

# OPPORTUNITIES FOR ADMIXTURES IN THE GEOTECHNICAL ENGINEERING MARKET: THE U.S. MODEL

by  
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## ABSTRACT

Since mid 1996, the author has acted as a consultant to Master Builders Technologies (Cleveland Office). The goal of the relationship has been to enhance MBT's involvement in the various techniques which constitute the specialty geotechnical market in North America. The paper describes these techniques in general, and outlines the model by which the U.S. market has been effectively and successfully penetrated. Specific details are provided on the four major and most fertile fields of application to date, namely rock and soil grouting; the sealing of massive inflows involved with dams, mines, and quarries; deep mixing; and jet grouting.

## 1 DEFINITION OF THE MARKET

Technical Committee 17 (TC-17) of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) of which the author was the inaugural secretary, defines the group of techniques which constitute the geotechnical engineering market as follows:

1. Ground Treatment
  - 1.1 Rock Grouting
    - 1.1.1 Fissure
    - 1.1.2 Bulk/Large Voids (Natural and Artificial)
  - 1.2 Soil Grouting
    - 1.2.1 Permeation
    - 1.2.2 Compaction
    - 1.2.3 Claquage/Hydrofracture (including Compensation)
    - 1.2.4 Jet
  - 1.3 Deep Mixing
    - 1.3.1 Wet (slurry) methods
    - 1.3.2 Dry methods
2. Ground Improvement
  - 2.1 Mechanical Densification/Consolidation
    - 2.1.1 Dynamic Consolidation
    - 2.1.2 Vibro techniques
    - 2.1.3 Preloading
    - 2.1.4 Blasting

- 2.2. Drainage/Dewatering
  - 2.2.1 Wicks/Band Drains
  - 2.2.2 Sand Drains
  - 2.2.3 "RODREN"
- 2.3 Thermal
  - 2.3.1 Freezing
  - 2.3.2 Vitrification
- 3 In Situ Reinforcement and Ground Retention
  - 3.1 Anchors
  - 3.2 Micropiles
    - 3.2.1 Structural Support
    - 3.2.2 In Situ Reinforcement
  - 3.3 Soil Nails
  - 3.4 Diaphragm Walls (Slurry Walls)

The annual total construction value of this market in the United States is around \$1 billion, whereas the corresponding value for the piling market (including driven piles, continuous flight augers, and large-diameter drilled shafts, or caissons) is 70 to 100 percent larger.

These specialty geotechnical construction techniques find a wide range of applications within the broad market segments of construction, mining, quarrying, and environmental remediation. Depending on geological, logistical, financial and indeed historical factors, the techniques however, have distinct geographical applicability. Thus, as examples, compaction grouting cannot be used in hard rock environments, permeation grouting is not feasible in silts and clays, deep mixing is not practical in low headroom situations, and micropiles are not competitive in the deep clays of the Deep South.

## 2. TECHNICAL APPLICABILITY OF ADDITIVES

With reference to the techniques listed above, the following analysis of the potential for additives can be made

Zero Potential: All techniques under "Ground Improvement"

Reason: No grouts are used.

Minor Potential: Dry method deep mixing, anchors, micropiles, soil nails

Reason: Additives are only technically necessary under extraordinary conditions.

Medium Potential: Compaction and claquage grouting, and diaphragm walls

Reason: Additives currently are perceived to provide only limited advantages in very conservative technologies. Future developments offer greater potential.

High Potential: Both rock grouting applications, permeation and jet grouting, and wet deep mixing methods.

Reason: Grouts (and the special rheological and set properties of them) are particularly critical in these techniques, which often have to be used in extreme conditions for very specific applications.

### 3 BUSINESS DEVELOPMENT MODEL

Given MBT's reputation, history, structure, philosophy and capabilities, their preeminence in certain fields is logical and understandable: no civil engineering graduate in the United States is ignorant of the "concrete canoe" competition. However, in the geotechnical construction field, MBT were usually in the position of least leverage or influence, namely being an approved potential supplier of a minor amount of specialty products to a prospective subcontractor who was bidding to a variety of general contractors on a job-by-job basis. In such circumstances, there was virtually no chance of MBT being able to obtain "added value" based on the knowledge of the benefits of the product in question. Rather, such bids were simply an opportunity for the local sales representative to judge how low they had to go in price to defeat the competition and achieve a minor sale. Then, of course "if the product didn't work", these same representatives were quickly held totally responsible for the allegedly massive damages which follow as a consequence.

By the mid 1990s, MBT's Underground Division personnel had become aware of the scale and potential of the geotechnical engineering market, and determined to advance in this new direction.

