State of Practice Report: Session 3 – "Design of Deep Mixing Applications"

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1. INTRODUCTION

Session 3 contains 12 papers which, although all observe the "Design of Deep Mixing Applications" theme, cover a very wide range of aspects from numerical and centrifuge modeling to full-scale field testing. They describe applications ranging from road and railway embankments to harbor and port developments. They cover static, dynamic and seismic problems. Various types of Deep Mixing Methods (DMM) are employed, both wet and dry. Panels, columns and blocks of DMM material are studied. In effect this group of papers represents a conference within a conference.

The task of logically arranging these papers as a prelude to meaningful analysis and synthesis has clearly an equally diverse set of options. However, mindful of the title of the session, the authors have decided to divide the papers into three major groups which reflect principally the application of the work. This provides the groups shown in the table below.

This grouping is by no means unique and may not be ideal, but it does seem a logical way to deal with the great diversity at hand. The relative number of papers in each group reflects Terashi's statement (2002) that "nearly 60% of on-land applications in Japan and perhaps roughly 85% of Nordic applications are for settlement reduction and improvement of embankment stability by means of groups of treated soil columns."

GROUP	APPLICATION	COUNTRY OF STUDY	COUNTRY OF TECHNICAL INFLUENCE	AUTHORS	NUMBER
A	Stabilization of Soils under Embankments for Railways and Roads	Sweden	Sweden	Alén et al. (model)	1
		U.S.A.	Sweden	Stewart and Filz	2
		Sweden	Sweden	Alén et al. (tests)	3
		U.S.A.	Japan and Nordic	Han et al.	4
		Japan	Japan	Kitazume et al.	5
		Japan	Japan	Nozu et al.	6
		Germany	Germany	Schwarz and Raithel	7
		Germany	Sweden	Katzenback and Ittershagen	8
B	Structures on Treated Soil Masses	Japan	Japan	Kurisaki et al.	9
		Japan	Japan	Ohishi et al.	10
C	Seismic Issues	Japan	Japan	Namikawa et al.	11
		U.S.A.	Japan	Siddharthan et al.	12

2. EXISTING PUBLICATIONS, STANDARDS AND GUIDELINES

There is an increasingly rich literature dealing with all aspects of deep mixing. This was largely initiated by the original sponsors, designers and constructors of the deep mixing technologies, but has increasingly attracted, as at this Conference, university researchers whose specialties involve topics often peripheral to the deep mixing technology itself. A particularly encouraging trend is the increasing number of Master and Doctoral Thesis to emerge from the Nordic Universities on practical, useful topics. In addition to the (understandable) references to the authors' own previous works, there are a number of sources which are somewhat frequently and generally cited in the papers reviewed. These include:

- Proceedings of International Conferences on Soil Mechanics and Foundation Engineering (1981-Present).
- Proceedings of Asian Regional Conferences on Soil Mechanics and Geotechnical Engineering (1979 – Present).
- Proceedings of ASCE GeoInstitute Conferences (1997 – Present).
- Proceedings of International Conference on Deep Mixing in Tokyo (1996).
- Proceedings of National Conferences on Soil Mechanics and Foundation Engineering (in Japanese) (1980 – Present).
- Euro soil stab "Development of design and construction methods to stabilize soft organic soils," Design Guide (2002).
- Reports from Swedish Geotechnical Institute (1975 – Present), e.g., Carlsten P. (2000) "Handbook for lime and lime-cement columns."
- Report "Lime and Lime Cement Columns," by Swedish Geotechnical Society (1997).
- Reports from Port and Harbor Research Institute, and Public Works Research Center, Japan (in Japanese).
- "The Deep Mixing Method: Principle, Design and Construction," (Coastal Development Institute of Technology) (2002).
- Proceedings of Deep Mixing Workshop, Tokyo (2002).
- CEN TC 288 "Execution of special geotechnical works – deep mixing" (2002)

Clearly it is impossible to provide a synopsis of the vast amount of data enclosed in these and countless other publications. The authors also find it difficult to better the excellent synopsis provided by Hansbo and Massarsch elsewhere in this conference, when referring to the main objectives and aspects of the prEN 14679 on Deep Mixing:

"The object of design is to make sure that the ground treated fulfills the requirements for the intended purpose of deep mixing. Supported structures shall be fit for use during their intended life with appropriate degree of reliability and sustain all actions and influences that are likely to occur during execution and use. Iterative design, based on a follow-up of the results obtained by testing during the execution period, is an important part of the design.

The requirements for serviceability and ultimate limit states are to be specified by the client."

"So-called iterative design, based on a follow-up of the results obtained by various testing methods, is an important part of the design. Here, the main focus is placed upon those factors that are important for the execution and the purpose of deep mixing. The design is made for the most unfavorable combinations of loads, which could occur during construction and service."

3. DISCUSSION OF RELEVANT PAPERS

Session 3 offers an insightful look at promising new methodologies for the design and analysis of embankments and structures founded on treated soil. In this collection of papers, the Deep Mixing community of practice demonstrates a deep understanding of the fundamental nature of the internal stability of treated soil. Through numerical and centrifuge model studies, and by instrumented full-scale test sections, practitioners are developing new tools to more realistically depict the true behavior and fate of soil cement columns under service loads. A synopsis of the theme of each paper follows.

