Practitioner's guide to the deep mixing method

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The original techniques comprising the technology known internationally as the deep mixing method (DMM) were developed simultaneously in Sweden and Japan in the mid-1970s. Now DMM is a ground treatment, improvement, and support method of global application and increasing popularity and value. The authors have been funded over the last two years by the Federal Highway Administration (FHWA) to produce a comprehensive survey of DMM practice worldwide. The various volumes produced to date deal with the technology's evolution, application, construction, and engineering performance and verification. Further research is being funded on a design study. This paper provides a synopsis of the major findings of the research to date, including historical development of DMM, the generic classification of the methods identified, definition of pertinent terminology, description of basic principles of DMM and properties of treated ground, and an overview of commercial attractions and disadvantages.

Keywords: Codes of practice & standards; foundations; geotechnical engineering

Les techniques à l'origine de la technologie connue dans la communaute internationale sous le sigle de DMM (deep mixing method) ont été dévelopées simultanément en Suède et au Japon dans les anées 70. Actuellement, DMM est devenu une méthode de traîtment et d'amélioration des sols ainsi qu'une méthode de support d'excavation d'application globale, de plus en plus fréquemment utilisée. Pour le compte du Federal Highway Administration (FHWA), les auteurs ont passé en reveu ces deux dernières anées l'état de la technique DMM dans le monde. Les différents volumes édités à ce jour ont trait à l'évolution de la technologie, ses applications, les proédés de construction et ses performances en terme de réalisation et contrôle. Des recherches complémentaires sont financées sur les études et calculs. Cet article est un résumé de resultat de ces recherches à ce jour, ainsi qu'un rappel historique du développement due DMM, les classifications génériques des méthodes utilisées, les définitions de la terminolgie appropriée, la description des principes de base due DMM et des proprétés des terrains traités, ainsi qu'une vue générale des avantages et inconvénients d'un point de vue commercial.

Introduction

It is generally agreed that the various techniques which constitute the deep mixing method (DMM) have their origins in work conducted independently by the Swedes and the Japanese in 1967, although it is valid to argue the cause of an American contractor more than a decade before. In Europe, Asia and North America, DMM is widely recognised as a specialty geotechnical construction technique of wide applicability in soft, loose, and/or contaminated soils where some form of *in situ* treatment, improvement or remediation is required. DMM may be defined as the methods by which materials of various types, but usually of cementitious nature, are introduced and blended into the soil through hollow, rotated shafts equipped with cutting tools, and mixing paddles or augers, that extend for various distances above the tip. The 'binder' materials may be injected in either slurry (wet) or dry form. The treated mass that results generally has a higher strength, lower compressibility, and (usually) lower permeability than the virgin soil, although the exact properties obtained will reflect both the characteristics of the soil and the particular construction techniques and variables that are selected.

Given the growing use and potential of the method in North America, sustained by the increasing availability of English language papers and conferences (e.g. Tokyo, 1996; Stockholm, 1999) in the countries of origin, the Federal Highway Administration (FHWA) commissioned a global state of practice review by the authors. The study is broken into the following volumes:

(*a*) Volume 1: An Introduction to the Deep Mixing Method as Used in Geotechnical Applications (late 1999)
(*b*) Volume 2: An Introduction to the Deep Mixing Method as Used in Geotechnical Applications (Appendices) (early 2000)
(*c*) Volume 3: Verification and Properties of Treated Ground (to be published 2001)

The purpose of this short paper is to present a synopsis of the first three of these voluminous studies in order to help establish basic guidelines and levels of understanding for the rapidly increasing number of engineers touched by DMM. The need for this is clear: the method is often referred to, contrary to regard for proprietary trade names, as deep soil mixing (DSM), soil mix wall (SMW), or cement deep mixing (CDM). Each of these terms refers to one particular type of DMM, or may even be associated with one particular company and so there is a need for universal, non-proprietary terminology. Equally, one of the determinants of treated soil properties is the amount of cement (or binder) which is introduced into the soil. However, even this is expressed

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globally in different ways, ranging from the dry weight of cement per unit volume of soil, through weight ratio of grout to soil, to volume ratio of grout to soil. This also needs to be resolved. Another major issue revolves around the various different types of DMM themselves. Each has a common goal: to provide a homogeneous mixed soil/binder mass whose properties are in some way or ways, superior to those of the virgin mass. However, the means, methods, and equipment by which this universal goal is satisfied vary greatly: the authors have identified 25 different DMM techniques—albeit only in four generic classes—which are in use, or have been developed, globally.

