

## THE VALUE OF LIMITED MOBILITY GROUTS IN DAM REMEDIATION

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### Abstract

The great diversity of site settings for dams, and the high standards of performance expected in these structures have provided an effective proving ground for a wide array of grouting technologies. Many past ASDSO Conference presentations have dealt with case histories of dam repairs involving grouting. However, the majority of these discussions have related to fluid, slurry-type grouts intended to permeate small voids or fissures. This paper focuses on the use of limited mobility grouts (similar to stiff concrete or mortar). Explaining the differences and similarities between limited mobility, compaction and displacement grouts is the first step to understanding the applications of these materials. These grouts can be used for void filling, improving density for seismic considerations, remediating seepage in karstic geologies or lifting of structures distressed by settlement. As with any grouting operation, a correct application is dictated by site conditions. By providing a general overview of these technologies followed by examples of their successful application, the paper provides an understanding that can be applied to other projects.

### Background

Site preparation, construction, maintenance and remediation of dams have involved grout for over 100 years. Grouting goals have included seepage control, foundation surface treatment, seismic remediation and settlement control. The grouts are generally a fluid mixture of cement-based materials or, in special cases, chemicals. Numerous theoretical studies and case history papers have been presented that discuss this variety of grouting. A quick review of the ASDSO Conference Proceedings in the past 10 years revealed well over 100 papers that addressed fluid grout placement in dams.

A variety of cementitious grouting that is gaining recognition and application for dams is a very stiff formulation intended for densification, liquefaction mitigation, void filling, and treatment of karst conditions. This is not to say that these grouts do not serve similar purposes as the more fluid counterparts. Often these materials are injected into voids specifically to control seepage through a dam foundation. The additional benefits and applications address structural concerns which were often very difficult, if not impossible, to treat with the fluid mixtures.

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These stiff mixtures are often used for soil compaction and so are referred to as compaction grout. However, this name does not fully describe the material and may limit the understanding of the material application. The key property of this material is the ability to control its rheology. This is accomplished through proper mix design and injection procedures. Thus, a more appropriate "generic" name for this process is Limited Mobility Grouting (LMG). The following discussion addresses basic material properties, equipment requirements, applications to dams, and engineering considerations both during design and construction.

### **Limited Mobility Grout (LMG)**

A proper LMG formulation will include cement, soil/fine aggregate, water, and possibly some type of filler such as fly ash. Where site conditions dictate, gravel bentonite, anti-washing agent and/or fibers can be added to the mix. One of the key elements is that the fines content (amount of material smaller than the Standard US #200 Sieve) of the combined soil/aggregate/filler is generally on the order of 20 to 30 percent.

This mixture can be relatively low in cement content since the strength of the material is rarely a concern to the design intent. However, the water content and proportioning is tightly controlled to maintain a material with high internal friction. Due to this requirement, natural or artificial clay type substances are generally not permitted in the mixture since even small amounts of this will completely change the behavior of the material in the ground (Warner, 1992).



**Limited Mobility Grout Mixture**

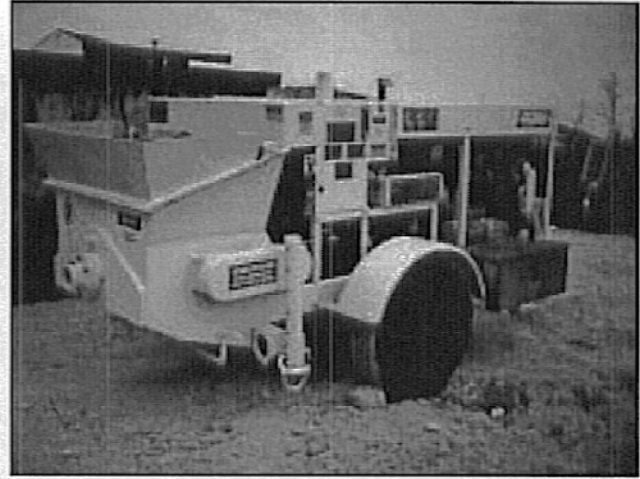
Although the ASTM C143 Slump Test does not specifically apply to this material, it is often used to evaluate quality/consistency of the mixture. In general, the slump measured immediately prior to placement would be less than about two inches. Often the mixtures would have a negligible measurable slump. Slump alone, however, is not the only measure of an appropriate LMG; internal friction is equally important.

