GEOENGINEERING IN THE NEW MILLENNIUM

TESTING AND PERFORMANCE MONITORING

W. Allen Marr, P.E., PhD

President and CEO

Geocomp Corporation

Boxborough, MA, USA

Abstract

In the author's opinion the geoengineering profession faces a major decision point: Will it continue towards becoming a craft, functioning at the call of others in a highly commoditized service or will it upgrade its services to produce higher value to clients and command the respect due to true professionals? The paper reviews some of the powerful tools for testing and performance monitoring that are available to the geoengineer but offers that these tools are infrequently used to their full effectiveness. The author explores ideas to expand the role and value of geoengineers in the new millennium to create more opportunities to use these powerful tools.

Key words: geoengineering, geomaterials, soil testing, rock testing, performance monitoring, risk management

INTRODUCTION

Geotechnology has become a mature field over the past 30 years. Concepts of shear strength; pore water and gas pressure, stress-strain behavior and geomechanics have advanced to methodologies for every day practice. Tools to see into the ground, test the ground and measure its performance have matured and are routinely applied in some practice. Major advances have occurred in the materials and methods for retaining structures, improving soil properties and controlling groundwater. Major accomplishments are possible with high quality geotechnical services as exhibited by some of the major projects of our time – theThree Gorges Dam in China, the Narmada Basin Development in India, infrastructure tunnels in Boston, Taipei and Singapore, offshore structures like the Red Hawk Platform in 1600 m of water in the Gulf of Mexico, the Udachnaya pipe diamond mine in Russia, environmental cleanup and remediation at Rocky Mountain Arsenal and foundations for massive buildings like those for the Petronas Towers in Kuala Lumpur and the new World Trade Center Towers in New York. But many notable failures with a geotechnical element have occurred – Teton Dam failure; levee collapses during Hurricane Katrina; earthquakes in Japan, California, Iran and Sumatra; massive landslides and debris flows on north coast of Venezuela taking 30,000 lives; Payatas Landfill Failure in the Philippines that buried more than 330 persons; tunnel collapses in London, Los Angeles and Dulles Airport; and excavation collapses like that at the Nicoll Highway in Singapore that took four people with other serious consequences.

In my opinion, the state of the practice lags far behind the state of the art of geoengineering. In my view the gap has increased in the past two decades, partly due to improvements in the state-of-the-art but mostly due to a decline in the state-of-geotechnical-practice over this time. Reducing this gap between the state-of-the-art and the-state-of-practice is the biggest challenge geotechnical engineers face in the new millennium. This paper explores these gaps to identify where opportunities and challenges lie ahead of us with a particular focus on testing and measuring field performance.

Geotechnical engineers are challenged by having to work with materials of wide ranging properties. Strength of geomaterials may vary from 0.1 KPa to 1 GPa (7 orders of magnitude). Stiffness may vary 10 KPa to 200 GPa (7 orders of magnitude). Permeabilility may vary from 10^{-16} to 1 m/sec (16 orders of magnitude). Compared to the materials used for the structural, mechanical and electrical components of a facility, geomaterials have much larger ranges in properties. Naturally occurring geomaterials, i.e. in situ soil and rock, also have higher variability than manmade materials like steel, concrete and asphalt. Added to this is the economic need to work with much lower factors of safety on material properties, than those implicit to structural analysis. These factors make geoengineering a more risky endeavor.

On a more technical level, soil and rock are generally 3-phase materials consisting of solids, liquids and gases. Our testing, analyses and evaluations must address all three phases to establish material behavior, which we do with Terzaghi's effective stress principle. Unlike our structural brethren who design with a specific strength of steel or concrete, the pressure of the pore water and that of the pore gas directly affect the strength of soil and rock. The properties of soil and rock also depend on stress level and stress history. A soil material consolidated to a stress level of 1 MPa will have much higher strength and stiffness than the same material consolidated to 0.1 MPa. That same material consolidated to 1 MPa, then unloaded to 0.1 MPa will have a strength and stiffness that are in between those measured on samples consolidated to 0.1 and 1 MPa. Soil and rock's memory of their past have an important effect on their future performance. The properties of geomaterials depend on the stress path imposed by the future construction. A soil element will have a different strength if loaded in the vertical direction than the same element loaded in the horizontal direction. Figure 1 shows typical stress paths for various geotechnical activities to illustrate how the strength of soil is case specific. The behavior of soil and rock also depends highly on its structure. A fractured rock has much lower strength than its intact value. A varved soil behaves much different than a soil with the same soil particles placed with a uniform composition.