This lack of global perspective has arguably held back the growth of DMM in the United States. Early practioners, shy to unveil the global practice, focused on one generic method, with the result that in the formative years of its use, DMM was unnaturally restricted in scope and competition. With the availability in the US of proponents of all four generic methods, DMM's growth potential has remarkably increased to the extent that it is one of the most rapidly developing ground treatment, improvement, and retention techniques in the country.

In the United Kingdom, early geotechnical potential (e.g. Greenwood, 1987) was not exploited, through a combination of factors including the overall economic situation, and resistance by competitors protecting more traditional technolgies. In addition, it was perceived that such DMM systems were very costly to acquire and difficult to operate to acceptable levels of quality and consistency. In more recent years, the ever-pressing challenges of environmental remediation (e.g. Al-Tabaa *et al.*, 1999) have focused attention back on the potential of DMM, and both European (e.g. Soletanche-Bachy, Inc.) and UK contractors (e.g. May Gurney (Technical Services), Ltd) have undertaken important works, while UK companies with foreign 'arms' are increasingly aware and sensitive to domestic potential.

It is against this background of a growing professional awareness, attractive geotechnical and environmental applications, but an obscure international perspective, that this paper is presented.

Background

Scope

The Tokyo conference may, in retrospect, be judged by our profession to be one of the more significant expressions of technical knowledge on a narrow range of subjects to have impacted US specialty geotechnical construction practice. The FHWA study was inspired by that conference and addresses only vertical, rotary methods, since the greatest amount of DMM work conducted globally involves vertical penetration by one or a number of mixing shafts to create descrete columns or panels. Depending on the application, these elements may be constructed to overlap to provide a variety of geometries of treated soil.

However, an increasing number of methods are under development that create either mass treatment by using inclined auger or conveyor technology or by using vertical beams with lateral jetting capabilities to provide thin, but continuous *in situ* membranes. Such applications mainly serve the environmental market—containment fixation, and retention, respectively—and are typically viable to relatively shallow depths (10 m). Nevertheless, future studies of DMM should entertain these methods alongside the conventional groups of methodologies.

Historical evolution

The FHWA study listed some 82 events considered significant in the growth of DMM since the original US concept in 1954, and the independent Japanese and Scandinavian developments in 1967. Most of these key events have occurred in the last decade, emphasising the ever-increasing rate of development by contractors, consultants, and owners—including federal agencies in the case of Japan, China, France, Sweden, and Finland. This theme is revisited in later sections.

Applications and advantages

In the most general terms, DMM may be most attractive in projects where the ground is neither very stiff nor very dense, nor contains boulders or other obstructions; to depths of less than about 30 m; where there is relatively unrestricted overhead clearance; where a constant and good supply of binder can be assured; where a significant amount of surface spoil can be tolerated; where a ralatively vibration-free technology is required; where treated or improved ground volumes are large; where 'performance specifications' are applicable; or where treated ground strengths have to be closely engineered (typically 0·1–5·0 MPa unconfined compressive strength (UCS)).

Extreme care should be taken not to overextend the limits of DMM capability without due regard to a true appreciation of the fundamentals of its evolution. Otherwise, inappropriately applied, designed, and constructed work will lead to owner disappointment, or worse. The viability, both technically and commerically, of DMM in its various potential applictions and settings will continue to be challenged by solutions based on other technologies and cultural preferences, and rightly so: deep mixing is not the panacea for all specialty geotechnical problems.