Nozu et al. studied the value of placing DJM columns at the toe of an embankment to reduce the stress induction and settlement caused by the embankment loading. The test soil was soft clay and the binder mix used was 100% Normal Portland Cement, applied at 140 kg/m^3, yielding unconfined compressive strength of 182-189 kPa. Tests were conducted on one row and two rows of interconnected columns that were installed in wall configurations at the embankment toe. The authors observed reduction in both adjacent ground settlement and lateral spread of the embankment, and that the magnitude of the benefit was greater with greater number of rows. The authors recommended that columns used as wall-type countermeasures should be installed down to the bearing stratum; that walls should consist of two or three rows; and that columns should possess a specified strength and stiffness.

Han et al. studied the factors that influence the deep-seated stability of column-supported embankments. They examined the effects of strength, spacing, and size of the columns, cohesion and thickness of the soft soil, and friction angle and height of the embankment fill. They compared the results of stability analysis using Bishop's simplified method to those obtained using the Fast Lagrangian Analysis of Continua, Version 4.0 (FLAC2D), modeled as shown in Figure 1.

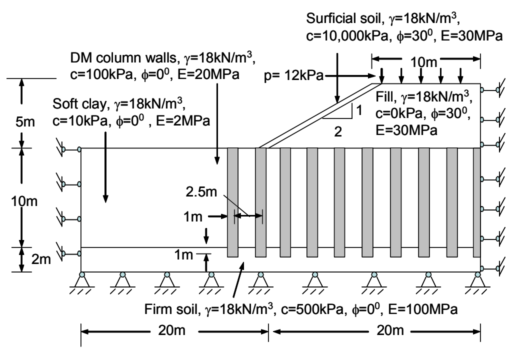


Figure 1. Numerical Analysis Model of the Baseline Case (Han et al., 2005)

Bishop's method yielded higher factors of safety than the numerical method, and the authors report that numerical methods might be more representative of the soil-structure interaction than limit equilibrium methods. Figure 2 depicts one example of the results from this parametric study, showing the influence of column strength on factor of safety.

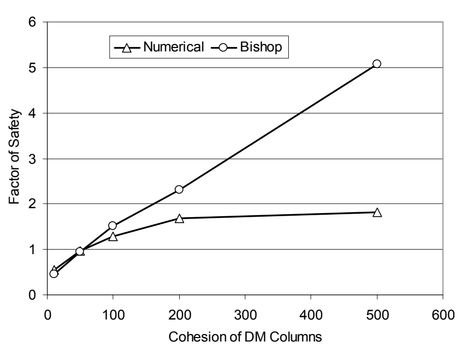


Figure 2. Influence of Column Strength on Factor of Safety (Han et al., 2005)

Stewart and Filz conducted a numerical parameter study for column-supported embankments to examine the factors that affect the soil-column load transfer. A significant contribution is their proposal of terminology that can be used as a common language to describe the load transfer between columns and soil. Their numerical analysis was conducted using FLAC. The results of parameter variation are reported in terms of their effect on the "column stress ratio," or CSR, defined as the ratio between the stress on top of the column to the average applied embankment stress at the level of the top of the column. Key findings include the observation that, where no column failure occurs, CSR values increase with increasing column modulus and increasing embankment height. Once column failure occurs, CSR values decrease with increasing embankment height.

The companion papers by Kurisaki et al. and Ohishi et al. present the results of centrifuge and numerical modeling studies investigating the bearing capacity and failure mechanisms of block treated soil. Study results by Kurisaki et al. clearly showed the generation of a wedge-shaped yield region beneath the footing, as seen in Figure 4, and the development of a shear plane rather than the occurrence of cracks. In the study, the authors found that an elasto-plastic simulated the centrifuge model tests in terms of the yield bearing capacity and load-settlement relationship.

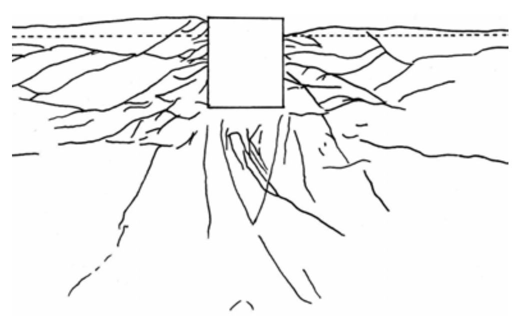


Figure 4. Deformation of ground after the tests (Kurisaki et al., 2005).

Ohishi et al. used the centrifuge and numerical analysis to study the failure of an earth retaining structure founded on block treated soil. They found that the block-type improved ground was found stable even when the internal stability by the current design method was not satisfied. They concluded that current design procedure could underestimate the true bearing capacity of block treated soil. In the paper, the authors also reviewed current design protocol for gravity structures on block treated soil and recommend appropriate reductions in allowable column shear strength to compensate for uncertainties in material properties.

Alén et al. monitored four column-supported test embankments for settlement. They found that current Swedish practices for estimating column settlement over predicted the observed settlement. The authors attributed this to underestimation of the column modulus and erroneous assumptions regarding load distribution between the columns and the natural soil. They also concluded that their data support the assumption of equal strain throughout the treated zone and reported inferior quality in the upper two meters of the columns.

In a companion paper, Alén et al. propose a new model for calculating settlement beneath a column-supported embankment. The authors use a simple, relevant approach based on Boussinesq's solution for an infinite half sphere to describe the stress distribution in a soil/column matrix. The model is meant to complement more rigorous design tools, such as numerical modeling, and the author recommends that more testing and evaluation must be performed before the model reaches final form.

