Testing at hazardous waste sites has cost billions and produced reams of data, but provided little cleanup.

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HAZARDOUS DATA EXPLOSION

During the 1980s, the public's growing demand for a cleaner environment combined with stricter government regulations has spawned the huge hazardous waste management industry while opening a Pandora's box for civil, geotechnical and geological engineers. Although billions of dollars have been spent, few hazardous waste sites have actually been cleaned up. Instead, engineers have been hamstrung by both their work environment and the dizzying amount of data that result from hazardous waste site characterization.

At waste sites, engineers work under radically different conditions than their counterparts in older, more established businesses. The hazardous waste industry is a virtual infant, lacking the set of standard practices that evolve over years of experience. Because of the multidisciplinary nature of the work, experts from outside fields, including chemistry, toxicology, biology, hydrology, hydrogeology and computer modeling, often work as equal partners with engineers. Further, since the industry is heavily regulated, agency officials as well as attorneys often play a prominent role in determining site investigation programs and remedial actions. Even when they do assume a major role, engineers often must choose the safest course (i.e., the one that would be easiest to defend in court) rather than the most cost-effective or technically appropriate.

Yet the most distinctive feature of the hazardous waste industry is the change in the site characterization process, a common element of traditional geotechnical and geological investigations. Generally, whenever a dam, highrise building or other major construction project is planned, soil borings are drilled in the area of the proposed construction. Samples recovered from the borings are used to generate geological profiles of the site, and some are also tested for such properties as shear strength, density, water content and Atterberg Limits. The information is then used when designing the structure.

Site characterization is also an important component of remedial investigations at hazardous waste sites. Not only is information gathered about site geology and soil properties, but also about the nature and extent of contamination. Data are then used in developing a cleanup plan and designing an appropriate remedy.

How has the critical site characterization process evolved, and more importantly, how can the process be improved so that more rapid, effective and economical cleanups are achieved?

THE GOOD OLD DAYS

Classical geotechnical site characterization, based on the observation method, has been immensely successful on projects ranging from the construction of offshore oil platforms to nuclear powerplants. Ralph B. Peck, the father of the observation method, best defined its six steps back in 1969:

- Conduct an investigation of sufficient scope to establish the general characteristics of a site.
- Assess the most probable conditions and the deviations from them.
- Develop a design based on the most probable conditions.
- Determine what courses of action should be taken if the conditions deviate from predictions.
- Measure and evaluate actual conditions during construction.
- Modify the design, as needed, to suit actual conditions.

What's crucial about the observation method is that engineers do not try to eliminate all the uncertainties of subsurface analysis. Since there can never really be enough data and analysis, the scope of the investigative phase is limited to characterizing the most

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likely set of conditions as well as any reasonable deviations. But this doesn't end the process.

Abundant opportunities to collect data and assess conditions also exist during construction. As materials are excavated or other subsurface work is performed, tests are run to verify that the design criteria are being satisfied. Ongoing feedback reduces the possibility that the completed structure will fail due to an inaccurate characterization of subsurface conditions.

TESTS AND MORE TESTS

With the growth of the hazardous waste industry, the site characterization process has become more complex. The tendency now is to study sites nearly endlessly in the hope of limiting uncertainty. This "study to death" syndrome is propelled both by attorneys, who want to minimize the possibility of a lawsuit if a site is improperly characterized or a cleanup program is ineffective, and regulatory agencies, which would rather request another study than commit to a particular solution. Considering the litigious nature of our society, and the public's perceived unwillingness to accept some risk when it comes to cleanup action, these stances are understandable.

Standard geotechnical and geological techniques are not sufficient to characterize subsurface conditions at hazardous waste sites. In addition to geotechnical testing, ground water, surface water, sediment, soil and/or waste samples must be chemically analyzed to assess the extent of contamination.

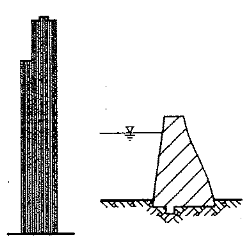
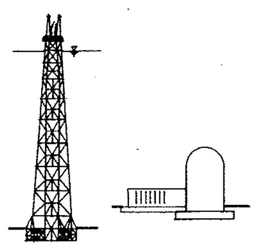
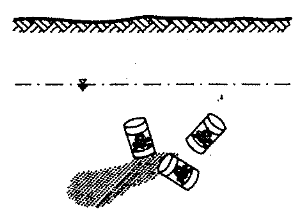
The number of parameters for which samples are tested varies from site to site and can be as high as several hundred. EPA's list of priority pollutants, for example, contains 127 parameters. Another common grouping, the Appendix IX Ground Water Monitoring List, contains 228 metals and organic compounds. EPA and other government agencies, though, have had little time to ascertain which of the thousands of manufactured chemicals and their by-products pose the greatest risk to the public health and the environment. As toxicological and epidemiological studies continue, it's a foregone conclusion that the number of lists and chemicals on each list will increase in the coming years.

The cleanup of the 27 sq mi U.S. Army Rocky Mountain arsenal near Denver—one of the largest ongoing hazardous waste projects in the nation—is a striking example of the data explosion in action (Fig. 1).

