

Grouting in Dams and Levees: The Fundamentals

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ABSTRACT—Grouting for dam and levee remediation is typically conducted in the natural foundation materials. In addition, even though the embankments must be penetrated by boreholes to provide access to the foundation, the embankments themselves may also be targeted for treatment. Three grouting techniques are most commonly involved, namely rock mass fissure grouting, void filling and jet grouting.

This paper describes best practices for each grouting technique, and highlights the real time instrumentation which should be employed as part of the QA/QC and Dam Safety Monitoring programs integral to contemporary practice.

1. INTRODUCTION

There is a wealth of information readily available to dam engineers on grouting technologies. It is to be found in conference proceedings, textbooks and practice manuals. However, the world of grouting is very wide, even though it remains a quintessential specialty engineering subject. Although great technological leaps have been made over the last two decades in particular (Bruce, 2017), there remain misunderstandings and errors, a situation which applies equally to owners, consultants and contractors.

Contemporary drilling and grouting efforts in and under dams and levees are most often conducted to locate and seal voids, to treat fissured rock, and/or to cement unconsolidated materials, both natural and artificial. In former days, permeation grouting, usually with sodium silicate grouts or more rarely with true solutions, was a relatively common technique to create a seepage barrier. This is now an uncommon practice as such works in soils are now routinely accomplished by other means, such as diaphragm walls or Deep Mixing. Similarly hydrofracture (claquage) grouting has no market in dam and levee projects, partly due to its very limited technical applicability, but largely due to engineering concerns over the use of the elevated grouting pressures implicit with this method on dam safety during construction.

These considerations drive the technical scope of this paper, which therefore deals with:

- rock mass fissure grouting
- filling of voids
- jet grouting

This paper does not address permeation or hydrofracture grouting.

Each of these techniques has its own particular set of means, methods, materials, mentalities, and experiences. However, there are important commonalities between them, specifically relating to the design, control and verification of the works, to the drilling phases, and to the monitoring of the structure and its foundation during and after the execution of the works. These commonalities are reviewed first, as background to the three main topics listed above.

2. COMMONALITIES

Relating to the design and control of the works:

- Every grouting intervention should be referenced to a specific Potential Failure Mode (PFM). In this particular case, a loss of impounded water sufficient to cause significant financial loss should also be regarded as a PFM because such loss will have compromised the mission of the overall scheme, even if it has not initiated a “generic” PFM such as piping or structural instability. Depending on the particular project, it may be necessary to consider PFM’s arising during construction, also so that the safest and most applicable construction methodologies can be selected (and others prohibited).
- Every project must be designed – or at the very least – peer reviewed by a knowledgeable and experienced grouting engineer. Designs based on internet searches by inexperienced engineers may often have flaws which can lead to performance inefficiencies and/or contractual disputes.

- Real-time monitoring, control and analysis must be conducted on every project, regardless of scale or apparent complexity, to ensure the design is being implemented correctly, in accordance with the prevailing Plans and Specifications (and best practical contemporary standards of care), and to ensure that the progressive influence of the grouting and its impact on the ground are being recognized and acted upon.
- The goals of the program must be established logically and communicated clearly between all stakeholders. Such goals and their “measures of success” must be reasonable, realistic and verifiable.
- Appropriate details of structural, foundation, and instrumentation monitoring must be established. These will reflect the goals of the grouting, and the nature of the PFM’s. All instruments must be installed and baselined as early in the project as feasible. A Joint Instrumentation Monitoring Program (JIMP) must be established, prior to a drilling and grouting program commencing, detailing which instruments are to be read, by whom, how frequently, and with which Alert and Threshold Levels. On larger projects, these details may vary with the location and state of progress of the actual activities being undertaken at any given time.