Kitazume and Maruyama used centrifuge modeling to investigate failure patterns of embankments supported on column rows. They found that a collapse failure pattern, Figure 5, in which interconnected column walls distorted and collapsed like dominos, was the most critical failure mode. The resulting bending moments in the column wall exhibited a varied moment distribution pattern at ground failure. Stability calculations based on simple shear of the improved area due to unbalanced active and passive earth pressure for the collapse failure pattern yielded a better fit to the physical model data, Figure 6. The authors caution that conventional analysis often overlooks this failure pattern, thereby overestimating the external stability of the system.

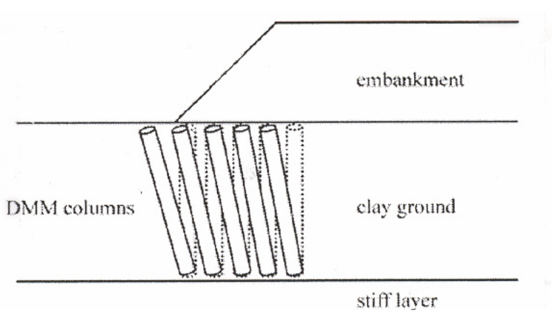


Figure 5. Collapse failure pattern of DMM improved ground (Kitazume et al., 2005).

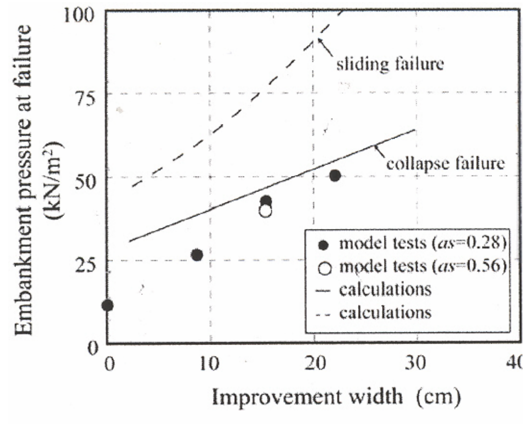


Figure 6. Relationship between embankment pressure at ground failure and width of improved area (Kitazume et al., 2005).

During earthquake loading, dynamic earth pressures can be transmitted to improved ground walls. Namikawa et al., examined the ability of lattice-shaped ground improvement, Figure 7, to withstand the associated external shear and tensile forces. The authors conducted three-dimensional finite element analysis using the dynamic effective stress analysis code (Shiomi et al., 1993), and modeled the cement-treated soil by an elasto-plastic formulation to express post-peak strain softening and tensile failure. Their results showed that, although tensile failure occurred at the corner of the improved grid, the lattice-shaped walls continued to reduce excess pore pressure in the unimproved sand deposit.

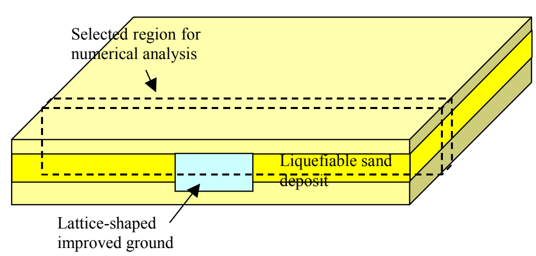


Figure 7. Two grids improved ground in a line (Namikawa et al., 2005).

For mitigation of liquefaction potential in granular soils, Siddharthan et al. investigated the spatial limitation of deep mixed columns on reduction in pore water pressure increase during earthquakes having magnitude 6.5-8 for loose sands and silts. Using a two-dimensional effective stress program, they found that the maximum beneficial effect was near the ground surface, and that the benefits of soil treatment were limited to a zone equal to three column diameters from the edge of the treated area.

Katzenbach and Ittershagen conducted field tests to investigate the speed-dependent dynamic soil-structure interaction of railway lines founded on soft soil to assess the benefit of soil treatment in the reduction of long-term track deformations. Their field measurement data showed that the RMS-Values (Root Mean Square) of the ground oscillations were lower for constant speed trains on improved soil. Numerical back calculation analyses were then conducted on the field data to develop a design tool that could be used to predict the results for different natural soil characteristics and soil treatment patterns. They concluded that use of the RMS-Value is a practical and useful index.

Schwarz and Raithel provided a case study for the combined use of Mixed-in Place columns with geogrid to stabilize and reinforce soft organic soil, having an organic content of 25 to 80%. To upgrade a railway line for higher speed traffic, the rail loads were distributed to a more competent bearing layer 5 to 8 m below the ground surface. In all, 3,260 columns were installed, each having 0.63 m diameter, and in a square 1.5 m x 1.5 m grid. The binder consisted of water, cement, and bentonite. The authors also provide a description of the theoretical bearing and deformation behavior and their design calculation methods.

4. ASPECTS OF WET AND DRY MIXING (ADVANTAGES AND LIMITATIONS, TECHNICAL AND ECONOMIC)

This being a design-oriented session, the papers reviewed do not primarily contain a great deal of information on the particular aspects of dry and wet technology. Indeed, in most cases, each paper is written in full (implicit or explicit) support of deep mixing as a general technique and without comparative analyses of competitive technologies. Thus it may be theorized that little new is added to the basic store of knowledge on this particular aspect already established through previous conferences (e.g., Tokyo 1996, Stockholm 1999, and New Orleans 2003) and existing reports and overviews (e.g., FHWA 1999-2000, SGI (2000), and CDIT (2002).