Messrs. Minnillo, Gause (and later Brooks), and the author formed an alliance to achieve this goal. The basic strategies were:

1. To introduce MBT at a high technical and personal level to key consultants, owners, and contractors – as "problem solvers", not only as additive salesmen.
2. To leverage MBT contacts already made as a result of previous successful interventions (e.g., in hard rock tunnels).
3. To identify "product gaps" in the market and to research, develop and advertise the solutions actively (e.g., the clay dispersant technology).
4. To have MBT clearly and primely listed in Specifications.
5. To seize the technical "high ground" via publishing of technical papers, membership of technical societies, speaking at short courses, and so on.
6. To penetrate key geographic areas and/or specific project opportunities.

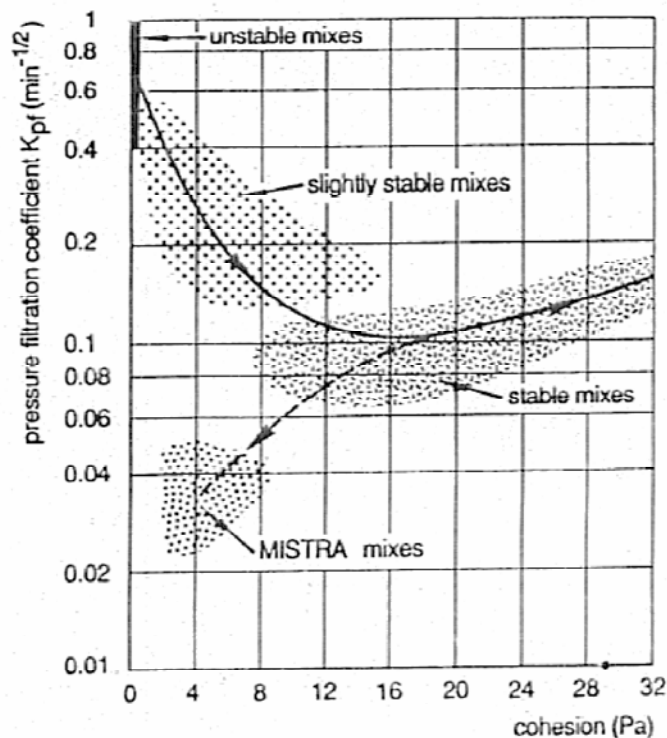
Each of these strategies was aggressively implemented and its progress constantly monitored. As a consequence, the progressive achievement of the corporate goal has been achieved in the United States. Planning continues as to the implementation of this model in other regions, and already positive steps have been made with MBT in Australia and Brazil.

#### 4 TECHNIQUES/APPLICATIONS OF PARTICULAR RELEVANCE TO MBT

##### 4.1 Rock Fissure Grouting and Soil Permeation Grouting

Only in recent years has the very conservative grouting community in the United States truly begun to accept the concept of correctly formulated, balanced, particulate grouts as a way to enhance penetrability and durability. Prior experience has focused on unstable mixes of cement and water, with only sporadic use of even bentonite, let alone dispersants or other admixtures.

There can be no doubt as to the benefits of correctly formulated grouts on the two key parameters of pressure filtration coefficient, and apparent cohesion (Figure 1), although this fundamental impact has often been ignored by engineers who believe that reducing particle size is the most important change which can be made. Even microfine grouts can exhibit excessive pressure filtration, high cohesion and other unattractive rheological and hydration characteristics if inappropriately formulated.



**Figure 1.** Relationship between stability under pressure and cohesion for the different types of mixes.

The author has been involved with numerous soil grouting projects in the last few years, using the tube à manchette method, where excellent results have been achieved with suites of additivated particulate grouts. However, one of the most insightful case histories was recently published by Wilson and Dreese (1998) relating to a fissure grouting operation for a new dam curtain.

The new Penn Forest Dam in eastern Pennsylvania is being constructed to replace the old Penn Forest Dam, which was a severely ailing earth embankment dam. The new dam is being constructed with roller compacted concrete just upstream from the old dam, and is approximately 54m high and 600m long. It includes a three-line grout curtain, designed to have a maximum residual permeability of 3 Lugeons on a 4.5m width. The lines were 1.5m apart to a depth of 42m.

An accelerated construction schedule resulted in the grouting being split into two separate but consecutive contracts, the first for one line (A); the second for the other two lines (B and C). Due to the short design period duration and other factors, the A-Line grouting contract was issued specifying "conventional" methods (for example, neat cement grouts, agitator tank dipstick measurements, and pressure gages). However, sufficient time was available for ECO to design the second contract using "advanced" methods, such as balanced, stable cement based grouts and computer assisted grouting control and analysis.

Whereas Line A used neat cement mixes of w/c from 3 to 0.7, Lines B and C used a suite of multi-component mixes comprising Type III cement, flyash, bentonite, welan gum and dispersant, as determined during extensive pre-construction field testing. Particular attention was paid to minimizing the pressure filtration coefficient (below  $40 \times 10^{-3} \text{ min}^{-1/2}$ ) to promote efficient penetration and long term durability.