Relating to the drilling processes, detailed guidance can be found in Bruce and Lyons (2018), in the USACE EM 1807 (1997), and in the updated USACE Grouting Manual (2014). The commonalities for grout hole drilling are as follows:

- Typically 3 to 12-inch diameter.
- Typically ≤ 200 -foot depth.
- Typically within 30° of vertical or horizontal.
- Mostly beneath the water table.
- Required in all types of ground, natural or placed, unconsolidated or lithified, and will often encounter obstructions.
- May face Federal regulations, such as USACE (1997).
- Must cause minimal damage to the ground or existing structures.
- Must allow completion of the hole in one day.
- Must be consistent and able to be controlled and monitored.
- Continuous, straight penetration.
- Constant diameter, stable and clean.
- Appropriate combinations of thrust, torque, rotation, percussion, flush to be used.
- Cost effective.
- Methods to be dictated by the ground, not by historical bias.
- Environmentally compatible.
- The selection of the type of drill flush (“circulation”) and its operating parameters is extremely important in assuring safe and fast drilling, but is often overlooked by professional engineers. Instead, responsibility for these decisions is typically assumed by (or given to) the drillers themselves. Now this, in itself, is not necessarily a bad or wrong thing – competent drillers are the backbone of every grouting project. However, the owner should always clearly state what is not acceptable (e.g., the use of air flush in an embankment), and the designer must always prohibit certain practices which will compromise the effectiveness of the subsequent grouting (e.g., the use of air “mist” in rock fissure grouting). Otherwise, the project Specifications should be very much “Performance” and not “Prescriptive” based. The all-important Up-Hole Velocity (UHV) of a flushing medium is calculated based on the following considerations:
 - Up-hole velocity (UHV) must be greater than the “sinking velocity” of particles
 - In water, the sinking velocity (V_z) is $V_z \approx 10^6 \times d^2$ m/s where d is the diameter of the largest particles to be removed.
 - Ability of the flush to carry or suspend cuttings is dependent upon:
 - rate of flow of fluid
 - Viscosity of fluid
 - size and shape of cuttings
 - s.g. of fluid and cuttings

It is simply calculated as follows:

$$\text{UHV (m/min)} = \frac{1274 \times \text{Flush Pump Rate (Liters/min)}}{D^2 - d^2 \text{ (mm)}}$$

where D = drill hole diameter (in mm)
d = drill string diameter (in mm)

The minimum value of UHV necessary to efficiently clean the hole is clearly dependent on the nature of the flushing medium, viz:

DRILL FLUSH MEDIUM	RECOMMENDED UP-HOLE VELOCITY
Air	1500 m/min (maximum 2100 m/min)
Water	36 m/min (maximum 120 m/min)
Medium viscosity mud (35-s Marsh)	30 m/min
Thick mud (more than 50-s Marsh)	18 m/min
Foam	12 m/min

Source: Australian Drilling Industry Training Committee Ltd., 1997.

- Drilling is often the most critical, costly and difficult part of the grouting project, especially in remedial applications requiring deep, frequent and safe penetrations through potentially vulnerable embankments. It is therefore reasonable to try to extricate as much information on the formations being drilled as is practical (and useful), from every production borehole. “Monitoring While Drilling” (MWD) is receiving increasing attention, originally using manual methods, but more recently and precisely by automated, real-time instrumentation (e.g., Jean Lutz system). With the latter, diagnostic drilling parameters are recorded in real time and these are then integrated into the unit of Drilling Specific Energy (e), thus:

$$e = F/A + 2\pi NT/AR$$

where e is specific energy (kJ/m³), F is thrust (kN), A is the cross-sectional area of the hole (m²), N is rotational speed (revolutions per second), T is torque (kN – m), and R is the penetration rate (m/s)

MWD therefore permits the “drillability” profile of the structure and foundation to be displayed for every production hole (Figure 1). If required, such profiles can then be compared to and correlated with data from more traditional sources (e.g., coring, SPT, or CPT) as retrieved in dedicated investigatory holes. Borehole collar location and elevation, as well as the inclination of the drill rig mast, must always be recorded, whereas the actual trajectory of the hole itself (i.e., in the ground) is only infrequently necessary or useful to measure, and such measurements may interrupt drilling progress. Production boreholes can also be subjected to Optical or Acoustic Televiewing, other in-situ photography, or in-hole geophysics.