The following synopsis is provided as the basis for the subsequent review:

PAPER	ADVANTAGES AND DISADVANTAGES	TECHNICAL AND ECONOMIC ISSUES
1	LCC used for stabilization of soft soils under embankments over 3 decades. Development of design practice needed.	New model for calculation of settlements presented, for "floating columns." Supported by field observations.
2	"No clear agreement on design methodology," although "trends disclosed by the analyses" are presented. Two methods used for analysis (effective stress parameters for DMM columns).	DMM "increasingly being used in U.S. to support new embankments over deposits of soft soil." Pressure cells responded quickly to fill placement levels (at top of columns).
3	LCC columns considered for foundation stabilization for high speed railway and road development. LLC columns "inferior" in quality in upper 2 m.	Results of four test embankments can be related to numerical model (Paper 1). Research backing from several interested parties made available.
4.	Columns can fail due to shearing, bending, rotating, or tension or a combination. Comparison of 2D finite difference and Bishop's method provide differences.	Bending strength is much lower than shear strength. Paper only addresses groups of columns.
5	Design procedure for DJM columns produced (1999). However, various possible failure modes exist. Further research on failure mechanism and evaluation of stability for each pattern necessary. Current design method overestimates external stability.	Failure embankment pressure for improvement ratio of 0.56 almost same as for 0.28.
6	"Design method for DJM wall is not well established yet." Low embankments are considered (≤ 4 m).	The need to install 2 or 3 rows of columns, full depth to bearing stratum, as recommended, may raise overall cost of a DMM application.

PAPER	ADVANTAGES AND DISADVANTAGES	TECHNICAL AND ECONOMIC ISSUES
7	Due to lack of previous experience – and recognized design guides – “individual approval” had to be obtained from authorities. Excellent performance attained.	Use of wet “MIP” method. Excellent data on quality control results and monitoring data.
8	Very systematic and relevant testing provides excellent design baseline data.	Consolidates value of field *and* numerical tests. Strong collaboration with Swedish research confirmed also strong input from “related” fields, e.g., railroad engineering dynamics.
9 and 10	Uses industrial waste products in DM. Strong, basic design rationale provided for a very important application of DMM. Performance (load-settlement) can be adequately predicted.	Very clear analysis of failure modes permits heavy structures on treated soil. Focuses on advantages of low strength DMM. Value of centrifuge testing underlined.
11	Provides strong support for use of lattice DM patterns in seismic applications (three dimensional effective stress analyses). “Partial failure” can be permitted while still preventing liquefaction.	Provides examples of actual successful performance. Provides strong design basis.
12	Parametric study (two dimensional effective stress program) conducted which may support effectiveness of DMM in seismic applications.	

The main observations are as follows:

1. Despite the recent wave of norms, standards, and guidelines there is still a general feeling that there is no single, totally applicable design methodology. In this regard the work of Stewart and Filz is very significant (Paper 2), in that it provides solid data on the fundamental load transfer mechanisms as does the work of Alén et al. (Paper 1) and Kitazume et al. (Paper 5). It is not a helpful situation for the industry when proponents have to obtain “individual approvals” for specific projects as our German colleagues were obliged to do (Schwarz and Raithel, Paper 7).
2. Nevertheless, variants of both wet and dry methods are commonly used with great and documented success on a variety of embankment support projects throughout the world. This must reflect technical performance, the cost effectiveness and a high degree of quality control and assurance (e.g., Figure 11 from Paper 7).
3. Developments in technology are affording designers significant opportunities to offer very responsive schemes by being able to provide target DMM properties with good consistency.
4. Otherwise, it is clear that there remains a strong and growing market for deep mixing technologies — appropriately designed, constructed and verified — for construction in and over very soft ground, for both static and dynamic loading conditions.

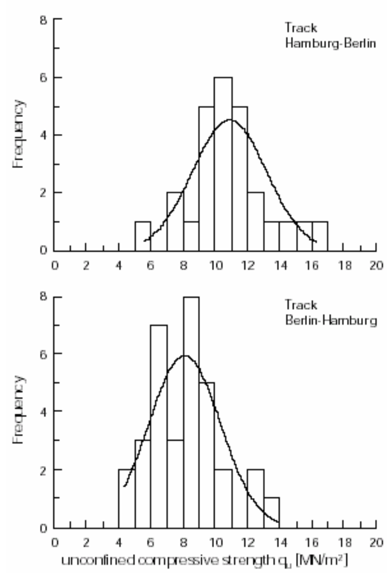


Figure 11. Unconfined compressive strength (Schwarz and Raithel, 2005).

5. There is an increasingly impressive body of information derived from full-scale,

instrumented test sections, as noted in Section 6 of this Report. Given the ever-improving analytical techniques developed by researchers, the onus should be on researchers to monitor, record and document all the site conditions and circumstances as thoroughly as possible so that future generations will have a mine of accurate and comprehensive information into which to delve, and from which to eventually draw definitive conclusions which will permit reliable design methodologies to be properly derived.

6. Jet grouting and deep mixing technologies have the potential to produce similar materials in situ, i.e., "soil-cement," "soilcrete," "treated soil," and so on. However, there appears to be a growing tendency to *equate* this product with the two, distinctly different, technologies which produce them, namely mixing and jet grouting. We should not automatically assume that these two processes do in fact produce the same product, or that the significant differences in the techniques permit us to assume equivalency of performance. Therefore, it is prudent to consider, separately, design rules for deep mixing, and design rules for jet grouting, allowing that there are indeed commonalities in the basic principles and resultant properties.