Lines B and C were injected using ECO's special "CAGES" software, which according to Wilson and Dreese, provided many advantages over the traditional manual methods:

- Real time data are obtained at much smaller time intervals (5 to 15 sec. frequency vs. 5 to 15 min. frequency).
- Eliminates potential for missing critical events such as pressure spikes.
- Data obtained are more accurate.
- Higher grouting pressures can be used with confidence.
- Formation response to procedure changes (mix or pressure) is shown instantly.
- Damage to formation due to over-pressuring can be easily detected and mitigated.
- Significant acceleration of pressure testing and grouting operations.
- More consistent grouting procedures due to central control location.
- Reduction in inspection manpower requirements.
- Provides detailed, permanent graphic records showing the entire time history for each operation on each stage.

The authors also found that the “advanced” system required less grout to reach the target curtain permeability, largely as a result of the enhanced penetrability of these stable grouts. Financially, the construction cost savings were about 10%, the inspection cost savings 25%, and the construction schedule savings 25%, relative to those incurred during the previous, traditional grouting phase.

A slightly different example – where a grout curtain was successfully installed under a 219-m high existing concrete dam (Dworshak, Idaho) – illustrates the applicability of contemporary methods for remedial applications. In this case, the fissure flow was as high as 11,500 liters/min under full reservoir head (Bruce et al., 1998a).

#### 4.2 Sealing of Solution Channels in Karstic Limestone

During the last two years, two major projects were designed and managed by ECO wherein MBT products were extensively used, namely Tims Ford Dam, Tennessee and at a limestone quarry in West Virginia.

Regarding the latter (still under a strict confidentiality agreement) water flows of over 150,000 liters/min were occurring through karstic pathways from a nearby river into this huge 70-m deep limestone quarry. It may be reported only that a 14-month program of investigation and grouting with a variety of grouts (bitumen, low mobility and slurry) succeeded in completely eliminating this flow, under the most arduous geotechnical and hydrological conditions. Permission to publish the full story of this highly significant case history is still being actively sought.

Bruce et al., (1998a and b, and 1999a) summarized the work at Tims Ford Dam, an embankment structure on the Elk River approximately 14 km west of Winchester, Tennessee. This water regulating Tennessee Valley Authority (TVA) structure is about 460m long with the crest at Elevation 227.4m. The right (west) abutment of the dam intersects orthogonally a natural ridge running nearly north-south, and consisting of clay and weathered chert overburden overlying a karstic foundation of various limestones. The crest of this right rim abutment varies in elevation from 287m to about 292m with the top of rock generally around Elevation 274m. The maximum pool elevation is at Elevation 270.7m.

Seepage through the right rim was recorded from first impoundment in 1971, prompting some local “conventional” grouting. However, a major seepage at Elevation 260m, about 290m upstream of the dam center line persisted. It grew steadily each year until 1994 to about 15,000 liters/min, but increased dramatically in 1995 to over 29,000 liters/min following a record reservoir drawdown. TVA determined that a remedial grouting program be effected to reduce this flow to less than 4,000 liters/min at maximum pool by sealing major karstic features thought to be present at that location.

An exploratory drilling and water testing program defined the geographic extent and depth of the remediation.

A multi-row grout curtain was designed, approximately 240m long. The holes were inclined at 30 degrees to the vertical to encourage intersection of (sub) vertical features and were oriented in opposite directions in the two outside rows. Primary holes in each row were foreseen at 12-m centers, with conventional split spacing methods to be employed (to 3-m centers or closer). The central, tightening, row was vertical. The grouting was to be executed between Elevations 270.7 and 256m - locally deeper if dictated by the stage permeability tests conducted prior to the grouting of each stage.

Because of the suspected high flow conditions, the downstream curtain row holes that encountered voids and active flow conditions were designated to be grouted with fast-setting (1 to 3 minute set time) hydrophillic polyurethane resin to provide an initial semi-permanent flow barrier. Holes that did not encounter voids or active flow were to be grouted with cementitious grouts. Upon completion of the downstream row, it was anticipated that the active flow conditions would be mitigated, thus allowing the entire upstream row followed by the third, central, closure row to be grouted with balanced cementitious grouts to form a permanent and durable grout curtain. The grouting was designed to be performed using upstage methods, although it was anticipated that poor foundation conditions could locally require utilization of downstage methods. The grout holes were to be cased through the overburden from the surface to the top of the curtain.

The Specifications contained provisions that required monitoring and limitations to outflow pH and turbidity to protect the downstream environment. TVA agreed to draw down the reservoir to Elevations 260.6m (3m below minimum normal pool) to minimize hydraulic gradient and flow through the rim. The curtain was to be constructed by first grouting the far ends, so conceptually channeling the flow through a middle zone which would then be treated.