Relating to QA/QC and Verification, it is fair to state that:

- Each grouting method has its own special QA/QC requirements.
- The method of verification must reflect the goals of the project, and the grouting method. Thus, fissure grouting is invariably conducted to reduce rock mass permeability. Therefore, verification drilling is conducted after it is believed, from close analysis of the drilling, routine stage water pressure testing (Paisley, et al, 2017), and grouting data, that the target residual permeability of the curtain is most likely to have been met. Such holes are subjected to multistep permeability tests, the rationalizing of which is enhanced by close study of Optical and/or Acoustic Televiewer logs. These tools remove the necessity of having to core Verification Holes, since routine destructive, production drilling methods can be used. Observations of relevant piezometers, dye tests, weirs or other seepage points, or “trolls” are also potentially extremely valuable.

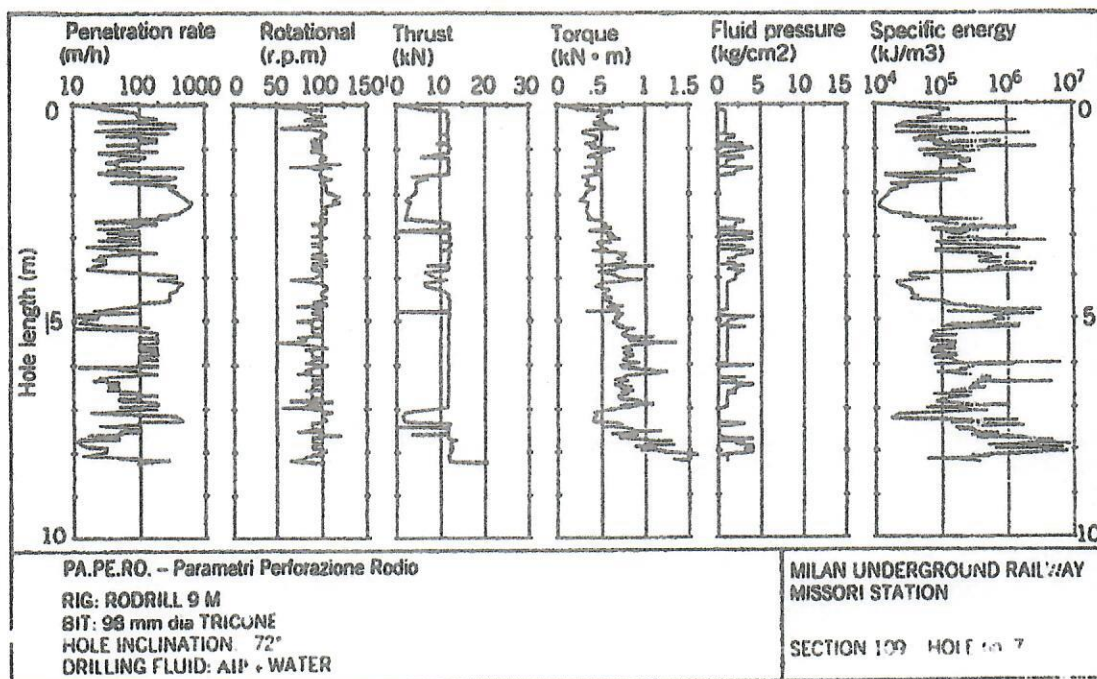


Figure 1. Plots of measured parameters: rate of penetration, rotational speed, thrust, torque, fluid pressure, and specific energy (DePaoli et al., 1987).