7. In certain soil types, prewetting of the ground, in advance of dry mix methods, may be necessary, even through conventional wisdom may suggest that there is sufficient moisture content in the soil.

8. The design of deep mixing in dynamic and seismic conditions calls upon extremely sophisticated approaches. However, based on the type of approaches described in Papers 8 (Katzenback and Ittershagen) and 11 (Namikawa et al.) in particular, there is justified confidence that design approaches can be logically optimized.

9. In many cases the significance of "mixing number," or "blade rotation number" has been pointed out in other papers in this conference as a prime contributor to treated soil strength and homogeneity. Designers must pay special attention to this since this critical factor, classically described in Tokyo (1996) should be a fundamental consideration in design, given its ramifications.

10. The increasing popularity of "mass stabilization" techniques merits close attention. Designers must ask whether the results obtained by Mass Stabilization are indeed comparable to those attained by "column" methods and, therefore, if the fundamental design assumptions are equivalent. There seems little doubt that Mass Stabilization is a technique of considerable potential in appropriate conditions. If its growth does truly accelerate, then it is essential that its design basis is solid.

11. Several papers remind us that DMM technologies can usefully employ "industrial waste products." This has been exploited in Finland and Japan, in particular, for years, but nevertheless does provide a most interesting prospect especially in countries (such as China) where DMM technologies have such enormous economic potential.

12. Equally, Paper 9 (Kurisaki et al.) confirms that a goal of DMM treatment is not necessarily to achieve high strength: "When a construction involves excavation of improved ground, or when a construction involves pile or sheet pile driving in the improved ground, the low strength improvement is far superior to the ordinary high strength improvement."

13. In order to properly validate design assumptions, it is essential that material testing protocols (either in the lab or in the field) are standardized. The paper by Jacobsen et al. in this conference notes that the results from two different firms, presented with the same samples, gave a four-fold difference in 28-day strengths (Figure 2). This difference was related to air drying and rewetting of the soil prior to mixing with binder. The same Paper illustrates the potential benefit of "contour plots" (Figure 7) of strength with various binder rates. The companion paper provides added support (and guidance) for the trend to look at statistical analyses of strength data. However, it is a fact of life in deep mixing that typical coefficients of variation of strength are, naturally, high. (Range 0.17 to 0.75.) This is a fundamental design challenge.

14. Although the focus of our studies is primarily technical, the paper by Rydberg and Andersson (2005) illustrates that there is another very important dimension that designers must address — life cycle assessment, to evaluate the environmental impact. It is not unreasonable to assume that such studies will become increasingly common — and relevant — in years to come, especially in "First World" countries.

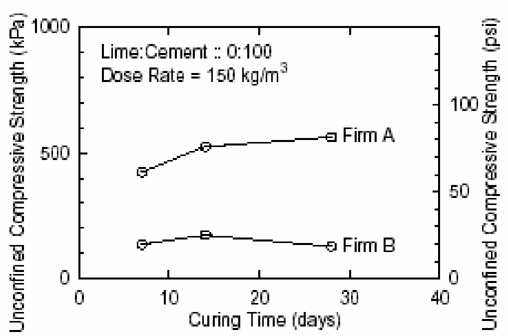


Figure 2. Test Results from Two Different Laboratories, on Nominally Identical Samples (Jacobsen et al. 2005).

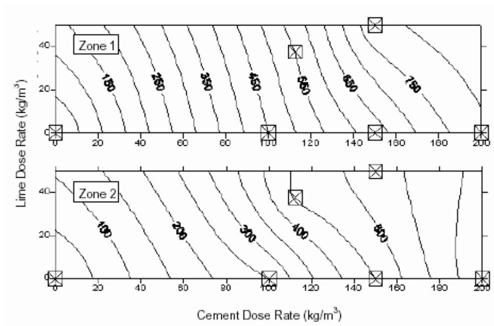


Figure 7. Contour Plots of 28-day Unconfined Compressive Strength (kPa) for State Route 33 (Jacobsen et al. 2005).

15. As always, the discerning reader must distinguish between what has been written, and what actually represents current and viable practice. The papers in this conference provide a classic illustration of opposite ends of the spectrum in terms of what is truly understood, and what is executed as if by rote, but is known to perform in an acceptable fashion. The same reader must also decide which of the techniques or approaches are truly representative of reasonable and sustainable practice, and which are otherwise — namely concepts projected from limited laboratory testing or numerical analyses or techniques applied once in a field test program and later found to be neither technically successful, nor economically viable.

5. APPLICATIONS AND CASES ILLUSTRATING THE TOPIC

A potentially large market exists in the United States for the economical application of deep mixing technology to improve the stability and settlement problems inherent with constructing highway and flood control embankments founded on soft soil. Cali et al. present an example of such an application in their Session 5 paper. Here deep mixing technology was proposed to improve slope stability of a 610 m long Mississippi River flood control levee to be constructed in conjunction with a proposed new ship lock, Figure 8. Other projects planned by the U.S. Army Corps of Engineers include construction of 255 km of new flood control levees in coastal Louisiana. These embankments would be built predominantly in marsh environment, where the foundation conditions consist of soft organic clay and peat. Conventional construction methods require multi-lift earthwork placement, allowing long intervals for foundation consolidation to occur. As well as being expensive, this method requires more borrow material for construction of stability berms, further damaging the fragile coastal marsh environment, and delays the protection against hurricane flooding.

