event whose outcome cannot accurately be predicted.*

RISK VALUE is the *integrated quantitative assessment of the probabilistic measure of the occurrence of the hazards, with a measure of the consequences of those events*

Risk Assessment.

Modern quantitative methods for risk assessment of projects identify four main areas of risk which are cost, program, performance and revenue. Performance includes technical aspects of security, safety and control. These risks are all interrelated, and assessors may not rank them in the same order. The viability of a project, assessed as the revenue risk, can be influenced by cost timeliness and performance. On many occasions recourse is made to the use of AGF after the originally selected alternative ground treatment of grouting has failed to ensure a safe and secure excavation which affects the cost and program and ultimately detracts from the project's revenue.

Program Risks

The assessment of program risks, the risk of not meeting critical dates, is based on the allocation of probable durations, or ranges, of the various tasks necessary to complete the AGF or grouting stages of the project. It may be possible to carry out some of the tasks concurrently. This may provide guidance on how much contingency or float to build into the schedule of specific tasks. For example, the time for closure of a freeze wall may be predicted within a range of so many days or so many weeks depending on the magnitude of the operation and the chosen method of refrigeration. Groundwater velocity should also be considered as it can retard or even prevent the formation of the frozen earth structure. The risk assessor must decide, using his knowledge and experience, what the most likely duration would be. Similarly, a risk assessment would be carried out for a grouting option. However, in this case, the program duration is not so easily defined. Depending upon how much groundwater reduction is required, and how much grouting material would be required for its achievement, these items can only be estimated at the beginning of a project with less accuracy than for the AGF system and requires more contingency time to be built into the estimated program.

Technical Risks

Considering an excavation project, the technical hazards may include water-bearing strata, artesian and sub-artesian conditions, weak or running strata, groundwater flows, saline or aggressive groundwater, any or all of which, without suitable treatment, could be detrimental to the programmed completion of a project. The aim of a well-designed scheme is to provide temporary security so that the ground within the freeze wall or grout curtain may be safely excavated without risk of flooding or collapse. Once the permanent works have been installed, in the case of an AGF scheme, the freeze can be withdrawn in a controlled fashion. The grouting scheme remains in place permanently. The environmental impact of permanent barriers altering groundwater flow regimes is rigorously evaluated on many current projects.

Revenue Risk

The client will be very aware of the potential costs/losses that he will incur through lateness of completion, although the Contract may well include for Liquidated Damages as some form of "compensation" should this happen. He will, however, prefer the method in which he can be confident that the program will be met. This inter-relates with the assessment of program risks.

The drilling and installation of either the freezing or grouting boreholes may also present a critical risk related both revenue and schedule. Two main factors impact the risk of both freezing and grouting boreholes. The most obvious factor is the ability to actually drill the holes on schedule. These factors are the actual drilling penetration rate and production and also the deviation of each individual borehole.

Obstructions such as cobbles and boulders as well as loss of drilling fluid circulation resulting from loose granular soils can significantly increase both the required time to drill and install the grout or freeze pipes and the costs associated with those delays.

The deviation between adjacent boreholes is often a substantial risk. Design parameters for both freeze and grout holes always stipulates the maximum allowable difference. It's often not a specific measurement as evaluation and modeling of the actual locations is needed. This evaluation often results in the need for additional pipes to "fill the gap" created by the drilling deviation. These additional boreholes and pipes add time to the project schedule and costs associate with it. Projects that have failed to consider the effects of this deviation are known to finish behind schedule and way over budget.

In the case of ground freezing, additional pipes required to compensate for the deviation will require additional refrigeration capacity. In some cases where excessive redrills are required, additional freeze plants have been required. This increases both the equipment costs and long-term power costs.

Most deep mine shafts that are lined as the excavation progresses, can be frozen with a single row of freeze pipes and the re-drills required for deviation. The deviation is almost always minimized with the use of directional drilling. The directional drilling systems required considerably more up-front costs, but on the deep shafts there is no alternative.

Assuming that a deep shaft requires the up-front costs for directional drilling, these costs will apply to either AGF or grouting. While the AGF can be completed with a single row of pipes, grouting typically requires primary and secondary holes, and in some cases tertiary. While these additional pipes not only double or triple the installation costs compared to AGF, but they also triple the risk associated with obstructions or fluid loss during drilling.