- When the goal of the operation is to fill voids, then the best verification is to supplement individual hole volume-pressure-time characteristics (for each order of holes) with settlement monitoring data, and to drill and attempt to inject final order “check” holes. On occasions, filling voids will be linked with seepage reduction, and so, as for rock fissure grouting, information from piezometers, weirs, and trolls will be most valuable. On very rare occasions, the Limited Mobility Grouts commonly used for void filling may have had to be used for true soil densification. Clearly, therefore, in such cases, testing the ground for density changes during and after grouting is the most appropriate verification method, in concert with deformation measurements.
- Compared to the other techniques reviewed herein, jet grouting has been used somewhat infrequently in relation to dam and levee projects. However, success has been achieved, under challenging conditions, at several projects in the last 15 years or so, including those at John Hart Dam, BC, Wickiup Dam, OR, Herbert Hoover Dike, FL, and for relatively minor but highly important “ancillary” solutions in the Sacramento, CA and New Orleans, LA levee systems, amongst others. Jet grouting processes involve the use of high energy, high pressure injections of fluid cement-based grout, so the highest standards of care and caution must be in place in real time when used in a dam or levee environment. Verification of a jet grouted “curtain” will involve some, or all, of the following checks for continuity, strength, homogeneity and permeability:
 - Coring, including lab strength testing of samples.
 - Optical/Acoustic Televiewer.
 - Falling/Rising Head Permeability Test.
 - Probe Holes (to verify column diameter).
 - Analysis of “theoretical” column diameters based on contractors’ in-house “diameter to Jet Grouting Specific Energy” databases.
 - Analysis of column verticality data.
 - Lab strength testing of bulk and/or grab sample.
 - Proprietary geophysical measurements of column diameter.

As a word of caution, however, jet grouting for dams and levees is only considered and undertaken when it is evident that other techniques are not feasible (usually due to access restrictions, including the presence of preexisting underground structures): a great deal of erosive energy is applied in a short time. Such operations always demand an

elevated level of care with particular regard to the security of the structure (and its foundation) during the drilling (and predrilling, if necessary) operations.

3. ISSUES SPECIFIC TO EACH GROUTING TECHNIQUE

3.1 *Rock Mass Fissure Grouting*

Publications detailing the various issues relating to rock mass fissure grouting are particularly numerous. The overview by Bruce et al. (2017) provides perspective on the best – and worst – of contemporary practice, while detailed descriptions may be found in Weaver and Bruce (2007) and Bruce (2012).

3.1.1 Design Considerations

- At least 2 rows of grout holes are used, each row being inclined in opposite directions. The length and depth of these rows must reflect the site-specific hydrogeological model, and not some archaic rule-of-thumb. In this regard, preliminary site investigation should acquire as much permeability testing data as feasible, so that the boundaries, lateral and vertical, of the curtain can be determined logically.
- At least three successive phases (orders) of holes should be anticipated, the Primaries being spaced so that the Tertiaries (where required) will be at 5 to 10-foot centers in each row.
- Upstaging is preferred, but downstaging of the upper part of the curtain is good practice for dam safety reasons in that it provides a grouted “umbrella” protection to the sole of the embankment.
- Injection pressures (water or grout) should be as high as possible without causing damage to the embankment or the foundation. Such pressures are easy to determine and control using computerized management systems.
- Each stage must be brought to a proper *refusal*, say 0.25 - 0.75 gpm at maximum pressure for at least 5 minutes, in order to maximize the effectiveness of the drill holes. The closure criterion must be selected in advance of construction and will reflect many factors (Houlsby, 1990). Most targets are in the 3 - 10 Lugeon range, but lower values can be achieved – at a cost – in amenable geologies.