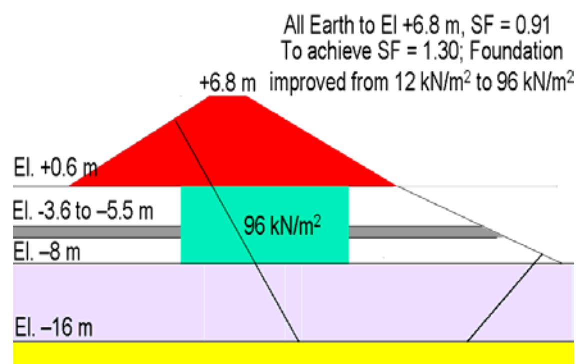


Figure 8. Using DM for flood control levee construction in coastal Louisiana, USA (Cali et al., 2005)

Similarly a comprehensive study is being undertaken in the Netherlands to assess the possible application of deep mixing to improve the stability of Dutch river dikes, as shown in Figure 9 from the paper by Wiggers and Parzon (2005).

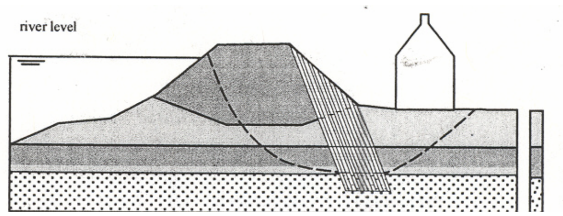


Figure 9. Mixed-in-Place Dike Improvement (Wiggers and Perzon, 2005)

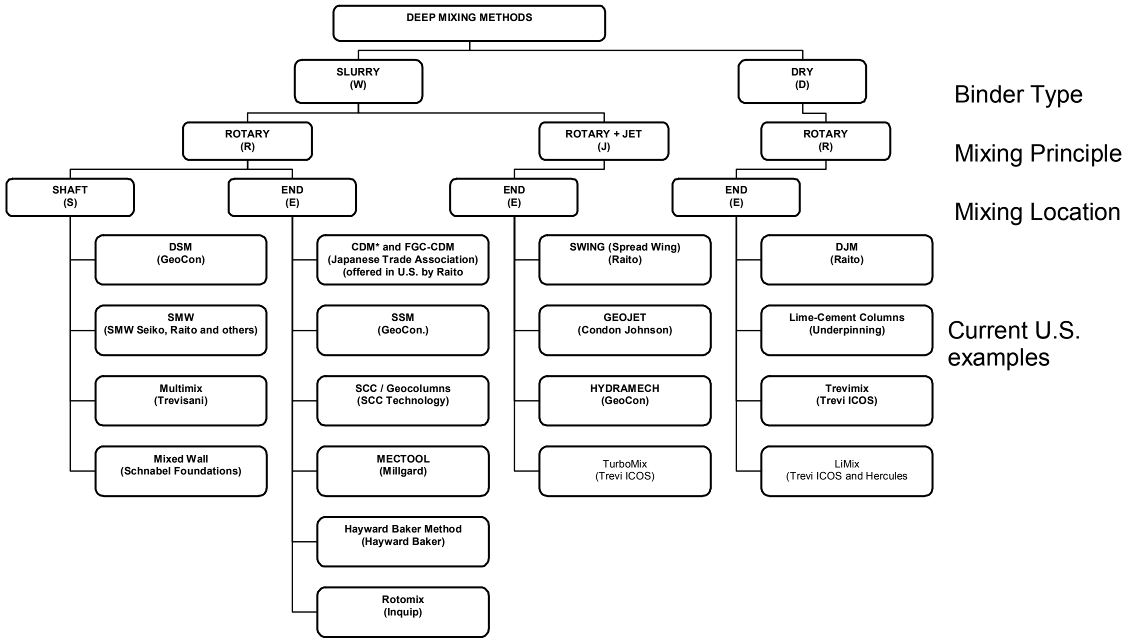
6. DIVERSITY AND LIMITATIONS IN RELATION TO GEOLOGY, EQUIPMENT AND TRADITION

As documented in other sessions of this conference, developments continue to be made in aspects of Deep Mixing relating to equipment, materials and processes. However, it is fair to say that these developments typically represent incremental improvements on well-established principles observed in distinct regions. So, for example, technological modifications to the dry DMM market in Nordic countries revolve around the use of new "binder" material, or the concept of prewetting in countries such as the U.S. where Nordic practices are being introduced in less than ideal or typical soil conditions. Japanese developments explore the combination of jet grouting and traditional DMM methods, or seek to modify practice to minimize movement of adjacent soil masses or structures. Chinese developments appear to be focused on optimizing the effectiveness of productivity of older Japanese origin systems, and on accelerated construction processes. In all cases, strong emphasis continues to be placed on QA/QC aspects and, for example in the U.S., on developing statistically-based acceptable strength criteria.

Nevertheless, it would still seem that design methodologies lag behind these other more practical aspects: this weakness is deterring the growth of DMM techniques in certain countries, especially in Western Europe and North America as noted by Druss and Yang (2005). The more recent advances in design methodology, as illustrated by the papers of this session, are described elsewhere in this Report. The following table summarizes key factors relating to diversity and limitations as reflected in the papers.