Six basic groups of applications can be identified for contemporary deep mixing methods:

(*a*) *Hydraulic cutoffs*. DMM walls to prevent water movement through or under water-retaining structures, such as dams or levees and into deep basements excavated below the water table.

(*b*) *Structural walls*. DMM walls containing steel elements to resist lateral earth pressures in the construction of deep excavations, such as for cut-and-cover tunnels and deep basements.

(*c*) *Ground treatment*. Block treatment to strengthen in a uniform manner large volumes of foundation soil in conjunction with deep excavations and structural foundations.

(*d*) *Ground improvement*. Discrete DMM elements (columns or panels) used as reinforcing elements to improve the overall performance of large, compressible soil masses under relatively lightly loaded structures, such as road or railway embankments.

(*e*) *Liquefaction mitigation*. Interlocking DMM box or cellular structures to reduce the tendency for mass liquefaction and lateral spreading during seismic events under large embankments or buildings.

(*f*) *Hazardous materials*. DMM walls to contain, or DMM block treatment to fix, environmentally unacceptable materials.

Globally, the novelty now arises when local technologies are developed for new applications, or when established methods are used in new geographic areas, often by contractors who are seeking to develop their own variant of the method in response to a particular project's challenges. Thus we may anticipate in the next decade's technical press a plethora of case histories dealing with environmental and liquefaction mitigation, and *in situ* earth reinforcement from practitioners in countries as diverse as the UK, Indonesia, Trinidad and Australia, based on the authors' current project awareness.

Classification of methods

A generic classification of the numerous methods used internationally can be made on the following simple basis:

(*a*) Is the cementitious material injected in a slurry or wet (W) form, or in a dry (D) state?
(*b*) Is this binder mixed with the soil by way of rotary energy only (R) or is the mixing enhanced/facilitated by high-pressure jet (J) grout-type methods?
(*c*) Is the mixing action only occurring near to the drilling tool (E), or is it continued along the shaft (S) for a significant distance above it, by way of augers and/or paddles?

The classification shown in Fig. 1 has therefore been developed by the authors, and four categories of methods—WRS, WRE, WJE and DRE—have been identified. No methods have been found in the DRS, DJE, or DJS categories since dry injection methods only feature end mixing with relatively low pressure binder injection pressures by way of compressed air, and jetted methods only feature end mixing (hence no WJS).

A total of 25 different methods—mostly fully operational and patented—were indentified (Fig. 1). This classification, of course, only applies to those deep mixing systems employing vertical mixing principles (as previously noted). A new 'arm' to this classification will be necessary to accommodate the 'mass', or 'lateral jetting' variants.

The authors have received peer reviews of this proposed classification from specialists worldwide, and have monitored global practice for three years to date. The generic classification of Fig. 1 has, in patent terms, 'satisfied' these challenges, and so is considered appropriate.