While grouting can be carried out from the surface for deep shaft sinking, in most cases cover grouting from the shaft sump as sinking proceeds is more common. In this case, numerous grout covers at different depths with multiple rings of holes, depending upon what groundwater is encountered, may be required.

Minimizing the Risk

The basic principles of AGF are very straightforward, and the technical risks already identified are, therefore, small. Frozen ground is a barrier to flow of groundwater, and subsequently increases the strength of weak soils. The technical risks can be reduced still further by good site investigation and materials assessment, by careful control during execution, and by corrective action before an adverse situation can develop. The grouting option does not guarantee full water inflow prevention depending upon what level of grouting is carried out in terms of groundwater inflow reduction and the time required to achieve the required reduction amount. The benefits of ground freezing are greatest when dealing with complex strata, incidence of groundwater and deep excavations. The Risk Assessment should reflect these perceived advantages.

Method of Risk and Value Assessment

Two models, A and B, are referred to in TM5 which can be adapted to suit particular requirements.

MODEL A

In Harvey's Model A, a value analysis based on comparison of Contractor's proposals, the control of ground conditions and groundwater and safety during excavation and lining are each scored 0-100 according to set criteria of the proposal. Groundwater control is considered to be more sensitive than the other headings and is weighted 1.5 against the other criteria weightings of 1.0. The sum of the scores is divided by the Tender price to yield a highest-is-best order of Merit.

The following set of suggested conditions is applied to each Contractor's submission for scoring purposes.

Ground Conditions (Weight Factor = 1.0)

100 - Has assessed all data and understands varying soil properties. The method proposed is not affected by ground conditions as the excavation is continuously supported.

75 – Has assessed all data and understands varying soil properties and taken this into account in the method. Includes plans to deal with changes if they occur.

50 – Has assessed all data plus aware of variable ground conditions. Has made provision for change of excavation method but no detailed plan.

25 – Has fair understanding of ground conditions and referenced possible method changes. Methods to be finalized as the excavation progresses.

0 – Has taken no account of varying ground conditions.

Control of Groundwater (Weight Factor = 1.5)

100 – Method proposed is not affected by water and can operate under any soil or groundwater conditions.

75 – Understands groundwater problem and details control of water flowing prior to excavation commencing.

50 – Has assessed water flows at various horizons. No plan to control water before excavation but has plan in event of water flows being encountered.

25 – Has understanding of groundwater regime but no specific plan to deal with water during excavation.

0 – Has taken no account of site hydrology.

Safety (Weight Factor = 1.0)

100 – Has provided precise detailed safety plan. Ventilation and hoisting systems duplicated. Need to test for gas. HSE approved methods.

75 – Uses conventional excavation methods and detailed safety arrangements. Has detailed equipment to be used and critical equipment duplicated.

50 – Has provided outline details on safety in respect of hoisting, ventilation, gas testing. Has not detailed critical equipment which is duplicated.

25 – Has stated that safety plan will be drawn up later. Very little mention of safety in presentation.

0 – Has provided little or no information about safety standards. Cavalier attitude to safety at presentation (trust us, we know what we are doing).

Using Harvey's worked example based on an actual contract, a comparison can be made between AGF and Grouting (see Table 1).

Table 1. Risk and Value Assessment for AGF Versus Grouting based on Harvey's Model A

Temporary Works Proposal	Tender Price £k (a)	Control of Ground Conditions (b)	Groundwater Control (c)	Safety During Excavation and Lining (d)	Total (b)+(c)+(d) (e)	Total/£k (e)/(a)	Ranking
Ground Freezing	100 Up front cost known	45 x 1 = 45	60 x 1.5 = 90	55 x 1 = 55	190	1.9	1
Grouting	70 Final cost unknown	30 x 1 = 30	43 x 1.5 = 65	25 x 1 = 25	120	1.7	2

A number of observations can be made based on the results of this exercise. The upfront and end costs for AGF are normally well known at the beginning of a project together with the program. For a grouting scheme, an estimate of the requirements can be made at the beginning of the project but the final costs and program are not so easily quantifiable. A Contractor is highly unlikely to give a fixed price for a grouting scheme but specify it on a labour and materials rate only basis. Nevertheless, Clients at the beginning of a project tend to opt for grouting, as opposed to AGF, to avoid the high up-front costs of the latter, in some cases to their detriment if the grouting fails and subsequent recourse to the use of AGF in addition is required. The control of ground conditions is considered to be better with AGF and so is the control of groundwater where inflow is removed entirely with AGF, but residual water inflows remain with grouting. Operating in a frozen ground environment is regarded as being safer than with the grouting option. In accordance with Table 1, the higher-ranking number for AGF would suggest it to be the preferred scheme.