PAPER	SOIL TYPE	DM* METHOD	COUNTRY OF EXECUTION	COUNTRY OF TECHNICAL INFLUENCE	NOTES
1	Soft clay	DRE	Sweden	Sweden	New mathematical model
2	Soft clay; mc varied 40-150%	DRE	U.S.A.	Sweden	Numerical analyses
3	Soft clay; mc = 70-80%	DRE	Sweden	Sweden	Four test embankments
4	Soft clay	DRE	U.S.A.	Japan and Nordic	Numerical analysis
5	Very soft clay	DRE	Japan	Japan	Centrifuge testing
6	Soft clay; mc = 43% for centrifuge	DRE	Japan	Japan	Centrifuge testing and field instrumentation
7	Very soft organic clays; mc = 80-330%, organic contents 25-80%	DRE	Germany	Germany	Field instrumentation
8	Soft organic clay	DRE	Germany	Sweden	Field tests
9 and 10	Soft clay; mc = 127%	WRE	Japan	Japan	Numerical analyses and centrifuge
11	Liquefiable soils	WRE	Japan	Japan	Numerical analyses
12	Loose sand	WRS/ WRE	U.S.A.	Japan	Parametric study

* Refers to the classification of FHWA (2000) below.



The following observations are offered:

1. Fundamental research, in the form of numerical analyses, centrifuge testing, laboratory (model) testing and full-scale field testing, is focusing on very soft cohesive soils, often with high organic contents. This very simply and clearly reflects areas of design deficiencies. Perhaps most impact, as measured by the value of the results, appears to be made by centrifuge testing and by full-scale field tests and instrumented sections.
2. Whereas DRE techniques for use in these soft clays (e.g., Lime Cement Columns or DJM) predominate in Asia and the Nordic countries, developments by French and German contractors seem to be focusing on wet methods (e.g., Colmix, MIP).
3. Activity remains high in those countries reflecting the traditional origins of the technology namely Japan and the Nordic countries, and in those countries most influenced by these practices for almost two decades (e.g., U.S.A., China). Expansion of DMM into other countries seems to depend on the efforts of entrepreneurial contractors, exporting traditional methods into classic applications, e.g., Nordic DRE into Malaysia, Holland, Vietnam, United Kingdom; European WRE or WRS into Australasia.
4. Predictably, the technology leaders in terms of understanding basic principles, leading to rational design approaches are:
   - Column-supported embankments: Nordic countries, Holland, U.S.A.
   - Seismic applications: Japan.
   - Dynamic loading: Japan and Germany.
   - Block stabilization: Nordic countries and Japan.
   - Properties: U.S.A., Nordic countries, Japan.
5. Mass stabilization techniques as practiced in Finland and Sweden, represent a relatively new arm of DMM, and are attracting considerable investigation. This trend will continue given the economic benefits of the concept.

7. BEST PRACTICE RECOMMENDATIONS

It would seem that despite the rapidly increasing quantity and quality of technical papers dealing with design related aspects of DMM, there are still issues which are not completely resolved. However, in the authors' opinion, there is much that can truly be considered recommended practice, including:

1. Design protocols for column supported embankments, with and without the use of geogrid reinforcement. Excellent research detailed in this conference can be used to support older papers, especially by Nordic

practitioners, and published guidelines such as those produced by the Euro soil stab program, and CEN.

2. Similarly the design of support of heavy structures (e.g., harbor walls) is greatly advanced by the efforts of Japanese researchers and Japanese public agencies.
3. Seismic and dynamic design remains extremely complex, but appears to be most effectively addressed by the Japanese school, and by European researchers involved in high speed rail projects.
4. Several papers illustrate the value of results from full-scale field tests and instrumented test sections. These papers also provide clear guidance on the planning and execution of such tests. The fact remains, however, that schedule and economic restraints often prevent a full engineering analysis being conducted from the mass of information generated by such tests. The authors recommend that academic researchers be encouraged to focus future studies on these full-scale tests, as opposed to on numerical or lab-scale tests (useful so they may be). This will require closer and more pragmatic collaboration between the various parties and an end to the reluctance by certain owners or contractors to make the test data available.
5. Many disputes in DMM projects revolve around the issue of the actual in situ strength achieved, and its variability. This issue is addressed in other sessions. However, it does have a fundamental influence on design assumptions and approaches. Certain papers in this session clearly illustrate what, for many practitioners outside of Japan and the Nordic countries, has become regular and routine, namely the use of filtered statistical analyses of strength data. It is also necessary to observe standardized laboratory and field testing protocols.

8. FUTURE NEEDS IN RESEARCH AND DEVELOPMENT

A field as diverse as deep mixing has many research and development needs. Sharing of knowledge and experience by the deep mixing community of practice in conferences such as Deep Mixing '05 brings to focus the commonality of design issues. The number of papers that are prefaced by a welcome review of theoretical behavior, failure mode, and load transfer exposes a need among practitioners for a better understanding of the basic physics of soil-column interaction and practical design methodology. Concise, comprehensive design manuals are needed. More projects should be instrumented and the data disseminated as widely as possible for analysis or discussion by the community of practice. There is always a need for more reliable quality assurance and quality control testing methods. Column uniformity and strength are recurring topics of concern among the papers presented at this conference. High quality, reproducible testing instills confidence among project designers and planners, who in turn recommend wider adoption of innovative construction methods.