About 3,400 soil borings and 1,600 monitoring wells have been drilled at the Rocky Mountain arsenal site for the purpose of site characterization. This many borings and wells would seem sufficient to assess the conditions at the site and devise a cleanup plan. However, additional investigations are under way or in the planning stages to gather more data on the contaminant levels. Assuming that:

- 10 samples are obtained from each soil boring;
- one ground water sample is collected from each well;
- each soil sample is tested for five geotechnical properties (samples are generally tested for 3–5 properties);
- and each soil and and water sample is tested for 125 chemical parameters, a staggering total of 2.5 million data points were generated during the initial round of

FIGURE 1.
THE EVOLUTION IN SITE CHARACTERIZATION: 1960–90.

	1960s		1970s		1980s		1990s
	High rise buildings large dams infrastructure		Offshore platforms Nuclear powerplants		Hazardous waste sites		
							
Approximate number of soil borings required for subsurface characterization	5–10	20–50	1–10	50–100	Panoche facility ~400	Rocky Mountain arsenal 1,600 borings 3,400 wells	?
Risk associated with catastrophe (in human lives)	Moderate 10–2,000	High Over 5,000	Moderate 10–300	Extremely high 50–50,000	No immediate risk (low) (continued risk of exposure)		
Environmental risk	Low	Moderate	Very high	Extremely high	High	High	

sampling. Ground water sampling would probably continue on a periodic basis after the first sampling event, thereby generating another 200,000 data points for each additional round of sampling.

To grasp the magnitude of the data explosion, compare the average amount of data collected in the 1960s, '70s and '80s for industries typical of these periods (Fig. 1). In the 1960s, the construction industry was dominated by large infrastructure projects, highrise buildings and dams. The typical number of soil borings drilled to characterize sites for these structures was between five and 50, depending on the size of the project and the complexity of the subsurface conditions.

Assuming that 50 borings are necessary to characterize a site and 10 samples from each boring are analyzed for five parameters, the exploration process produced only 2,500 data points.

During the energy crisis of the 1970s, much money was invested in the development of offshore oil fields and nuclear powerplants. Due to the cost of offshore drilling, usually no more than 10 borings are drilled to characterize the seabed beneath a platform. If the same formula is applied (using the same number of samples collected and tested) 10 borings would produce just 500 data points.

Since the safety of a nuclear powerplant is very dependent upon the integrity of the foundation, it's not uncommon for as many as 100 borings to be drilled when characterizing the subsurface at a powerplant site. Using the same formula, about 5,000 data points are generated for a typical nuclear powerplant site characterization.

RISK ANALYSIS

Regulatory agencies and the public may have lost sight of the risks involved in improperly characterizing a waste site compared with the risks involved in other engineering projects in terms of loss of life due to design failure and impact on the environment.

A foundation failure of a highrise building, for instance, would have little environmental impact but could result in several thousand deaths (Fig. 1). Dam failure could lead to a higher death toll with more environmental damage. An even greater catastrophe would be the failure of a nuclear powerplant. Tens of thousands of people could die—some immediately, others from related diseases years after the failure. The impact on the environment would also be devastating, resulting in substantial loss of animals and vegetation and making the area uninhabitable for years to come.

Compare these risks with those associated with living in proximity to a hazardous waste site. The long-term risks, which may lead to increased mortality rates, of course, cannot be ignored. And a hazardous waste site can have a severely adverse effect on the environment, endangering nearby animal and plant populations for many years. Generally, though, hazardous waste sites pose no immediate risk to the surrounding populace, leaving one to wonder whether the number of borings drilled on the sites is justified in light of the immediate and long-term risks.

Granted, the comparative data between the scenarios are somewhat misleading since characterization of hazardous waste sites involves the added element of testing for contaminants. Still, the question remains whether the changes that have occurred at these sites are in society's best interest when the investigative phase takes years to complete; millions of dollars are spent, but no cleanup action is started.

IDEAS FOR REFORM

The "study to death" syndrome plaguing many hazardous waste investigations fails to recognize that uncertainty will always exist in the analysis of subsurface conditions. Since uncertainty can never be eliminated, the hazardous waste industry should adopt a procedure similar to the classic observation method used for traditional geotechnical investigations.

For this approach to succeed, engineers must be given greater decision making authority in the field. General agreement must be reached by all parties involved in field work, including attorneys and regulators, regarding alternative courses of action as they become necessary. Once a consensus is reached, field operations can proceed with minimal interruption, with many decisions made by the supervising engineer based on the conditions he encounters during remediation.

Even if a partial return to the observation method is implemented, investigations of hazardous waste sites will still generate enormous amounts of data because of the large number of chemical analyses performed on field samples. The problem becomes even more acute when more than one round of sampling is performed. Unresolved questions persist: How can engineers best manage the large collection of information during the exploration program? How can experts automate the procedure of collecting, processing and displaying that information? Finally, How can site engineers interpret all the data in the most efficient manner?

It seems unavoidable that new or improved automated data processing techniques will be needed as the hazardous waste industry evolves. Automation can provide tools that help shorten the time it takes to obtain specific test results, extract the most significant finds, produce reports and display information graphically. In the long run, the exploration and testing program could be made more flexible and dynamic, ultimately leading to fewer samples and more focused investigations.

Eventually, many of the hurdles engineers face when reviewing and evaluating site data will be eliminated with the implementation of expert systems. Currently used in other technical fields, expert systems employ methods of artificial intelligence for interpreting and processing large bodies of information. By automating the characterization process, decisions about appropriate sample redundancy and the number of tests can be made while work proceeds at the site.

In short, automation could help ensure that the mistakes of the 1980s will not be repeated in the '90s: Namely, that the dollars spent and piles of data collected will actually translate into more cleaned up sites.

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