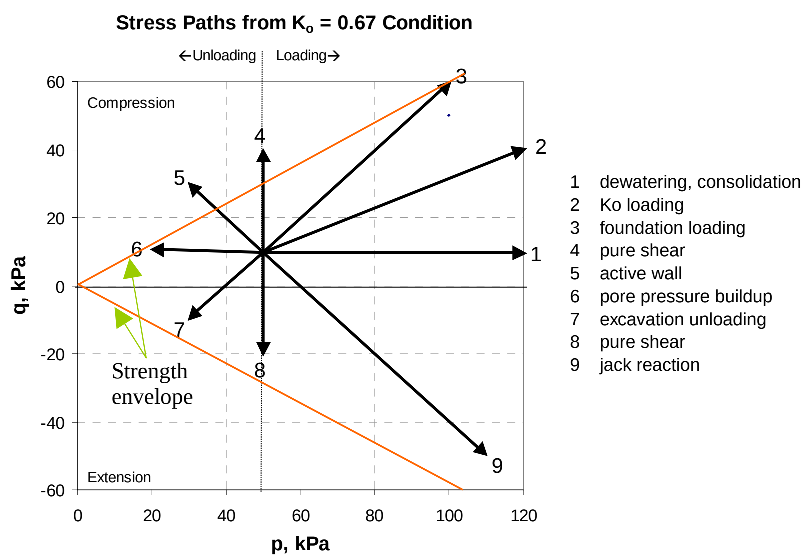

Figure 1: Stress Paths for Typical Applications

These factors have led geoengineers to develop a wide variety of laboratory and field testing equipment to characterize soil and rock and measure their mechanical properties. As an example, there are more than a dozen ways to measure the shear strength of soil and each one gives a different value. These include unconfined compression, unconsolidated undrained triaxial, consolidated isotropically and sheared undrained, consolidated anisotropically and sheared undrained, consolidated isotropically and sheared drained, consolidated anisotropically and sheared undrained, direct shear, direct simple shear, Handy borehole shear, cone, field vane, lab vane, torvane, dilatometer, pressuremeter, Standard Penetration Test, plus others. Which one should be used for a specific project? The answer requires careful consideration of the past, present and future values of stress that representative elements of soil or rock will experience. In principle, we should chose the test device that comes closest to duplicating the stress history and stress path that representative elements of soil and rock will experience in the design under consideration (Lambe and Marr, 1973; Ladd and DeGroot, 2003). A comprehensive review of these various devices is provided in Sabatini, et. al. (2002).

LABORATORY TESTING

Traditionally soil and rock testing devices were labor intensive, took days to weeks to complete, were prone to problems and required technicians with extensive training, In too many cases, these issues produced questionable results that came too late in the design process to be of value to the project. As a consequence, many designers resorted to empirical correlations and conservative designs to avoid laboratory and field-testing altogether, except for Standard Penetration Tests with samples and rock cores with some simple index testing.

However improvements in testing equipment and testing technology have overcome many of these problems. Today it is possible to produce a reliable test result for the specific project conditions within a few days. This has been accomplished with automated testing equipment in the laboratory and field. Figures 2 and 3 show two typical automated test stations for testing soils and rocks and the types of tests these devices can perform. These devices test soils and rocks along various stress paths to simulate what happens in the field. They provide strength, stiffness and permeability. All phases of a test, such as initialization, the equipment runs backpressure saturation, consolidation and shear automatically after it has been programmed with the appropriate test variables. We typically complete a triaxial test in this device within 24 hours and a constant rate of strain consolidation test within 36 hours with each

Unconfined compression
California Bearing Ratio
Unconsolidated Undrained Triaxial
Any Triaxial Stress Path
- -Isotropically Consolidated Undrained/Drained Triaxial Compression Loading/Unloading
- -Anisotropically Consolidated Undrained/Drained Triaxial Compression Loading/Unloading
- -Isotropically Consolidated Undrained/Drained Triaxial Extension Loading/Unloading
- -Anisotropically Consolidated Undrained/Drained Triaxial Compression Loading/Unloading
- -Failure by increasing pore pressure

Triaxial testing of partially saturated soils
Cyclic tests for any triaxial stress path
Resilient modulus testing for pavement design
Swell/Collapse tests
Incremental Consolidation
Constant Rate Consolidation
Rowe Cell Consolidation
Constant gradient permeability
Constant flow rate permeability

Figure 2: Geocomp Universal Test Station - Type I

requiring about one-person hour to run the test and produce a test report. With traditional test equipment, a triaxial test might take 1 to 5 days and an incremental consolidation test up to 3 weeks with each requiring more than 10 hours of labor to run the test and several more hours to reduce and report the data.