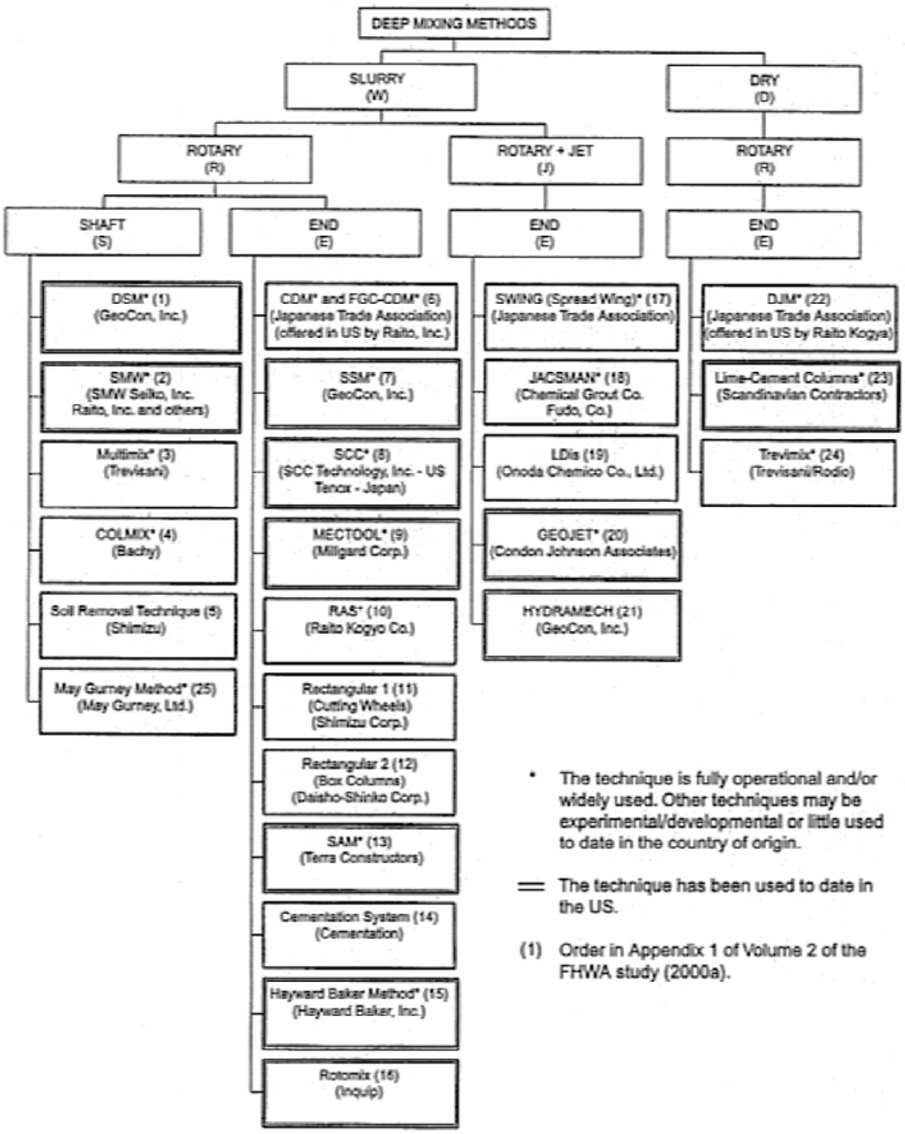

Fig. 1. Generic classification of DMM techniques

Definition of terminologies

While most of the DMM terminology is either well known or obvious, it is important that two terms in particular are defined clearly at the onset:

(*a*) *Cement factor* (also known as the α factor): defined as the weight of dry binder introduced into the ground to be treated, divided by the volume of ground to be treated. The weight can refer to the actual weight of binder used in dry methods, or the actual weight of binder used in the slurry in wet methods. It is expressed in units of kg/m^3. Alternatively, the term a_w is also used, and this is the ratio of dry binder to dry weight of soil (expressed as a percentage). This and the natural water content of the soil dictate the actual cement factor.

(*b*) *Volume ratio*: defined as the ratio of the volume of slurry injected (in wet method systems) to the volume of ground to be treated. This is expressed as a percentage.

Fundamental principles and properties

Volumes 1 and 2 of the FHWA study (1999, 2000a) provide extensive data on each of the methods identified in Fig. 1. Space restrictions prevent more than a brief summary of the more significant methods being provided here. The following general points may be made:

(*a*) New methods, refinements of existing methods, and developments in materials (e.g. use of fly ash, gypsum and slag in slurries; clay dispersants to aid penetration and improved mixing efficiency) are continually under way.

(*b*) As noted by Taki and Bell (1997), the technical goal of any DMM technique is to provide a uniformly treated mixed body, with no discrete lumps of binder or soil, a uniform moisture content, and a uniform distribution of binder throughout the mass. The most important requirements for installation are therefore: thorough and uniform mixing of the soil and binder; appropriate water/cement ratio; and appropriate grout injection ratio (e.g. volume of grout: volume of treated soil).

