of the open hole. Essentially, you get control over the final material. There is less control in soil mixing, and it’s very dependent on in-situ conditions. These factors make it difficult to rely solely upon installation parameters, quality control (QC) and verification tests. At some point, you may need to apply some engineering judgment.

Start at the Beginning

The availability of sufficient and accurate geotechnical data (soil type, heterogeneity, shear strength parameters, variability, etc.) is important in establishing the material that will be drilled. This data will also help in determining the proper mix design to achieve the desired soil cement properties. Many factors must be considered when designing the mix and the mixing program, including any debris in the ground, different soil properties and varying moisture contents.

Each of the various factors affect the final properties of the soil cement, so it really takes careful planning and evaluation of the mix design through iterations by looking at the soil types and adjusting the mixes. Clay is going to behave very differently than sand in both mixing efficiency and final properties. That is, the presence of clays results in more difficulty in achieving higher strengths and to physically mix the soil and the binder, whereas the presence of sands results in more difficulty controlling the final permeability.

It all starts at the preproduction stage. It is necessary to develop some anticipated mix designs based on previous experience, the soil types and required parameters (e.g.,
Cored soil cement (photo courtesy of Malcolm Drilling)

strength and/or permeability). When developing a mix design, one must carefully evaluate the specifications and determine what are the requirements for permeability, strength, etc. This is where experience matters — past knowledge of how those materials should behave when mixing. These factors will produce the basis for design mixes, and should be based, when possible, on representative soil samples and groundwater from the jobsite. Then, the mix design should be determined for the worst-case soil conditions. That is, if permeability is the key parameter, look at the sand and gravel layers more than the clay layers; however, if strength is the key parameter, look at the clay layers more than the sand and gravel layers. For the preliminary mix, it is essential to evaluate a number of trial batches in the lab to establish a range of mix variables that can be implemented in the field.

**Test Program**

After choosing preliminary mixes, it is important to evaluate those mix designs onsite in test sections in the actual field conditions where the production work will be performed. Each mix design is programmed into the batching system and the test section is constructed using the means and methods expected for the production work. On occasion, a full-scale test program is not possible due to a number of reasons, including time constraints or that the job is so small that it doesn’t warrant waiting for results of a test program. In the event of no test sections, it is justifiable to proceed using a more conservative mix design, with the understanding that the mix design may need to change based on actual conditions encountered during mixing. However, a lot of information can be garnered from a formal test program, where the mix design can be optimized based on those test results.

**During the Soil Mixing Operation**

On site, the entire operation from the batch plant through the drilling system should be monitored. Secondary checks can be handled with conventional methods, such as a mud balance (a density measurement) to ensure the computer is accurate. Through the interaction between and innovation of contractors and manufacturers/suppliers, the industry has developed very accurate computer controls for soil mixing operations. In the early stages of the technology (e.g., at Jackson Lake Dam), it was sufficient to report how much cement was used during the day and how deep the columns were drilled; end of report. Now, computer controls can produce amazing amounts of data about the drilling parameters, grout mix, grout flow, etc. The installation is somewhat operator dependent, where the operator controls drilling speeds and rotation rates, but limits are established within the test program or by the calculation of mixing efficiency, which is based on the soil type and mix design.

The onboard computer system can monitor drilling variables to maintain the mixing energy necessary to produce, at least, the minimum required parameters. The type of mixing energy varies among equipment, blade rotation numbers or energy index. However, the computer algorithms evaluate the rotation speed and the amount of energy being supplied into the column, which, combined with the drilling speed, ensure a good, thorough blend of the materials is being created. The key principle is to ensure there are sufficient revolutions of the blades to ensure thorough mixing. These drilling para-

Core drilling operation (photo courtesy of Condon Johnson)
Coring is a common requirement to evaluate the efficiency of the soil mixing, and it provides a visual means to assess how thoroughly the mixing was accomplished. Yet, coring has its difficulties, especially with obtaining intact cores. One of the biggest difficulties to overcome is the quality of the recovered cores from a soil cement matrix. Since most soil mixing applications target strengths less than about 200 psi (1,380 kPa), coring this low strength material can be problematic, which is especially true in material with course in-situ material, such as gravels or debris from random fills. These larger particles and debris can come loose during the coring process and can destroy the soil cement matrix.