- When drawdown of the reservoir reached Elevation 261.8m, the outflow from the leak completely and naturally stopped. As a consequence, much of the grouting work could be done in "no flow" conditions, therefore, largely eliminating the need for the polyurethane grouts, and extending the applicability of cement based formulations.
- Larger than anticipated open or clay-filled features were encountered by the down-the-hole drilling methods, especially in the upper 6m or so of the curtain. For technical, commercial, environmental and scheduling reasons, such features were treated with a low mobility "compaction grout" (slump 50 to 150mm; containing also water reducing and antiwashout agents).
- A suite of cement-based grouts (Table 1) was developed to permit the appropriate match of mix design and "thickening sequence" to the particular stage conditions as revealed by drilling and permeability testing (both multi- and single-pressure tests).
- In response to conditions revealed during the treatment, observations of the seepage and further dye testing, extra groups of holes were added the north end of the curtain, including 11 orthogonal to the original curtain, to allow specific treatment of key features.

Ingredient	Unit	Mix A	Mix B	Mix C	Mix D
Water	lb	141	141	94	94
Bentonite	lb	4.7	9.4	4.7	4.7
Cement	lb	94	94	94	94
Rheobuild 2000	oz	15	30	20	30
Rheomac UW450	oz	0	0	0	5
Volume of batch	gal	20.8	21.0	15.1	15.1
Specific gravity		1.39	1.4	1.53	1.53
Bleed	%	<5	<1	<1	0
K <sub>pf</sub>	min <sup>-1/2</sup>	<0.104	<0.042	<0.042	<0.042
28-Day Compress.	psi	500	500	800	800
Marsh time	sec	35	50	60+	100+
Stiffening time	hh:mm	4:30	4:30	4:00	4:00
Hardening time	hh:mm	10:30	8:30	8:00	8:00
<b>Water and slurry volumes</b>					
Bentonite slurry volume	gal	8.0	16.1	8.0	8.0
Additional water volume	gal	9.9	2.8	4.2	4.2

Table 1. Compositions and properties of cement grout mixes (Tims Ford Dam, Tennessee).

About 1,550m<sup>3</sup> of compaction grout, 1,530 liters of polyurethane, and 605m<sup>3</sup> cement based grouts were injected into a total of 250 holes (comprising 3,400 lin. m of rock drilling).

Throughout the work, closest attention was paid in real time to data from the drilling, water testing, and grouting activities in addition to information from leak monitoring, piezometers and dye testing. The curtain was thus brought to an engineered refusal. During refilling of the reservoir, the leak had been totally eliminated with the level at Elevation 265m, when, for financial reasons, the work was terminated. The most recent reading, with the lake at Elevation 269m, indicates a seepage of around 950 liters/min (net of surface runoff contributions) - about 5% of the flow at the equivalent lake elevation prior to grouting. Data from piezometers and dye testing support the existence of an efficient and durable curtain.

#### 4.3 Sealing of Solution Channels in Active Potash Mine

As described by Bruce et al. (1998a), during the late fall of 1996, minor leaks were detected in one of the highest areas of a major potash mine, near Sussex, New Brunswick. This mine operates with the room and pillar method of excavation. In the area of the inflow, the back of the stopes was close to the shale caprock. At the time, the water inflow was judged insignificant as it did not affect production, and so was not treated, although an accelerated backfill program in this area was launched to provide more support and to try to prevent the problem from



escalating. It was hoped that the seepage would drain a small isolated reservoir in the overlying strata and would eventually disappear.

However, the inflow continued to increase, as the roof started to deteriorate and collapse. By late May 1997, the inflow had escalated, to a point that the mine was forced to shut down. Inflows were estimated to be in the order of 10,000 to 15,000 m<sup>3</sup> per day. The water was fresh, and believed to originate predominantly from a water-bearing zone located approximately 200 to 300m above the mining horizon. The inflow dissolved thousands of tonnes of salt per day and cut a pathway down to the basalt below the salt horizons. From there, it moved laterally to a point where it was intersected and pumped away. However, the mine's dewatering system could only handle 5,000 m<sup>3</sup> per day, which resulted in a gradual flooding of the mine.

Following suspension of mining activities, the Owners selected the program proposed by ECO, even though it was understood that the chances of success were estimated at only 1 in 3, so severe was the structural deterioration caused by solutioning. The foreseen methodology featured the injection of hot bitumen in conjunction with modified cement based grouts. Importantly this plan was to be implemented in conjunction with the simultaneous drilling of pressure relief holes, installed from the underground workings, to control the inflow and channel it to pump stations. These holes would also serve to provide data on the effectiveness of the grouting operation in real time. If pressure relief were not properly effected, then rapid build up of water pressure in the cavern and formation would otherwise lead to hydrofracturing of the formation, and so increased flow rates.