(*c*) Despite their generic similarity, there are major and significant regional and procedural variations. For example, UCSs of treated soil using WRE, WRS, and WJE are typically higher than 1 MPa, except (e.g. FGC-CDM) where lower strengths are deloberately engineered. For DRE methods in Japan (e.g. DJM) a minimum UCS of 0·5 MPa is obtained, whereas for the comparable DRE Scandinavian method (lime-cement columns), rarely are strengths in excess of 0·15 MPa designed and/or acheived. Furthermore, treated soils in Scandinavia may be considered as providing vertical drainage, while similar soils in other countries, by other methods, may be regarded as relatively impermeable.

(*d*) Volume 3 of the FHWA report (2000b) illustrates the mass of experimental data available on the properties of treated ground. Reinforced by these data, performance prediction models can be established and optimised. Typical of the systematic Japanese approach is the work of Saitoh *et al.* (1996), colleagues in the Takenaka group of companies. Fig. 2 is a standard conceptual flow chart for determining and achieving target treated soil strengths.

(*e*) Table 1 (Terashi, 1997) summarises the factors influencing the strength of treated soil. In laboratory testing, there is no way to simulate factors III and IV except for the amount of binder and the curing time. Thus laboratory testing features standardisation of these factors, and so it must be realised that the strength data provided by such tests are 'not a precise prediction' (Terashi, 1997) but only an 'index' of the actual strength. Field testing is essential, and invariably appears to provide, for a number of reasons, inferior and more variable strength data. Likely field strengths can then be estimated using empirical relationships from previous projects, and exercising engineering judgement. A standard test procedure was proposed by Terashi in one of the Port and Harbour Research Institute (PHRI) reports in the late 1970s. The Japan Society of Soil Mechanics and Foundation Engineering (JSSMFE) standardised the laboratroy test procedure in 1983, which is essentially the same as the original proposal by PHRI. After experiencing a couple of revisions, currently the standard procedure is coded as JGS 0821-2000 *Practice for Making and Curing Stabilized Soil Specimen without Compaction*. (Note: JSSMFE changed its name to Japan Geotechnical Society (JGS) a couple of years ago.)

(*f*) Regardless of the level of expertise of the contractor, and/or the level of understanding of the particular site conditions, some type of pre-production test pro-

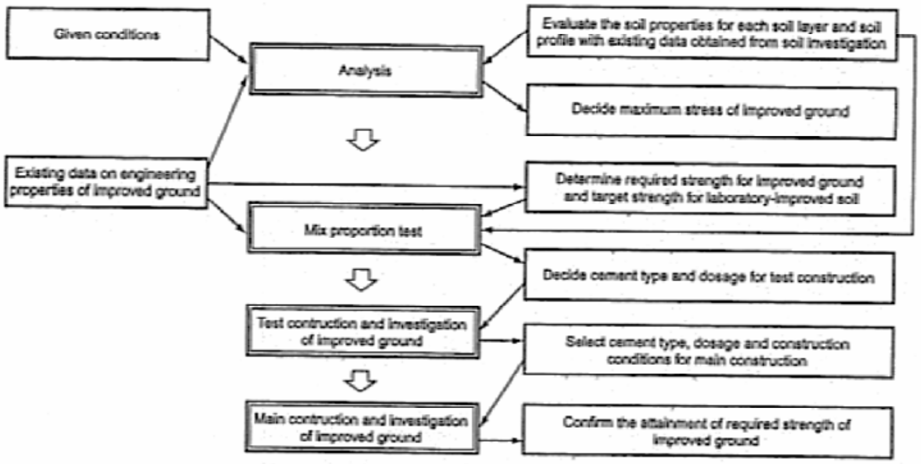

Fig. 2. Flow chart of work involved to determine and achieve required strength of improved ground (Saitoh et *al.*, 1996)

Table 1. Factors affecting the strength increase of treated soil (Terashi, 1997).

