THE RETURN OF DEEP SOIL MIXING

Deep soil mixing, a technique originally developed in the U.S., is making a comeback here, thanks to mechanical improvements made in Japan.

DONALD A. BRUCE

Deep mixing was a main focus at the Second International Conference on Ground Improvement Geosystems in Tokyo earlier this year. Well over half of the 140 papers presented at the conference, organized by the Japanese Geotechnical Society and the Technical Committee 17 (Ground Improvement, Reinforcement and Grouting) of the International Society for Soil Mechanics and Foundation Engineering, dealt with the subject, which accurately reflects the growing importance of this technology in Japan. The technology was used in recent projects such as the Trans-Tokyo Bay Highway megaproject and at the Kansai Airport.

In light of the rapid growth in the use of this technology in the U.S. for projects such as the Boston Central Artery, it is timely to reflect on the nature of this technology, its roots and its potential.

HISTORICAL PERSPECTIVE

According to the Federal Highway Administration, the first ground-treatment technique using mechanical equipment to mix cementitious materials with in-situ soil was the mixed-in-place piling technique. The procedure was developed in 1956 by the now-defunct Intrusion Prepakt Co. The method featured the use of a square, hollow shaft that was tipped with a mixing head. Grout was injected as the shaft was rotated to full depth and then extracted. The patented system was used for cutoffs beneath dams and retaining walls in more than 30 projects in the U.S., principally in fine gravels and sands. Wider acceptance occurred in Japan, however, and in 1961 alone, over 300,000 linear meters. of these piles were installed under license, mainly for cutoff walls for revetments.

Soon thereafter, the Port and Harbor Research Institute of the Ministry of Transport further developed the technology, using granular or powdered lime as a stabilizing agent. The technique was named the deep lime mixing (DLM) method. The method was brought into practice throughout Southeast Asia in 1974 using granular quick lime and was ideal for stabilizing soft, cohesive soils. Also in 1974, two papers on deep mixing—one on the Swedish lime column and the other on the Japanese DLM method—were presented at a conference in India. It was recognized at this point that the two countries had progressed independently along similar lines. A technical exchange subsequently occurred.

By 1980, the Japanese Ministry of Construction had developed the dry jet mixing (DJM) method, which superseded the original DLM system in Japan. DJM is used with powdered cement or lime, and is used

The two augers of this deep-mixing machine are guided by a vertical steel lead on a track-mounted base.

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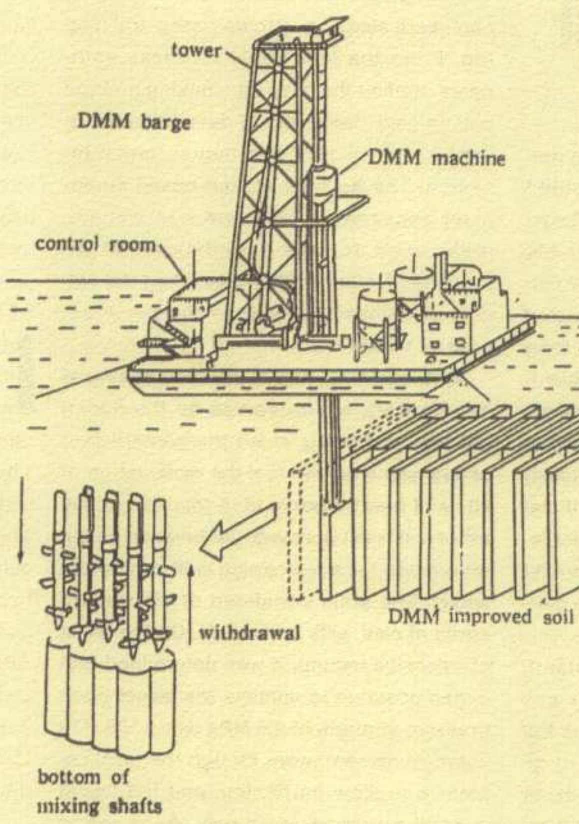
Above: Engineers get a closeup of a mixing tool. Below: The concept of deep mixing for marine works.



only for projects on land.