**Verification and Evaluation**

After installation, the verification process begins. The type of tests and the extent of these tests, which correlate back to the level of confidence in the installation process, can substantially affect project costs and time. Wet sampling during the production process, coring after the fact, compression load testing or permeability testing all provide a means to evaluate the possibility of when things did not go perfectly. As a secondary or a double check of the sampling results or the coring, other tests such as video logging and in-situ permeability have been also incorporated into a project.

Video logging was introduced to offset the predicament of disturbance to the soil cement matrix evidenced in the recovered core. After coring, it is possible to take a video of the core hole and to determine if the results (core and video) indicate a simply bad core or a poor mixing job. Video logging was meant as a check to verify mixing for problematic cores; unfortunately, it has turned into an added verification test that is now used to evaluate the mixing regardless of the quality of the core, which ultimately leads to another set of tests required.

**Engineering Judgment**

Verification testing can be as much as 20% to 25% of the total cost of the project, which may seem excessive considering all of the computer-controlled monitoring used to show that the installations were performed consistently and repeatedly. This is where the engineer and owner need to apply engineering judgment to the process. For instance, video logging was an attempt to add a secondary check to determine whether it was a bad core or an improper mixing job, and then to use visual observation to make an engineering judgment.

There have been other ideas proposed that facilitate the use and justification of engineering judgment for acceptance of the work, including the use of a 10-point moving average to evaluate the significance of a few poor test results and their impact on the overall project. As an example, during the evaluation of stability along a potential failure plane, it is most critical to use the shear strength in the area around the failure plane than it is to include the test results from an upper fill zone that is well above this failure plane. Furthermore, it has been well established that soil cement increases in strength over very long periods, and this understanding can be used to alleviate concerns over borderline
results of shear strength during early portion of the life of the soil cement.

Many times, the owner and engineer understand that the material is acceptable, yet they are concerned that an oversight agency will not accept the judgment made. Perhaps, there should be additional dialog up front about what happens if test results are not consistent and then how to evaluate the final product. The mixed material will never be completely ‘homogeneous’ unless the in-situ soils were homogeneous from the onset. Ultimately, the desire of a soil mixing operation is to provide a good, thorough blend of in-situ materials and binder material.

Each of the items discussed above, in addition to others, would allow the client flexibility to apply engineering judgment to the results and to ‘put it all out there on the table’ using the drilling records, cores, videos and evaluation of the results. If there is difficulty coming to a consensus whether it is an acceptable project, one should look at the work globally, in that, if 90% of the QC boxes are checked, the work is likely adequate for its proposed function. However, if there was no quality control, no care in the blending, no control over rotation/drilling speed and no grout control, then it will be quite difficult to be able to convince an owner or engineer that what’s in the ground is acceptable. That is, it will be difficult to convince someone of the quality unless the installed work is excavated and exposed, which is not practical or financially prudent.

**Conclusion**

A QC program is an extremely beneficial tool, which has been enhanced using a computerized operation system, and has brought about a better understanding of the results. With the available tools and methods, real data is obtained to verify that the installation of each element was performed consistently and in similar manner compared to the test program. Soil mixing is an extremely valuable, useful technology that can enable infrastructure to be placed atop some of the least favorable ground conditions. It has been proven that soil mixing has reliable strength gain over time while minimally affecting the environment. In sum, soil mixing can be priced reasonably and competitively if the work is monitored carefully, has a reasonable QC protocol and verification requirements, and can apply engineering judgment where necessary.

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