I	Characteristics of hardening agent	Type of hardening agent Quality Mixing water and additives
II	Characteristics and conditions of soil (especially important for clays)	Physical chemical and mineralogical properties of soil Organic content pH of pore water Water content
III	Mixing conditions	Degree of mixing Timing of mixing/remixing Quality of hardening agent
IV	Curing conditions	Temperature Curing time Humidity Wetting and drying/freezing and thawing, etc.

Table 2. Typical data on soil treated by deep mixing

Parameter	Description
UCS	0·2–5·0 MPa (0·5–5·0 MPa in granular soils) (0·2–2 MPa in cohesives)
k	10^{-6}–10^{-9} m/s (lower if bentonite is used)
E	350–1000 times UCS for laboratory samples 150–500 times UCS for field samples
Shear strength (direct shear, no normal stress)	40–50% of UCS at UCS values < 1 MPa, but this ratio decreases gradually as UCS increases
Tensile strength	Typically 8–14% UCS
28-day UCS	1·4–1·5 times the seven-day strength for silts and clays 2 times the seven-day strength for sands
60-day UCS	1·5 times the 28-day UCS, while the ratio of 15 years to 60 days UCS may be as high as 3 to 1. In general, however, grouts with high w/c ratios have much less long-term strength gain beyond 28 days

gramme is highly advisable, if not essential. Such a programme affords the opportunity for the contractor to demonstrate that the specified performance criteria, tolerances, and engineering properties can be met, even if two or more iterations have to be made. Once these criteria have been achieved, then the production parameters can be selected logically and only modified if there are obvious changes in the soil, or in the project scope. Such programmes require the scope of the testing to be clearly defined, together with the acceptance criteria for every aspect. Testing and sampling is usually more rigorous than in the subsequent production phase. Test programmes should also be a demonstration of the efficiency of the quality assurance/quality control and verification processes themselves.

(*g*) The materials injected are tailored to the method used, their local availability, the ground to be treated and the desired or intended result. Generally, for the methods using a fluid grout, the constituents include cements, water, bentonite, clay, gypsum, fly ash, and various additives. Water/cement (w/c) ratios typically range from less than 1 to over 2, although the actual in-place w/c ratio will depend on any 'predrilling' activities with other water, or other fluids. Most recently, dispersants (Gause, 1997) can be used, both to breakdown cohesive soils, and also to render more efficient the grout injected. For dry injection methods, cement and/or unslaked lime are the prime materials used.

(*h*) For wet methods (mechanically simpler and so preferable in 'difficult' geographic locations), the cement injected is typically in the range 100–500 kg/m^3 of soil to be treated. The ratio of volume of fluid grout injected to soil mass treated is typicall ~20–40%. (A lower injection ratio is preferable, to minimise cement usage and spoil.)

(*i*) For dry methods (in soils of 60 to over 200% moisture content), typically 100–300 kg of dry materials per cubic metre of treated soil is used, providing strengths of 0·2–20·0 MPa, depending very much on soil type (low strengths and solids contents in Scandinavia), with minimal spoil or heave potential.

(*j*) Treated soil properties (recalling that cohesive soils require more cement to give equivalent strengths than cohesionless soils) are usually in the ranges shown in Table 2.

(*k*) It must be remembered that different techniques are intended specifically to provide higher strengths, or lower permeabilities and so the figures cited above are gross ranges only, and that the data provided by the individual corporations supersede those presented above for specific applications.

(*l*) Regarding the future, the constructional developmental trends are towards improving the quality of the mixing process (e.g. systems 11 and 12); using less expensive binder components (e.g. system 6); obtaining larger diameter of treatment by way of jet assistance (e.g. systems 18 and 21); and improving the level of computer-assisted control (most systems, but for example, method 20).

Commercial attraction and disadvantages

In the United States, there are at least nine companies who offer, or claim to offer, deep mixing services. Four appear to have no links with foreign ownership or licensees, having developed their own systems. The others are either US operations with foreign ownership or use methods under foreign licence. Based on the authors' investigations, it would seem that from 1986 to 1992, the annual value of deep mixing work conducted was in the range $10–20 million, increasing by over 50% to 1996. Since then, as a result of massive works in Boston, Salt Lake City and the West Coast, this annual volume is probably now in the range $50–80 million. For DMM used in environmental applications, the annual market may be around $20–30 million, increasing at about 5–10% annually.