Drained direct shear
Undrained direct shear on clays
Residual shear
Direct simple shear
Cyclic undrained direct simple shear
Cyclic drained direct simple shear
Swell/Collapse tests
Incremental Consolidation
Constant Rate Consolidation
Unconfined compression

Figure 3: Geocomp Universal Test Station - Type II

Some advantages of automated laboratory testing are:

- Test completed faster
- Higher quality measurements and more data
- Less human error in reduction and reporting of data
- More standardized test procedures
- Can apply exact stress path that element will experience in the design so that important influences of stress history, stress level, future stress path and drainage are accounted for
- Higher productivity of labor force and more interesting work
- More test capabilities in a single test station rather than multiple devices dedicated to a specific test type.

The primary disadvantages of the newer automated equipment are a higher capital investment to purchase the equipment and the need for more qualified technicians with computer skills to use the equipment.

The opportunities produced with this new equipment are tremendous for the geoengineer. We can provide clients with better value by producing results quickly enough for use in the design and thereby reduce costly conservatism. We can perform more tests on more samples for less money to reduce uncertainty in the properties for the geomaterials used for design. We can run the appropriate tests to measure the material properties for the specific application and obtain a more reliable design. These all provide value to the client.

The challenge hindering broader use of this new equipment is primarily the difficulty the geo-profession has communicating value to its clients. We have a difficult time explaining how a better machine performing a more sophisticated test helps our client save money. Usually their impression will be the opposite – sophisticated tests cost more money and take more time so why bother? A corollary of this challenge is the competition within the geoengineering community from someone willing to produce a design with no or limited testing to "save the client money." This paradox is discussed later in the paper.

FIELD TESTING

Traditionally field-testing devices to measure properties of soil and rock used brute force approaches to gather indirect information on soil and rock strength that could be correlated with material properties through empirical relationships. These were primarily the Standard Penetration Test and rock coring with occasional use of in situ permeability testing and seismic reflection surveys. The empirical correlations were generally based on observed field behavior during construction. They incorporated significant conservatism in their use for design.

Advancements in technology and refinements in our knowledge have added significant tools to measure properties of geomaterials in the field. Table 1 presents a summary of these various tools and their primary application.

Some of the advantages of field-testing methods to measure properties for geomaterials include:

- Ability to measure something continuous over depth at low cost
- Some measurements possible from the ground surface
- Can avoid some of the disturbance to material caused by sampling for lab testing.
- Can test materials that cannot be sampled.

The primary disadvantages of field testing devices are that they don't impose the same stress path on soil elements as will the actual construction, many cause disturbance when placing the device into the soil, they involve unknown drainage conditions, and we don't know much about the tested material because we can't see it, or classify it.

The opportunities produced with this new equipment are considerable for the geoengineer. We can provide clients with better value by more carefully characterizing the site and reducing uncertainty about what's below the ground surface. We can test more locations for less money to reduce uncertainty in the design properties for the geomaterials. We can use site-specific correlations between results from lab tests and field tests to extend the more appropriate lab test results to larger areas with similar results from field tests. These all provide value to the client.

The challenge hindering broader use of this new equipment is the same as discussed for lab testing: the difficulty the geo-profession has communicating value to its clients. We have a difficult time explaining how more field-tests helps our client save money. Usually their impression will be the opposite – field tests take time and cost money so why bother, especially when another engineer is willing to base his design on conventional wisdom about conditions in the area? See more on this later in the paper.

PERFORMANCE MONITORING

Performance monitoring has been a key tool of geotechnical engineers since the beginning of construction activities. Before they could test and compute, our predecessors employed "trial and error" approaches. One planned a new church and observed its performance during construction. If it stood up the design was successful. If it started to fall down you stopped construction, propped it up and used it as circumstances allowed. Most of the pioneers of geoengineering used their observations of field performance to guide their chase for theories to understand and predict the behavior of soil and rock. It's probably safe to say that most major advances in geoengineering started from observations of field performance creating questions that dogged the minds of these pioneers.

Today performance monitoring has exploded to give us capabilities to measure just about anything, anywhere, and in real time. The declining cost of monitoring hardware and today's ubiquitous communications systems make real-time monitoring a cost-effective option. Table 2 summarizes the types of sensors we frequently use in geotechnical monitoring.