Two inclined drill holes were to be advanced from the surface to the cavern deliver the substantial amounts of materials: one line for bitumen, the other for cement grouts. The cavern was located 700m below the ground surface.

Some highlights of construction included:

- Directional drilling was used to successfully drill the two nearly vertical but curved holes in the cavern.
- Dye and air tests were performed through these holes to verify connection to the inflow, establish the size of the rubble pile at the base of the cavern, and calculate the volume of the cavern (approximately 19,000 m<sup>3</sup>).
- Injection of hot bitumen had never before been attempted to such depth, and the installation included grouting of the lower casing with insulating cementitious grout, hot oil circulation concentric piping systems, thermal expansion joints, bitumen delivery pipe with stringer and rupture discs, two thermocouples and wellhead attachment, bitumen reheating systems and heated storage tanks, and hot oil heating systems.
- For operational reasons, only two pressure relief holes had been completed prior to the grouting operation commencing.
- The bitumen plant was constructed to provide an average capacity of 20 m<sup>3</sup>/hr without interruption to handle the foreseen volume of 6,000 m<sup>3</sup>. The hot oil system was required for preheating the bitumen line to 125°C, as was the passage of a limited volume of "soft

bitumen". Bottom hole temperatures exceeded 150°C before the "hard bitumen" could be injected.

- Six different modified cementitious grout formulations were used for void filling and formation grouting activities incorporating MBT products. These mixes had well-defined performance characteristics (antiwashout, low pressure filtration coefficient, no bleed, high strength, durable, high abrasion and erosion resistance) within a wide range of viscosities and specific gravities. The antiwashout additive was added, for logistical reasons, downstream of the mixer.
- A fully automated and computerized colloidal mixing and pumping plant, capable of producing 60 m<sup>3</sup>/hr of balanced cement based grouts was specially developed. Continuous QA testing of grout properties was executed by the supervisory staff.
- An intensive manual and electronic monitoring program was implemented, with computers at the bitumen site, the cement site, and the main control center recording dozens of variables in real time on grouting progress, and the response of the groundwater.

The mechanical execution of this enormous and difficult task was flawless. After three days of continuous injection, following a detailed program a combined total of 2,000 m<sup>3</sup> of bitumen and cement grout had been successfully injected. The inflow began to decrease within 24 hours and the formation pressure began to rise. By the end of the third day, the inflow was completely stopped and the formation pressure continued to rise. Grouting continued at the same injection rates (25 m<sup>3</sup> of bitumen per hour and 45 m<sup>3</sup> of cement based grouts per hour). Within 36 hours, there was no more washout of the cement based grout.

On Day 5, however, a major collapse and settlement of the rubble pile and eroded salt backfill took place triggered by the greatly increased hydrostatic pressure. Although this event was predicted and special measures had been taken underground for the occurrence of this event, the devastation caused by the resulting "tidal wave" was overwhelming. After generating an inflow rate of over 3,500 m<sup>3</sup>/hr until the cavern had emptied itself, it returned to the pre-grouting flow rates within about 3 hours.

The grouting continued at slightly increased rates from both holes. Towards the end of Day 7, the rate of inflow started to decrease and the formation water pressures started to rise again. The increase of formation water pressure with time was much slower than during the first operation, indicative of a much larger cavern, caused by the collapse during Day 5. Towards the end of Day 10, the leak had again been reduced to a trickle and formation pressures were recovering faster. The inflow rates fluctuated for a few days: each slight increase in inflow triggered a decrease in formation pressure and vice versa.

Suddenly, during the thirteenth day of grouting, the entire area around the cavern collapsed. Most likely the undercutting, by solutioning of the salt layers at or near the contact with the basalt had been too extensive. A large block of ground collapsed, followed by a tidal wave, which flooded thousands of cubic meters of water into the mine from the cavern in 5 hours. A last effort was made involving the injection of bitumen at pump rates of 40 m<sup>3</sup> per hour and cement grout in conjunction with sodium silicate (via 2 concentric pipes) at a rate of almost 60

m<sup>3</sup>. However, the new cavern had become so large that the consultants, owners, and management all came independently to the same sad conclusion; the undermining by the fresh water had caused so much damage that the mine could not be salvaged, under these conditions.

So, after almost 15 days of continuous grouting, totally without down-time, the operation was terminated. A combined total of over 22,000 m<sup>3</sup> of bitumen and cement grout had been injected during this period.

#### 4.4 Deep Mixing (DM)

As described by Bruce et al. (1998c and 1999b), Deep Mixing (DM) is the blending in situ of soils or fills with some form of cementitious “binder”, using mechanical means. A classification of the 24 different methods which have been found worldwide (but primarily in Japan, Scandinavia and the U.S.) is provided on [Figure 2](#). Whereas all Scandinavian practice uses “dry binder” (principally cement and quicklime), the bulk of Japanese, and virtually all of U.S. practice currently uses “wet binder”, i.e., some type of cement-based grout.