### **LMG Equipment**

The equipment used to mix, transport and pump the LMG mixture is specially designed for this purpose. The very stiff consistency of the material, slow pumping rates and high pressures are often well beyond even specialized concrete pumping equipment capabilities. The equipment typically used for fluid grouts include colloidal

mixers, paddle agitator tubs, small diameter hoses, and screw type pumps (Muller and Bruce, 2000) do not have the capability to handle LMG mixtures.

The mixing equipment must be capable of thoroughly mixing the components. Furthermore, the mixing system must be able to accurately measure the aggregate, water and cement as it is added to the mixing unit. Regular calibration of the on-site systems should be performed throughout a project. Mixing is often performed with pug mill mixers, or mortar type paddle mixers. The on-site storage and dosing of materials can vary from stockpiles hand shoveled into the mixer for small projects, to premixed batch trucks attached directly to the mixer.



**LMG Grout Pump**

It is not uncommon for the grout to be delivered to the site as ready mix from a local material supplier. Where ready mix is utilized, difficulties are often encountered with mix consistency. Since the raw materials are not on-site, modifications of the mix to meet site conditions or improve a bad batch are not possible. Furthermore, since a proper LMG material has very low slump, it is difficult to discharge all of the batch from a standard drum delivery truck, which adds to waste and can result in conflicts over grout volumes injected into the ground.

The grout pumps are positive displacement piston pumps typically of the swing tube fashion. The key elements of these pumps are the very high pressure and slow rate of delivery required for this process. Often the refusal criteria include pressures of up to 600 psi measured at the point of injection. Depending on the distance from the pump, this can result in requirements at the pump approaching 1500 to 2000 psi. Grout delivery is often restricted to 0.5 to 2 cf per minute, so the pump must have the capacity to deliver a relatively smooth flow of material at these rates either through small cylinder sizes or very precise hydraulic controls.

Although the mixing and delivery systems are the most noticeable elements of an LMG system, some other ancillary points are important. For example, the pressure gauges must be visible from a distance. This may not seem like a major consideration, but due to the procedures for injecting this mix as a drill casing is being withdrawn, the placement and size of the gauge can be critical. Given the harsh nature of the LMG, the proper use of gauge savers is also critical. Each contractor has particular preferences and often proprietary means of separating the gauge from direct contact with the grout. Some of these involve diaphragms and others utilize a grease barrier. Each of these systems undergoes extreme stress from the abrasive action of the grout flow. Thus, the engineer and inspectors must be on the lookout for gauge failure.

The grout injection pipes are steel casing drilled or driven into the ground. These pipes should be a minimum of two-inch inner diameter. The delivery system from the pumps to the injection pipes can be flexible high-pressure hoses or steel pipes. Overburden drilling systems are classified by Bruce (1992).



**Grout hole drilling**

### **LMG Applications (General & Dam Specific)**

LMG has a broader application than traditional compaction grout, and thus the generic name. Since compaction grout is a type of LMG, densification of soils would be the first logical application of this material. Compacting soils through the injection of LMG under pressure is most effective in soils that can be compacted by squeezing water and air from the void spaces. Thus, fine grain soils such as clays, particularly below the water table, are not well suited for this method. Sandy soils, gravel and even silts are generally well suited to densification with LMG. Numerous examples of this have been published and include densification of loose materials beneath foundations to limit settlement, improvement of the loose soils to resist liquefaction potential, and densification of materials to improve strength properties.