9. CONCLUSIONS

Much can be learned from careful study of the twelve excellent papers in Session 3. However, sessions should not be regarded as independent since the papers from all six sessions are ultimately interrelated. Conferences such as Deep Mixing '05 bring together the deep mixing community of practice in their common interest in the same way that the body of literature that comprises the proceedings ties together the common principles of ground improvement.

This session also reminds us not only of the vast amount of information on DMM design currently available, but also the rate at which it has grown since the DMM conferences of 1996 and 1999. In the late 1990s it was a feasible task to contemplate a "state of practice" review (e.g., FHWA, 2000) that could be both comprehensive and contemporary. Today, there is no way that such a study could satisfy either criterion. This is very healthy for the industry, and clearly illustrates that DMM, although well established as a ground improvement and treatment technique of choice internationally, is still growing, vigorous and evolving.

10. ACKNOWLEDGEMENTS

The authors wish to thank the Deep Mixing '05 organizing committee for the opportunity to present this report. Also, the U.S. Army Corps of Engineers and Geosystems, L.P. are gratefully acknowledged as contributors of both time and funds for the report preparation and presentation.

11. ADDITIONAL REFERENCES AND BIBLIOGRAPHY

Cali, P., M. Woodward, and D.A. Bruce (2005). "Levee Stability for Deep Mixing (2) – Conclusions from Test Section Using Dry Mixed

Soil Columns." Proceedings of International Conference on Deep Mixing Best Practice and Recent Advances, Stockholm, Sweden.

Carlsten, P. (2000). Hand book for lime and lime/cement columns (Kalk- och kalkcementpelare, Vägledning för projektering, utförande och kontroll), SGF /Rapport 2:2000, Linköping, (in Swedish).

Coastal Development Institute of Technology (CDIT). (2002). "The Deep Mixing Method: Principle, Design and Construction," A.A. Balkema: The Netherlands.

Deep Mixing Workshop. (2002). The International Workshop of Deep Mixing, Edited by Masaki Kitazume and Masaaki Terashi, Tokyo, Japan, October 15-18.

Druss, D. and D. Yang. (2005). "Challenges of Employing Deep Mixing Methods in the US," Proceedings of International Conference on Deep Mixing Best Practice and Recent Advances, Stockholm, Sweden.

EuroSoilStab (2002). "Development of design and construction methods to stabilise soft organic soils," Design Guide Soft Soil Stabilization, CT97-0351, Project No.: BE 96-3177.

Federal Highway Administration. (2000). "An introduction to the deep mixing method as used in geotechnical applications." Document No. FHWA-RD-99-138, March, 143 p.; "Supplemental reference appendices for an introduction to the deep mixing method as used in geotechnical applications." Document No. FHWA-RD-99-144, 295 p.; and "An introduction to the deep mixing method as used in geotechnical applications: Verification and properties of treated soil." Document No. FHWA-RD-99-167, 434 p. Prepared by Geosystems, L.P.

Grouting and Deep Mixing Conference. (1996). The Second International Conference on Ground Improvement Geosystems, Edited by Ryozo Yonekura, Masaaki Terashi and Mitsuhiro Shibazaki, Tokyo, Japan, May 14-17.

Grouting and Ground Treatment. (2003). Proceedings of the Third International Conference, Geotechnical Special Publication No. 120. Edited by L.F. Johnsen, D.A. Bruce, and M.J. Byle, American Society of Civil Engineers, New Orleans, LA, February 10-12.

Hansbo, S. and K. R. Massarsch (2005). "Standardisation of Deep Mixing Methods," Proceedings of International Conference on Deep Mixing Best Practice and Recent Advances, Stockholm, Sweden.

International Conference on Dry Deep Mix Methods for Deep Soil Stabilization. (1999). Edited by H. Bredenberg, G. Holm, and B. Broms, Stockholm, Sweden, October 13-15.

Jacobson, J., G. Filz, and J. Mitchell. (2005). "Factors Affecting Strength of Lime-Cement Columns Based on a Laboratory Study of Three Organic Soils." Proceedings of International Conference on Deep Mixing Best Practice and Recent Advances, Stockholm, Sweden.

Public Work Research Center. (1999). "Design and construction manual on deep mixing method for inland construction," 326 p, (in Japanese).

Rydberg, T.V. and R. Andersson. (2005). "Environmental effect assessment (LCA) for soil stabilization," Proceedings of International Conference on Deep Mixing Best Practice and Recent Advances, Stockholm, Sweden.

SGF. (1997). "Lime and Lime Cement Columns – Guide for planning, construction and inspection." SGF Report 4:95E, Swedish Geotechnical Society, SGI (ed.). Linköping.

Shiomi, T., Y. Shigeno, and O.C. Zienkiewicz. (1993). Numerical Prediction for Model No. 1 Arulanandan and Scott (ed.) Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems, Blakema, 213-219.

Terashi M., M. Kitazume and T. Nakamura. (1988). External forces acting on a stiff soil mass improved by DMM, Report of the Port and Harbour Research Institute, 27(2): 147-184 (in Japanese).

Terashi, M. (2002). "Long-term Strength Gain vs. Deterioration of Soils Treated by Lime and Cement." Proceedings of Deep Mixing Workshop, The International Workshop of Deep Mixing, Edited by Masaki Kitazume and Masaaki Terashi, Toyko, Japan, October 15-18, pp. 39-57.