Large-scale systems may cost $80 000–200 000 to mobilise (much lower for methods such as lime-cement columns). Typical prices for treatment are $100–250/m^2, or $50–100/m^3.

In Japan, the CDM Association claims to have treated over 26 million m^3 of soil from 1977 to 1995 (30% in the period 1992–1995) with about 60% being offshore. The DJM Association records 16 million m^3 of soil treatment from 1980 to 1996, involving 2345 separate projects, and an annual volume now approaching 2 million m^3. By 1994, SMW Seiko, referring to its deep mixing wall system, had recorded 4000 projects worlwide for a total treatment of 12·5 million m^2 (7 million m^3).

In Scandinavia, there has been a rapid growth in Swedish applications (Åhnberg, 1996), and a strong but smaller and steadier market in Finland (about 250 000 m^3/year, 80% of which is lime-cement columns). Markets in Norway and the Baltic countries are much smaller but have considerable growth potential. Selling prices in Scandinavia are typically in the range $7–12/lin.m.

Similar data have not been found for other European countries, but there is no evidence that levels of activity in countries such as the UK, France, Germany and Italy currently approach those in the US. The main focus would appear to be on hazardous waste containment or fixation.

Notwithstanding the benefits and advantages which contemporary DMM techniques can offer, there remain a number of factors, often interrelated, which act as potential barriers to market entry for prospective contractors, and/or controls over market growth. These include:

- (*a*) *Demand for the product*. Given the national trends towards urban construction and redevelopment, seismic retrofit and environmental clear-up—all challenges to be solved *in situ*—then demand for DMM will continue to increase.
- (*b*) *Awareness of the product*. A wider range of active specialty contractors and consultants, more prolific technical publications, short courses and the coincidence of several high-profile DMM projects nationwide have combined to elevate awareness of DMM in general engineering circles, and will so continue to increase demand.
- (*c*) *Bidding methods/responsibility for performance*. The authors believe that the interests of a rapidly developing and complex technology such as DMM are best served by 'design–build' concepts. Thus, the rate of growth of DMM will be influenced strongly by the rate at which innovative contract procurement and administration vehicles are adopted.
- (*d*) *Technology protection*. Most of the 25 methods shown in Fig. 1 are protected in their technology by patent or similar. Thus new potential contractors must either invent their own system, or acquire a foreign licence. The latter seems more realistic, given the timetables and costs involved in conducting basic research and development.
- (*e*) *Capital cost of start-up*. Given the high levels of technical sophistication, and large physical scale of most systems, start-up costs are high. In addition, the larger projects may require several machines and so committed capital expenditures may easily rise to several million dollars. The equipment must also be regularly maintained and upgraded, leading to the general conclusion that DMM is a 'cash hungry' technology for the contractors who offer it—although the potential return on investment is high. Thus, the field of potential contractors is practically limited by the levels of their own financial resources.

Final remarks

The deep mixing method (DMM) is one of the most common ground engineering technologies in certain parts of the world for ground treatment, improvement, and retension. Its use is growing in countries where major structures have to be founded upon ground which is soft or loose and which therefore may give unacceptable performance under static or dynamic loading conditions. Within the last decade, increasing use is being made of DMM in environmental applications, with a concentration—now surprisingly—in heavily industrialised areas in the US and in Western Europe.

To a large extent, its relatively slow growth prior to the mid-1990s in countries outside of Japan and Scandinavia reflects the fact that the engineering profession had access only to papers published in languages other than English. The rapid recent international growth reflects not only causes related to technical or market demands, but largely, in the opinion of the authors, the increasing availability of English language technical information. This has offered both insight and perspective to a significantly wider range of engineers—both contractors and owners.

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