3.1.2 Construction-Related Issues

- Well constructed working platforms, preferably built with concrete, are a great boon to safety, productivity and quality. (This applies equally to the other grouting techniques also.)
- Drilling through embankments should follow USACE ER 1110-1-1807 (1997) in which the use water and/or air is prohibited. This explains the popularity of rotary sonic and dry double-head duplex casing systems. Drilling in rock is most commonly conducted with water-powered, down-the-hole hammers (and not with air, or “mist”).
- Particular care must be taken in the placement and sealing of the permanent standpipe (typically plastic) providing access to the underlying rock mass. Some type of Multiple Packer Sleeved Pipe (MPSP) is best practice, assuring that the embankment is effectively hydraulically isolated from the foundation, and that it will not be allowed to contain ungrouted voids around the standpipes at the conclusion of the work.
- Suites of stable, modified, cement-based grouts are used, being a blend of several materials, including also bentonite, viscosifiers/stabilizers, and superplasticizers. Marsh cone values are typically, for each successive mix, 30-35; 40-45; 50-60; and infinity, seconds. In most cases, a common pressure filtration coefficient of $0.06 \text{ min}^{-1/2}$ is reasonable, but this varies depending on the project goals from 0.04 to $0.09 \text{ min}^{-1/2}$. The use of high-speed, high-shear (“colloidal”) mixers is essential.

3.1.3 Specific OA/OC Issues

- Grout quality and consistency during production is best achieved by automating the mixing, storage and pumping of the grout to the maximum extent possible, and by using experienced, dedicated personnel.

- Routine QA/QC tests of the grout can be restricted to regular Marsh Cone, Bleed and Baroid Mud Balance (for Specific Gravity) checks. At the mix design stage (and perhaps at monthly intervals thereafter), these tests are supplemented by “classification” tests, such as for pressure filtration coefficient, stiffening and hardening times, temperature and strength. Further guidance is provided in Chuaqui and Bruce (2003).
- A Data Management System (DMS) is an essential element in controlling and assuring quality, and it should dovetail with the field injection computer control system. The contractor’s DMS must be devised and operated by a suitably qualified grouting engineer (not just an IT specialist). There must be a similarly equipped, dedicated and experienced engineer as counterpart on the owner’s side.

3.2 Void Filling

The detection and filling of voids in and below embankments in general involves concepts, techniques and materials which are somewhat less sophisticated than rock mass fissure grouting or, of course, jet grouting. However, an oversimplified and cavalier “drill and fill” mentality should be avoided at all costs, since the interim safety of the dam may well be threatened by inappropriate practices. Most void filling is conducted with Low Mobility Grout (LMG) which, eponymously, allows the contractor to control to a high degree the travel of the grout in the ground. Detailed guidance on the formulation and use of LMG can be found in many publications, and the reader is referred in particular to the papers by Warner in the Geo-Institute Grouting Conferences of 1982, 1992, 2003, 2012 and 2017; the Geo-Institute’s Compaction Grout Guide (2016), and the Logan Martin Dam, AL case history described by Findlay et al. (2015).

3.2.1 Design Considerations

- Vertical holes are typically acceptable, arranged in patterns so that an initial, peripheral “confinement” is generated, followed by internal infilling. This sequence also provides a good standard of statistical verification.
- It is essential to obtain, as a basis for design, an estimate of the volume and location of the void space. In this way, limiting stage volumes can be selected. A well controlled test section in typical conditions is particularly valuable in this regard.
- A set of refusal criteria must be developed, addressing maximum permissible stage volumes, pressures, and uplift/displacement limits.
- The most common field test for a LMG is slump. Although minimal slump (< 1 inch) is typically specified for LMG’s used for densification purposes, such slumps are notoriously difficult to deliver consistently, such are the natural and normal variations in the components and batching of the mixes. Therefore, for routine void fill, a slump of 1.5 to 2 inches is reasonable, with a tolerance of ± 0.5 inches.