During this period, research also had continued with grout-injection deep-mixing methods, and the development of a wide variety of variants on the same principle (as discussed later) occurred. All of these techniques belong to the cement deep mixing (CDM) family.

Although these CDM techniques became widely accepted in Southeast Asia, they did not regain general acceptance in the U.S. for many years because they were not perceived as being cost-effective. However, the mechanical improvements made in Japan increased productivity and the ability to treat more difficult soils. By 1986, "modern" CDM had been reintroduced into the U.S. and was being used in 1987 by a Japanese–U.S. joint venture for a massive liquefaction mitigation application at Jackson Lake Dam, Wyo. Several smaller case histories followed prior to the work in 1992–94 for the cut-and-cover support for the Ted Williams Tunnel that is part of the Central Artery in Boston. Even this project has now been matched for scale by a similar work done for the Cypress Freeway in Oakland, Calif., and will be dwarfed by the ground-treatment requirements using similar techniques at Fort Point Channel in Boston, also part of the Central Artery project.

Research continues into understanding the engineering properties of treated soil, the factors affecting lime and cement reactivity with the soil- nd the concepts for evaluating the s of treated ground. At the same tin actors continue to research new methods for improving productivity and quality—typically by combining the power of both jet grouting and mechanical mixing. Current examples include the Japanese JACSMAN (jet and churning system management) and the similar U.S. GeoJet system currently being developed by Kulchin-Condon and Associates, San Francisco.

CHARACTERISTICS AND CONSTRUCTION

Contemporary deep mixing uses large-diameter, hollow-stem, discontinuous flight augers to penetrate soils and to intimately mix them with materials introduced during penetration and extraction. The result is an engineered material comprising various proportions of the native soil and the injected material. The injected material may be in the form of a cement-based grout or dry cement/ lime.

In Japan, the former method, CDM, is widely applied to marine works (see figure at left) as well as land sites, and the latter method, DJM, can be used only on land sites.

The equipment includes a soil-mixing machine as the drilling/mixing unit and a mixing plant as the slurry preparation and flow-control unit. The soil-mixing machine carries augers guided by a vertical steel lead on a track-mounted base machine. The base machine and the lead are supported at three points during operation for maintaining accurate vertical alignment. This is critical to eliminate unmixed zones between columns and maintain the continuity of the treatment. A typical soil-mixing machine consists of an electric-drive auger machine, a multiple-axis gearbox, two shaft-joint bands, three auger shafts and auger heads. The multiple-axis gearbox distributes the torque from the auger machine to each auger shaft for drilling and mixing. It is capable of concentrating all drilling power to one single shaft for especially hard drilling. Each auger shaft is equipped with discontinuous auger flights and mixing paddles. The discontinuous auger flight is designed to provide a degree of vertical displacement for soil mixing, but to prevent the direct transporting of soil to the surface.

The design of the auger flights and mixing paddles on each auger shaft varies with soil type. The auger design can be tailored to meet specific project conditions. The auger flights and mixing paddles on adjoining shafts overlap at different elevations to produce overlapped soil-cement columns after mixing. The shaft-joint bands maintain the space between auger shafts and adjoining shafts as a rigid body to accurately produce one overlapped column panel with a single stroke.

The mixing plant consists of a grout mixer, grout agitator, automatic batching scales, grout pumps and a computer for mixing and grout-flow control. The automated batching system measures the water, cement and other additives by weight to produce grout of a better consistency than a volumetric batch system. The desired weight of each mix component can be entered at a control panel, and the mix design change can be made by simply adjusting the component weights at the control panel. A separate positive displacement pump supplies the grout to each of the injecting augers for accurate control of grout-injection volume.

Auger diameter varies from 0.70 to 1.5 m (land) and 1–2 m (marine). Deep mixing has been used to depths of over 61 m, although 40 m is a typical maximum for land works. Operational parameters depend greatly on the site conditions, but penetration rates of 0.5–1.0 m/min are common, followed by 2–8 min mixing and then 1 m/min during withdrawal. Rotational speeds of 20–60 rpm are typical, but lower during penetration than during withdrawal. The drilling rigs carry one to three augers per rig for land works and two to eight for marine works.