MODEL B

The Model B, proposed by Harris (1995), carries out a Value Analysis related to the performance characteristics of geotechnical techniques based on five headings, installation, strata changes, adverse groundwater, deformation and equipment breakdown (see Tables 3 and 4). An additional heading of hole drilling has been introduced.

Hazard - for each Hazard allocate a value for the Probability Factor within the ranges from 0 as the most adverse to 1.0 as totally successful.

Impact Factors – allocate Impact Factors for Security, Time and Cost taking account of all likely effects scoring on the same basis. At this stage, if one of the above four headings is considered to be of lesser or greater importance in the overall assessment, the value can be "weighted" up or down as appropriate.

Risk Factor - all four Probability/Impact Factors are multiplied together to obtain the Risk Factor.

Risk Value – for each Method it is then necessary to select a unique figure, which may be the average, or lowest, of the Risk Factors obtained under the various headings. This is the Risk Value.

Using Harris's worked example based on an actual contract, a comparison between AGF and Grouting can be made (see Table 2). The Order of Merit is obtained by dividing the Lowest Tender Value by the Risk Value, the lowest number being the best. Risk Values for Table 2 are obtained in Table 3.

Table 2. Risk and Value Assessment for AGF versus Grouting based on Harris's Model B

Method using Tender Prices	Lowest Tender Value (a)	Risk Value (b)	(a)/(b) Lowest is best	Order of Merit by Value
Ground Freezing	100	0.71	141	1
Grouting	70	0.35	200	2

Table 3. Generation of Risk Value for Model B assessment (Ground Freezing)

Method	Risk	Probability	Impact			Risk Factor	Risk Value
			Security	Time	Cost		
Ground Freezing	Installation	0.9	0.9	1.0	1.0	0.810	
	Strata changes	1.0	1.0	1.0	1.0	1.000	
	Adverse groundwater	0.8	0.8	0.7	1.0	0.448	
	Deformation	0.9	0.9	0.9	0.9	0.656	
	Inaccurate monitoring	1.0	0.8	1.0	1.0	0.800	
	Equipment breakdown	0.9	1.0	0.9	0.9	0.729	
	Freeze hole drilling	0.8	0.8	0.9	0.9	0.518	0.71

Table 4. Generation of Risk Value for Model B assessment (Grouting)

Method	Risk	Probability	Impact			Risk Factor	Risk Value
			Security	Time	Cost		
Grouting	Strata changes	0.6	0.5	0.6	0.4	0.072	
	Deformation	0.9	0.8	0.8	0.8	0.461	
	Preferred channels	0.6	0.6	0.5	0.4	0.072	
	Equipment breakdown	0.9	1.0	0.9	0.9	0.729	
	Grout hole drilling	0.8	0.8	0.8	0.8	0.410	0.35

Using Method B, AGF comes out again as the best option, as opposed to Grouting.

SUMMARY COMMENTS

In making a decision as to whether to use AGF or grouting for ground stability control or groundwater ingress prevention into an excavation, it is first necessary to carry out a thorough site investigation. The fundamental properties from the SI for decision making are the drilling risks, the ground strength (UCS), and any additional creep properties, for ground stability control during excavation, and the permeability of the ground for estimating groundwater inflow amounts. The design of the Grouting and AGF schemes can then be carried out. Once this is done, a Value, Risk and Cost effectiveness exercise should be carried out on both to determine the best scheme. The two Risk and Value assessment examples contained in this paper indicate that AGF would win over Grouting. However, as the up-front cost of AGF on a project is generally more than that for a Grouting scheme, Clients tend to go for the latter option. Generally, this leads to a much greater time and cost penalty in the end.

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