3.2.2 Construction-Related Issues

- The same drilling disciplines described above for rock fissure grouting apply, except that the temporary drill casing is also typically used as the tremie injection tube as it is progressively extracted in short stages (typically 1-5 feet). Such casings are rarely greater than 4 inches in diameter.
- Grouts can be prepared in a batch plant or in a properly equipped truck mixer, provided consistency checks are frequently made.
- It is essential for dam safety that line pressure loss curves are developed in advance of work commencing so that dangerously high effective injection pressures are avoided.
- In certain projects, for example the sealing of epikarstic horizons prior to the installation of a diaphragm wall (“composite wall concept”), the designer may elect to “tighten up” the ground previously treated with LMG. This second phase will feature HMG, injected through MPSP or tubes á manchette. LMG’s, or even sanded HMG’s (i.e., MMG’s) are incompatible with the use of sleeved pipe systems.

3.2.3 Specific QA/QC Issues

- Given the nature of the grout (slow moving, with high internal friction), it is more difficult to develop reliable and accurate automated injection parameter recording systems, although some valiant attempts have been made. Therefore, it is more typical that the volume injected is measured by counting the number of pump “strokes,” and multiplying that by the volume per stroke (typically around 0.5 ft³). Such records must be supported by regular checks on the stroke counter accuracy and the volume per stroke, and by reconciliation with the volume of LMG actually batched.
- Slump testing is the routine QC method for consistency, but some experienced engineers also conduct a “hand squeeze” test, which is of less reliability. Visual observation of homogeneity is always useful, while initial and final setting times, and cube strength, are regarded as “classification tests,” and not routine tests.
- As for the other types of grouting, an effective DMS should be developed in advance.
- During void filling operations, particular attention should be paid to nearby piezometers (especially for detection of non-transient, longer lasting, pressure “spikes”), and to any and all deformation measuring instrumentation.

3.3 Jet Grouting

Jet grouting systems have the great advantage that they can treat all soil conditions, given an appropriate selection of injection parameters. However, it must be noted that some materials (e.g., sands, and silts) are easier to cut and blend than others (e.g., plastic clays). Further, it will be practically impossible, without full diameter predrilling, to cut very dense soils, or rock masses over about 400 psi in unconfined compressive strength. Also, jet grouting involves the use of high energy, high pressure (typically over 4,000 psi) injections at high flow rates. Hence, significant damage can be done to fragile structures if control over the process is lost, even for a few seconds. This is one major reason – the other being cost – why jet grouting tends to be used as a “last resort” to complete cutoffs in circumstances (e.g., low headroom, buried structures) where other methods cannot be used.

Copious information can be found in various sources, but especially in the proceedings of the Geo-Institute’s conferences, referenced above. In addition, the Geo-Institute’s Grouting Committee have developed a Jet Grouting Specification (last revised in 2016) which is most useful.

3.3.1 Design Considerations

- The designer must specify the length, depth, location and minimum thickness of the jet grouted structure. He should also specify the strength, permeability, and homogeneity criteria. However, each jet grouting contractor utilizes his own “proprietary” means and methods, and so it is typical that the contractor will determine the plan dimensions of the individual jet grouted elements (circular or elliptical columns) and so therefore the required center-center spacing in order to achieve the required overlap.
- Compressed air is used in most common jet grout methods, including the two- and three-fluid systems, “Superjet” and similar variants. However, in a dam or levee environment, particular thought should be given to the use of compressed air which, under adverse circumstances, can cause pneumatic fracturing.
- Each contractor has his own database of past projects which allows him to predict column diameter to grouting specific energy relationships, for each ground type. Although this is the basis for his preliminary estimate of column diameter, it is essential that this is proved with a Preproduction Test Program. The contractor will, understandably, be very keen to “push on” from this program straight into Production. However, this should not be permitted until the test columns have been properly investigated to demonstrate compliance with the design criteria. Verification of the Test Program is conducted via a combination of tests, the selection of which will vary from site to site, but which will include:
 - Probing by destructive drilling
 - Coring
 - Televiewer in core holes
 - In-situ permeability testing (falling or rising head)
 - SPT, CPT

The best verification is, of course, by excavation and exposure, but this may not be feasible given access, depth and groundwater factors. Careful thought to the verification and compliance methodologies must be given at the design stage. Recent developments have been made using geophysical techniques to estimate column diameter during construction. However, their accuracy and reliability remain in question.