The broader application of LMG would be to projects where void filling, and displacement of soft soils are the goals of the project. In these cases, the soil type, or rock properties are not necessarily the controlling factor. Where the goal is to fill voids, control of the grout material properties to limit the unrestricted flow of material in the ground is the primary consideration. Void filling is often associated with karstic geology,

voids within a rock foundation, piping channels, or filling conduits. Often, the grouting associated with karst terrains will also include the densification or displacement of the very soft soils overlying the rock surface and trapped in the solution cavities.

## **Engineering Considerations in LMG Use**

As with all grouting applications, the goal of the engineering is to first understand the problem, then the soil conditions, the behavior of the grout, and finally the means and methods necessary to complete the construction.

Determining the problem is often the most difficult issue; adequate field exploration including test borings, test pits, in situ testing, laboratory testing, visual reconnaissance, and surveying will all add to the information data base of a project. Sufficient sampling must be completed to identify the range of subsurface materials that will have to be treated. Gradation analysis, water content and index tests are the basic properties needed. If the project goal is to improve density and strength, base line properties should be measured for future comparison and quality assurance testing. As the field data are gathered, it is the engineer's role to evaluate this information and determine how it relates to the problem at hand. Definition of the problem will allow the engineer to focus on the next step which will be to find the optimum remediation technique. The final step is to determine the definition of success.

Assuming that the problem is one that is suitable for the application of LMG, i.e. densification, displacement or void filling, the engineer must now define the critical elements of the grouting process which will correct the problem and the construction steps. Although there is not a clear understanding of the properties within a grout mix that result in acceptable performance, it does seem that very tight control over the mix design and injection process is particularly important when densification/compaction is the goal of the project. A good discussion of the critical mix design components as well as hole spacing, and injection process was presented by Graf (1992) and Warner (1992), and should be referred to for a basic understanding of compaction grout.

Strict control of the material gradation, in particular limitations on fines content and inclusion of clayey material, is dictated by the high internal shear requirements of traditional compaction grout. Field tests have shown that when the fines content and cohesion of a grout mix increase, the more stable the grout is to pressure filtration. Unstable mixes or poor injection procedures can have a tendency to fracture the soil matrix along the plane of minimum stresses (usually vertical).

Often the void filling goals of a LMG program are related to seepage control within a dam. In these cases, the rheology and stability of the grout being injected into the dam foundation is critical since the grout is often being placed within flowing water. The use of anti-washout agents can help maintain the integrity of the grout during placement until closure is achieved. Maintaining a stable mix during placement and curing is critical to the long term performance of the repair "permanence". If the cement

is washed from the mix during placement, the aggregate will not be sufficiently solidified to resist seepage pressures and repeated gradual erosion of the channel.

The layout of the grouting program must again consider the goals. Often, the goals are best met by working on site coverage, then filling in the area to develop closure. This can take the form of a grid of widely spaced holes on 10 to 15 ft centers, which are then split spaced to a smaller grid with subsequent holes. Alternatively a perimeter can be completed and in-filled with subsequent holes as is often done in mine filling operations. This process allows comparison of injections as the phases are completed. Split spacing also provides improved resistance that the secondary holes are able to capitalize on to meet the goals of the project. Rarely will the required density improvement be achieved with only primary holes. Secondary and subsequent phases should be planned and budgeted in every project.



**LMG Placement**

Unlike fluid grout mixtures, precise measurements of volume, pressure and mix components are not always easy or accurate. As such, indirect measurements are often considered for quality control. These will include grout mix appearance, slump tests, pump behavior, pressure changes at the injection point during a stage, differences as compared to adjacent holes already complete, and ground or structural movements.