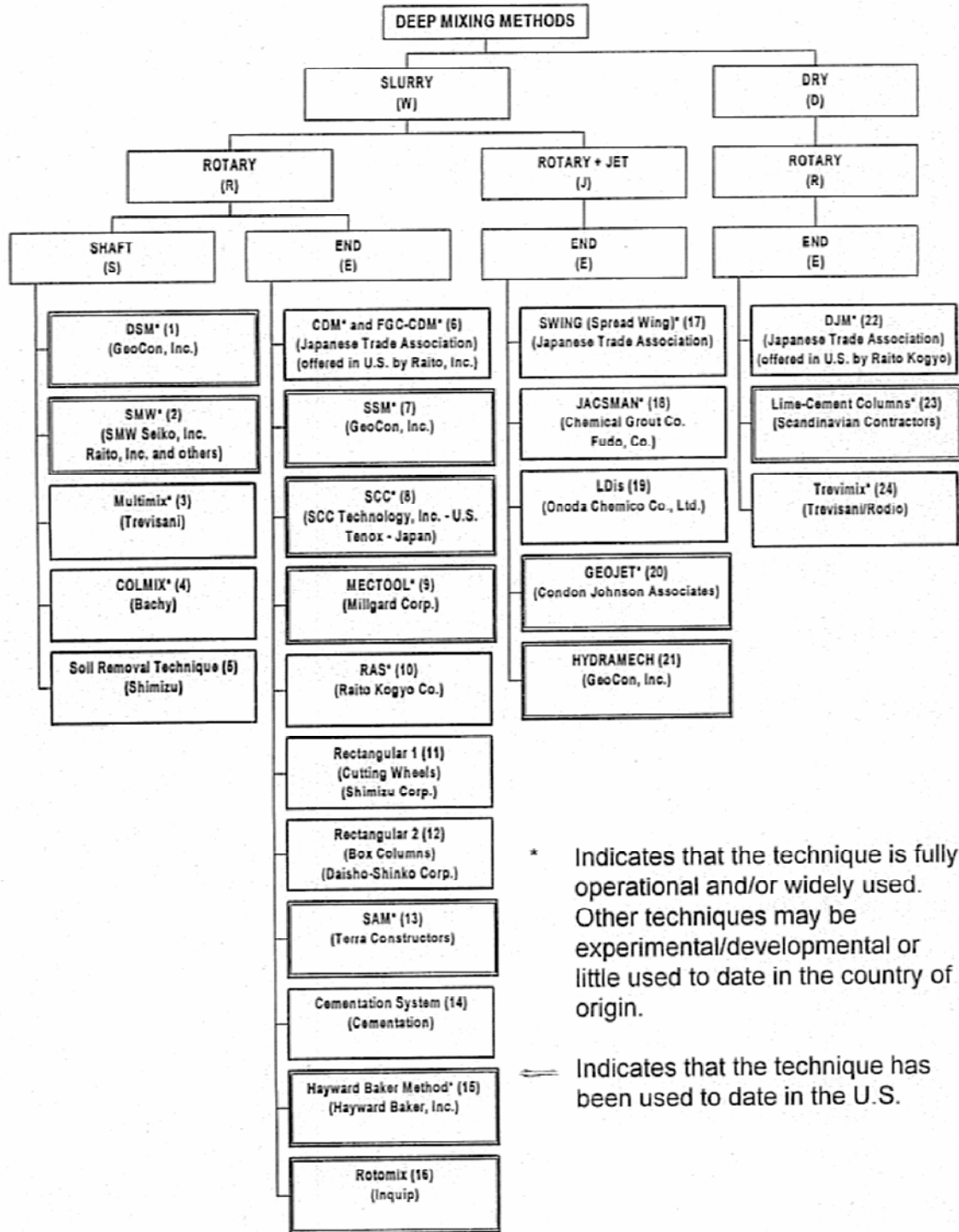
Various “shapes” of treated soil can be created in the ground [Figure 3](#), with individual columns typically 0.8 to 1.5 m in diameter (depending on technique), and usually no deeper than 35 m.

DM is most applicable in soils and fills which are soft to medium in stiffness (cohesives), or loose to medium dense (cohesionless). For soils which are stiffer or denser, and/or contain obstructions such as old structure or boulders, DM is often not technologically or economically viable.