3.3.2 Construction-Related Issues

- The same drilling disciplines described above for the other types of grouting equally apply. Predrilling (to the full diameter of the anticipated column) may be necessary in certain conditions and the need for this must be identified in the project specifications: unless subsequently eliminated via a Value Cost Engineering Proposal, all contractors should bid under a common set of construction requirements. Predrilling is required in very stiff or dense soils, or when rock is encountered with a UCS in excess of about 400 psi.
- The largest threat to dam safety (and to achieving design parameters in the columns during jetting), is losing flush return to the surface for longer than 5-10 seconds. During such periods, the grout/soil mix is being forced laterally away from the intended column geometry, to cause hydrofracture. Thus, it is essential the contractor develops an Emergency Response Plan to restore the flush as quickly as possible (e.g., by “restroking,” a technique involving rapidly lifting and lowering the jet grout tooling). As a worst case, pumping is ceased and the drill/jetting rods are withdrawn. After the grout has reached final set, operations are resumed in that hole, usually several feet below the elevation reached by the previous grouting. (Jet grouting is, of course, conducted from the “bottom up.”)
- Grouts are HMG’s (water, cement and sometimes bentonite) produced in automated batch plants using high-speed mixers.
- Given the high pressures used, operator safety is a major concern during jetting. All non-essential personnel must be kept away from the rig at that time.
- Depending on specific site conditions, elements can be installed in a typical “Primary-Secondary” sequence, or “fresh-on-fresh.”

3.3.3 Specific OA/OC Issues

- Routine checks on the fluid grout (Marsh Cone, Specific Gravity, Bleed) are made on samples taken from the batch plant. Spoil samples (i.e., grout return plus eroded soil) are taken at the drill collar for making cylinders to later test for density and strength. Sampling of the setting column, for example with a “wet grab” sampler, is typically not successful given the rheology of the grout-soil mix at depth, and its relatively rapid hydration characteristics.
- It is now standard practice that all grouting parameters are recorded and displayed in real time. Rate of flow and pressure are set at the batch plant, while rpm and withdrawal time and distance (“Step Time”) are measured at the drilling/jetting rig. Flow rate, grout pressure, and step time data are then integrated into a Jet Grouting Specific Energy factor, expressed in kJ/m units. This then allows the operator to confirm that the correct Energy is being applied to the soil to achieve the targeted diameter, as proved during the Trial. This energy can be varied in any one hole, in response to the soil type.
- Given that the jet grouted mass can reach significant strengths (e.g., over 500 psi), coring is a legitimate exploration tool – when using experienced drillers and the correct choice of equipment and coring systems. However, if there is a large proportion of very coarse soil in the column, then the core may not meet typical recovery standards (typically 85% minimum). At such times, the Optical Televiwer is most useful as a verification tool.
- Inclined core holes are very useful in that they can intercept multiple inter-column overlaps. Inclinations over 25° off vertical may be problematical to control from a deviation viewpoint, and may interfere with lowering and retrieving Televiwers.
- On certain projects, measurement of column verticality is required, in order to predict that sufficient column overlap is most likely to have been achieved. The equipment needed to do this is very sophisticated (but reliable), but its use will negatively impact productivity.

- As for the other techniques, a functional DMS is essential, while close monitoring of all relevant aboveground and in-situ instrumentation must be conducted during and after jetting.

4. FINAL REMARKS

The world of grouting is very wide and often complex: a vast amount of technical information and case history studies have been developed and, of course, have never been easier to access. The purpose of this paper has been to provide practical guidance for the application of three particular grouting techniques in dam and levee projects. The focus has been on best practices in the design, construction and control of such works. Whereas there are many important commonalities between the three methods, there are also details particular to each which must be recognized. It is hoped that this paper will be of value to designers, owners, and contractors, in that it may provide a useful basis for discussion and practices throughout the life of their project.

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