Quality control is the key to all projects. Where the goal of the LMG is improved density, standard penetration tests, cone penetrometers or other direct measurements are often used to confirm the goals of a project. A case study from Croton Dam (Perkins and Harris, 1999) demonstrates one method of verification using the Grout Intensity Number (GIN) which normalizes grout take, pressure and hole spacing into a value that is used for quality control.

However, where void filling and grouting within soft karstic infills are the goals, direct measurement of soil improvement is often impractical. Since the soils are fine grain material, they are not readily compacted during the LMG process. As the grout is injected, the bulb takes on an irregular shape as it expands to the point of least resistance. This often involves moving very soft materials out of the way. If an in situ test is performed between grout injections to be compared to baseline measurements before grouting, these test soundings are likely to hit grout, extend through materials that may not have been the weakest soil, or encountered soils still maintaining elevated pore pressures. Each of these conditions means that accurate comparison of before

and after conditions is very difficult if not impossible. Given these difficulties, the quality control must revert to accurate measurements of the drilling and grouting process, understanding of the subsurface conditions, and clear project goals that can be related to the injection records and subsurface conditions. This requires both experienced field inspection staff and focused interpretation by the project engineers as the grouting is proceeding.

## **Dam Case Histories (published and anecdotal)**

### ***Tim's Ford Dam, Tennessee***

Tim's Ford Dam is an embankment structure located on the Elk River west of Winchester, Tennessee. Owned and operated by the Tennessee Valley Authority, this 1,500 ft long dam was constructed in 1971 over clay and weathered chert overburden underlain by karstic limestone. During initial filling, two leaks occurred on the downstream side of the right rim. A grout curtain constructed of cement grout containing calcium chloride accelerator was installed to limit flows, but was not intended to seal the leakage. Flow from these features was monitored until 1994 when a dramatic increase in flow was recorded. An exploratory drilling program found voids and open channels in the area and indicated that there would be substantial water flow through these features during the remedial grouting.

The planned grouting program included hydrophilic polyurethane resins in areas where large voids and heavy water flows were encountered in the primary grouting stages of the project. However, when the reservoir was drawn down for construction, water flows ceased. Furthermore, larger than anticipated open and clay filled features were encountered, thus, much of the polyurethane grout was replaced with LMG containing water reducing and anti-washout agents. The use of the LMG assisted the contractor and engineers in achieving an engineered refusal within this grout curtain. (Bruce et al, 1998).

### ***Croton Dam, New York***

The Croton dam was constructed in 1906 utilizing hydraulic filling methods that resulted in zones of loose saturated sands near structures, including the powerhouse. These loose sands were found to be susceptible to liquefaction during the design earthquake and required rehabilitation. In order to improve the density of these materials to a uniform medium dense sand, a compaction grouting program was completed. A total of 340 grout holes were installed amounting to 13,000 lf of drilling. The holes were laid out on an eight foot grid with remedial holes added at split space locations where required to meet the desired density improvement.

As presented by Perkins and Harris in 1999, the Grout Intensity Number (GIN) concept was applied to this project for quality control purposes. Based on the results of a test program on-site, the site specific calibration was completed and the GIN correlated well with the follow on Quality Assurance testing completed at the site. The GIN combines the grout volume injected, the pressure during injection and the hole grid

spacing to normalize the measurements and provide a mean for evaluating the ground performance during grouting.

The LMG consisted of locally available soils of very low plasticity and about 15% fine gravel, with a maximum size of  $\delta$  inch. The added cement and water resulted in a mixture with a low slump of about one inch. Grouting was completed through four inch pipes to pressures of up to 800 psi below 20 ft. Lower maximum pressure criteria were applied above this depth. A maximum injection of five cubic feet per foot of hole was used.

### ***Dam in Maryland***

An earth dam in southern Maryland, operated by a utility, contained a 30 inch diameter corrugated metal pipe that was used during construction for temporary water diversion. This pipe was abandoned in place. Seepage believed to be associated with water migration along this structure was observed at the downstream face of the dam, leading the owner to require that this pipe be located and sealed. The dam was approximately 65 feet high as measured from the downstream toe, and approximately 550 feet long along the crest.