When using the CDM method, mix design must address both the grout and soil/grout mix ratio, among other criteria. A portland cement grout is most commonly used, with bentonite added for increased workability and stability. Other materials such as slag cements and gypsum are used in saline or organic conditions, or for stabilizing soils containing pollutants. Water/cement ratios typically vary from 0.6 to 1.3 (by weight), with 1.0 being the most popular choice (especially in cohesive materials). For the typical range of treated soil strengths (0.5–3.0 MPa), cement contents usually vary from 100 to 300 kg/m^3 of in-situ treated soil.

CASE STUDIES OF DEEP MIXING

A collaboration of some of Japan's major foundation contractors decided that construction of the Trans-Tokyo Bay Highway project would be feasible only through deep mixing; a total of 1.8 million m^3 of in-situ treatment was completed for the project in 1994. The 15.1 km long highway comprises two 9.5 km long shield-driven tunnels and a 4.4 km long bridge. The tunnels start from an embankment at Okishima Access on the west (Kawasaki) side, pass through the Kawasaki artificial island and end at the Kisarazu artificial island. Along the route, the water is about 30 m deep, and the seabed materials are generally poor.

At the Kawasaki man-made island, 132,200 m^3 of ordinary deep mixing was conducted in the soft clays around the lower part of a diaphragm wall, 98 m in diameter and 119 m deep. Soft deep mixing was used to treat an additional 168,000 m^3 of Holocene clay, through which the 13.9 m diameter tunnels were then excavated. The cement content of under 0.7 N/m^3 was half that used for the ordinary treatment.

This soft treatment was also used for a 620 m length of 1.25 million m^3 in volume at the Okishima embankment. The target compressive strength was around 2 MPa. A further 289,000 m^3 of similar treatment was provided at Kisarazu artificial island in order to improve soft clay in buried valleys beneath the fill, facilitating the safe advance of the shield tunnels.

In a ground-treatment project in China, engineers also chose to use deep-soil mixing. From the late 1960s, Chinese engineers studied the deep lime mixing method and cement deep mixing developments in Japan, and by 1977 had begun formal research. The first set of land-based equipment appeared in 1978 and was immediately used for the foundations of an industrial facility at Shanghai. The total volume of Chinese soil treated since is in excess of 1 million m^3.

Between 1987 and 1990, deep mixing at Tianjin Port, which serves as the ocean gateway of Beijing, aided the construction of two new wharves and the reclamation of 60 ha of new harbor land. A total of 513,000 m^3 of soil was improved, underwater, as the foundation for a restraining wall behind the wharf. The soils consisted of alternating strata of clay, silts and sands. On the basis of intensive testing, it was determined that it was possible to achieve the target compressive strength of 2.5 MPa using 150–170 kg/m^3 of cement, even though the local cement was slow hardening, and the target strengths were achieved only after a period of 60 days. Subsequent monitoring of the performance of the structure built on the deep mixed soil mass has, however, confirmed it to be an extremely well chosen technique.

By 1992, a collaboration with Japan had given birth to the first cement deep mixing fleet and, for a recent small harbor development at Yantai Port, a total of 60,000 m^3 of offshore treatment was designed and executed independently by Chinese engineers.

See also "Boston Blockbuster" in this issue, page 40.

STATE OF THE INDUSTRY

In Japan, there are two major trade groups involved in deep mixing. The CDM group was established in 1977, and their output more than doubled between 1987 and 1993. They represent as many as 50 contractors, and there are about 10 dominant members. The less powerful DJM group, which saw its output drop by half between 1987 and 1989, has less than half that number of contractors and is dominated by three large companies. Although the Japanese specialty geotechnical construction market is, at best, flat, it remains two or three times the size of the U.S. market. At least 55% of the total expenditure involves deep mixing of some type.

In addition to the execution of major harbor works in new overseas markets, especially in the People's Republic of China, the main growth potential for these companies is—post Hanshin—in the treatment of sandy and gravelly soils for liquefaction mitigation. Close behind, however, is the use of deep mixing in environmental applications—a sector that U.S. practitioners seem to have taken the lead using both deep and shallow (but larger-diameter) systems. ▼

Donald A. Bruce, M.ASCE, is principal of ECO Geosystems, Inc., Venetia, Pa.