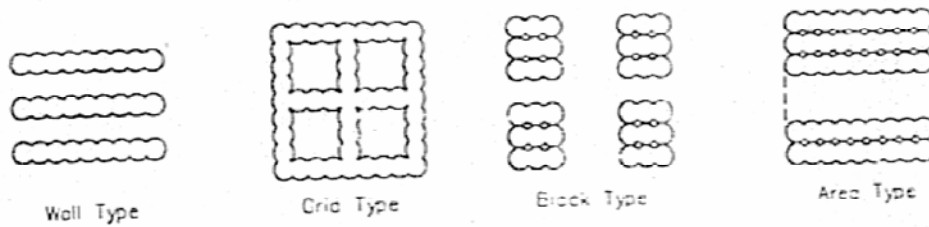
The properties of the treated soil are dictated by a large and complex number of variables but especially the nature and properties of the soil itself, and the various construction parameters used. In this regard, the composition of the slurry (principally its components and water/cement ratio) and the amount injected per unit volume of soil are critical variables. Two key measures are typically reported:

- Volume ratio (volume of slurry pumped divided by virgin volume of soil to be treated)
- Cement factor (dry weight of cement injected divided by the virgin volume of soil to be treated)

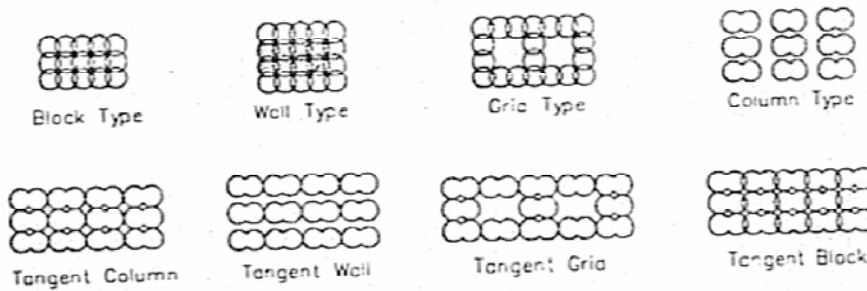
Focusing on the “wet” methods, a certain minimum volume ratio is needed for each method in order to facilitate penetration and withdrawal of the mixing tool(s), and to promote efficient blending with the soil. However, this ratio may be well over 50% in certain cases so resulting in a large volume of spoil, which of course will contain wasted grout. At the same time, some contractors use high water/cement ratios to enhance the “lubrication” effect needed, and this simply results in a high water content in the treated soil mass, producing low strength and low durability (including freeze-thaw resistance).



**Figure 2.** Classification of Deep Mixing Methods based on “binder” (Wet/Dry); penetration/mixing principle (Rotary/Jet); and location of mixing action (Shaft/End).



Basic SMW Treatment Patterns on Land



Basic CDM Treatment Patterns in Ocean

**Figure 3.** Basic deep mixing treatment patterns.

Observations of the difficulties encountered by one certain contractor in very stiff clay in Boston, Massachusetts, prompted MBT to begin researching a new family of clay dispersants. The concept was that such a dispersant would reduce the clay resistance to penetration and, in its dispersed state, the clay would be more quickly, efficiently, and homogeneously mixed.

Consequently volume ratios, and water/cement ratios could be reduced, leading to considerable economic, technical, and logistical advantages. Use the dispersant developed (PT1158), soil cement strength could be doubled, or twice the volume of clay could be treated using only 60 percent of the cement factor necessary without dispersant.

This is highly encouraging and significant, and several DM contractors in the U.S. are extremely interested in exploiting the advantages. (Unfortunately this option is not possible in the Boston job for various reasons, most politely described as "contractual" in nature.) In addition, MBT has also been introduced into the Australian market, as a declared "team member", for a potentially massive DM project in Sydney, (as well as for other rock grouting projects).

Regarding the future, MBT and ECO have made a proposal to the U.S. Government to conduct further deep mixing research, using dispersants, at the Cleveland facility. It is believed that wherever in the world wet DM techniques are contemplated in cohesive soils, clay dispersant technology can be very significant, while other options such as for Delvo, and UW450 are also to be explored.

#### 4.5 Jet Grouting

In contrast to DM, the principle of operation of jet grouting involves the use of ultra-high pressure fluid jets which destroy the virgin soil structure and remove and/or replace and/or blend with it to create a soil-cement material similar to that created by (mechanical) DM.

As defined by Bruce (1994), there are basically three types of jet grouting methods:

- F1 – One-Fluid System: The fluid is grout, and in this system the jet simultaneously erodes and injects. It involves only partial replacement of the soil.
- F2 – Two-Fluid System: This method uses a cement jet inside a compressed air cone. F2 gives a larger column diameter than F1 and gives a higher degree of soil replacement.
- F3 – Three-Fluid System: Here an upper ejection of water inside an air envelope is used for excavation, with a lower jet emitting grout for replacement of jetted soil (Figure 4).

Table 2 provides a general summary of operational parameters and grouted soil strengths.