The design drawings showed the general location of the CMP; however, the downstream outlet was buried. The location of the pipe was established by geophysical methods (Traylor & Reholdt, 1999) and an LMG program was developed to fill the pipe with a cement based grout where it was not blocked by a soil plug.

The grouting program began at the downstream toe and proceeded upstream and terminated at the upstream end of the CMP. The LMG was utilized grout "plugs" at intermediate intervals along the CMP. More fluid cement grout mix designs would be used to grout the length of the pipe, along with sanded zones or mud-filled zones. The LMG served as a bulkhead to base all other grouting operations.



**Grout injection to fill CMP conduit in dam.**



### ***Pinopolis West Dam, South Carolina***

The Pinopolis West Dam is an 80 ft high homogeneous earth embankment constructed over loose sands. The foundation materials beneath this 6,600 ft long dam were found to be susceptible to liquefaction during the design earthquake. To remediate this condition, 1,600 grout elements were drilled and LMG was injected to densify the foundation sands in 1989. The primary hole spacing was 12 ft on center, with secondary and tertiary holes reducing this to 8.5 and 5.0 ft respectively. LMG grouting was selected over compaction piles due to the potential for penetrating the phreatic surface beneath the downstream toe of the dam and creating seepage problems with the compaction pile method. The LMG injection resulted in the measured SPT blowcounts increasing from about 4 to between 17 and 25 following grouting. (USCOLD).

### ***Chessman Dam, Minnesota***

The Chessman Dm is another example of an earthen embankment constructed over loose sands found to be susceptible to liquefaction during an earthquake. Again, several alternatives were considered for remediation of this 40 ft high, 440 ft long embankment, including deep dynamic compaction, compaction piles, vibrofoatation, and chemical grouting. Due to site constraints, each of these methods were found to be unacceptable and LMG was selected to densify the foundation soils. Primary injection locations were spaced at 10 ft centers with secondary injections reducing this to about 5 ft spacing. A total of 4,753 lf of drilling was completed and 5,600 cf of grout was injected. The foundation sands were generally about 5 to 10 ft thick with SPT blowcount values of about 4 prior to treatment. Based on a test section, the primary grouting resulted in increased SPT blowcount values of 10 to 16 and the secondary grouting increased these further to about 20 to 25. (USCOLD; Quinn, 1999)



**LMG grouting using 4 inch casing and rotary drill rig.**

## Closure

Grouting has been used for over 100 years to repair dam structures and their foundations. The variety of grouting types and injection methods are numerous. However, the predominance of the cement-based grout used has been a very fluid mixture best suited for penetration of fine voids and permeation of coarse grain soils. The applications of LMG to dam remediation have been expanding in recent years. LMG is well suited for: controlled densification of loose soil and even rock fills in some cases; filling of voids, whether related to foundation geology or structure failure within the dam; or seepage control. With all grouting programs, the site evaluation, engineering goals, and quality control during construction are critical to a successful program. Considerations must be given to the ability to access the problem, drill or drive the grout pipes to the desired depths, and place the grout without creating further problems. The mix design is also a prime concern as with all grouting. Stability and durability determine whether the grout can be pumped to the desired location and will remain in place throughout the life of the structure.

The variety of potential applications makes standardized quality control difficult. Thus, the criteria and measurement techniques must be established based on site specific conditions and goals. Often the most critical aspect of quality control on a project is experienced contractors and engineering oversight. It is important not to overlook the benefit of experience at both levels when applying LMG remediation to a project.

The application of LMG is expected to continue to grow in the new dam construction and repair markets, as the dam community begins to understand the general principals of its application. Mix design utilizing admixtures to control specific properties, as well as specialized equipment are being developed to meet the specific needs of dams and the creativity of the engineering and contracting community.

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