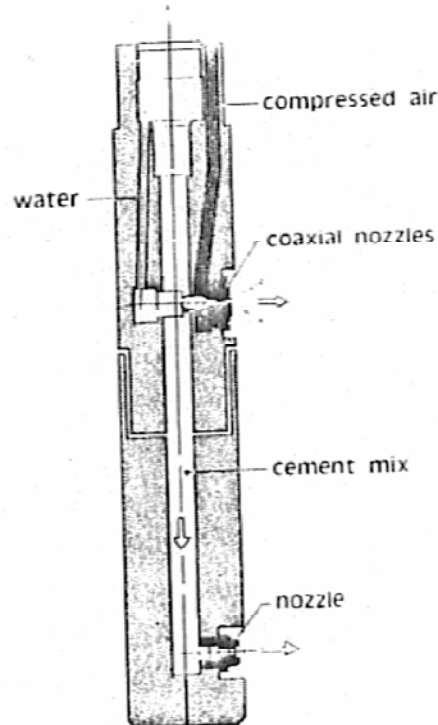


Figure 4. 3-fluid system monitor.

Jetting Parameter		F1	F2	F3
<b>Injection pressure</b>				
Water jet	(MPa)	PW <sup>a</sup>	PW	30-55
Grout jet	(MPa)	30-55	30-55	1-4
Compressed air	(MPa)	Not used	0.7-1.7	0.7-1.7
<b>Flow rates</b>				
Water jet	(liters/min)	PW	PW	70-100
Grout jet	(liters/min)	60-150	100-150	150-250
Compressed air	(m <sup>3</sup> /min)	Not used	1-3	1-3
<b>Nozzle sizes</b>				
Water jet	(mm)	PW	PW	1.8-2.6
Grout jet	(mm)	1.8-3.0	2.4-3.4	3.5-6
Number of water jets		PW	PW	1-2
Number of grout jets		2-6	1-2	1
Cement grout W-C ratio			0.80-1 to 2-1	
Cement consumption	(kg/m)	200-500	300-1000	500-2000
	(kg/m <sup>3</sup> )	400-1000	150-550	150-650
Rod rotation speed	(rpm)	10-30	10-30	3-8
Lifting speed	(min/m)	3-8	3-10	10-25
<b>Column diameter:</b>				
Coarse-grained soil	(m)	0.5-1	1-2	1.5-3
Fine-grained soil	(m)	0.4-0.8	1-1.5	1-2
<b>Soilcrete strength</b>				
Sandy soil	(MPa)	10-30	7.5-15	10-20
Clayey soil	(MPa)	1.5-10	1.5-5	1.5-7.5

**Table 2.** Typical range of jet grouting parameters and soilcrete formed using the 1-, 2-, and 3-fluid systems.

The grout is typically a neat water/cement mixture of 0.8 to 1.0. However, in extreme cases (e.g., Battery City Park, NY), additional components may be required to produce the appropriate rheological and set characteristics.

Given the high pressures, and relatively large fluid volumes utilized, it is essential that the spoils which are created at the drill tool, are allowed to exit at the ground surface freely. Otherwise, progressive build up of pressure will cause vertical and/or lateral movements in the surrounding ground and potential damage to the overlying structures. In addition, such pressure build-up will

act against the efficiency of the jetting operation, by suppressing the net energy effectively being applied in the soil.

This latter case has recently been encountered on a three-fluid jet grouting project in the Mississippi River in Missouri. The goal of the project has been to "repair" a karstic limestone block about 30 x 25 m in plan to accept comfortably the seismic loadings calculated to be imposed by a new bridge pier. However, due to a combination of factors, regular and efficient venting of spoils has not been achieved by the contractor using the "conventional" approach, and the quality of the treated clay in the karsts has not proved generally acceptable. Therefore, the MBT clay dispersant is being used, in the cutting jet water, to further break down the "clumps" of clay being transported back up the system to the surface, and to hopefully enhance cutting effectiveness, and so column diameter and homogeneity. In addition, typical cement dispersant is being used in the grout mix to keep rheological parameters in an acceptable range (the grout mix on this project has a lower water/cement ratio and also incorporates bentonite, for stability).

ECO and MBT believe that the appropriate use of dispersants, in both the cutting water and in the grout itself, can be very advantageous in jet grouting activities in cohesive soils.

## 5 FINAL REMARKS

This paper demonstrates the highly significant technological impacts that MBT's products can have in certain areas of the specialty geotechnical construction market. Several major jobs have been successfully completed in North America in the last 3 years in which MBT has had a significant and lucrative involvement. Opportunities and projects have also been generated in South America, Australia, and the Philippines by the MBT-ECO team.

There is no doubt in the author's mind that by systematically following the business development model developed to date, continuing to "educate" MBT personnel worldwide, and continuing to exploit our respective networks of clients, that MBT can continue its rapid and highly important penetration of areas of this market.

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