Table 1: Devices to Measure Properties of Soils and Rocks

Method	Applicable Soil/Rock Types	Obtained Information
Standard Penetration Test (SPT)	Soft rocks, sands, silts, clays	Stratification and sample Free draining: ϕ' , D_r Undrained: s_u
Electric Cone Penetrometer (CPT)	Sands, silts, clays and peat	Stratification Free draining: ϕ' , D_r , σ_{ho}' Undrained: s_u , σ_p'
Piezocone Penetrometer (CPTu)	Sands, silts, clays and peat	Stratification Free draining: ϕ' , D_r , σ_{ho}', u_0 Undrained: s_u , σ_p', c_h , k_h
Seismic Piezocone Penetrometer (SCPTu)	Sands, silts, clays and peat	Stratification Free draining: ϕ' , D_r , σ_{ho}', u_0, v_s , G_{max} , E_{max}, e_o Undrained: s_u , σ_p', c_h , k_h , v_s , G_{max} , E_{max}, e_o
Flat Plate Dilatometer	Sands, silts, clays and peat	Free draining: ϕ' , D_r , E, m_v Undrained: s_u , σ_p', K_0 , E, c_h , k_h , m_v
Pressuremeter	Soft rocks, sands, silts, clays	Free draining: ϕ' , K_0 ,E , G Undrained: s_u , K_0 , E, G, m_v
Vane Shear Test (VST)	Some silts, clays and peats	Stratification Free draining: not applicable Undrained: s_u , S_t ,σ_p'
Borehole Dilatometer	Fractured rock and weak rocks	E
Borehole Jack	Fractured rock and weak rocks	E
Plate Load Test	Fractured rock and weak rocks, all soils except peat	E, s
In-situ Direct Shear Test	Fractured rock and weak rocks, all soils except silts and peat	Peak and residual strength
Nuclear Density probe	Soils and rocks	Density and moisture content
DC Resisitivity	Soils and rocks	Soil layer thickness, depth to groundwater, delineation of discontinuities
Electromagnetic Ground Surveys	Soils and rocks	Delineation of discontinuities in soil, rock and groundwater including voids and sinkholes
Ground Penetrating Radar	Soils and rocks	Delineation of discontinuities in soil and rock, including voids and buried objects
Seismic Refraction	Soils and rocks	Depth to groundwater and bedrock Delineation of layers of different density
Spectral Analysis of Surface Waves	Soils and rocks	Depth to bedrock Thickness and stiffness of soil/rock layers
Crosshole/Downhole seismic	Soils and rocks	Depth to groundwater V_s and V_p for significant layers Identification of thin layers at depth
Suspension Logger	Soils and rocks	V_s and V_p for significant layers Identification of thin layers at depth
Electrical Logger	Soils and rocks	k, n Identification of thin layers at depth
Nuclear Logger	Soils and rocks	k, n Identification of thin layers at depth
Lithology Logger	Soils and rocks	Classification of soil or rock type Identification of thin layers at depth

Symbols used in Table 1

s	shear strength	e_o	in-situ void ratio
s_u	undrained shear strength	n	porosity
σ_p'	preconsolidation stress	ϕ'	effective stress friction angle
c_h	horizontal coefficient of consolidation	D_r	relative density
k	hydraulic conductivity (permeability)	K_0	coefficient of lateral earth pressure
k_h	horizontal hydraulic conductivity (permeability)	E	Young's modulus
V_s	shear wave velocity	G	shear modulus
V_p	compression wave velocity	S_t	sensitivity
G_{max}	small-strain shear modulus	m_v	coefficient of volumetric compressibility
E_{max}	small-strain Young's modulus		

Table 2: Devices to Monitor Performance

Instrument	**Application**
Observation Well	Measure depth to ground water
Piezometer	Measure total head at a specific location
Earth Pressure Cell	Measure total normal stress in soil
Contact Pressure Cell	Measure normal stress between soil and contact with more rigid material like rock or concrete
Load Cell	Measure force in a structural member such as a strut or tieback
Settlement Plate	Measure vertical deflection at a specific point
Settlement Gage	Measure vertical deflection of one point relative to another
Deformation Monitoring Point	Measure Δx, Δy, Δz, ΔL
Flow meter	Measure flow through a collector pipe
Flow weir	Measure depth of flow over a weir
Crack meter	Measure change in dimension between two points on opposite sides of a crack in 1, 2 or 3 planes
Strain gage	Measure change in length over a known short distance
Tilt meter, inclinometer	Measure deviation from vertical as indicated by the pull of gravity
Borehole extensometer	Measure change in distance between two or more points in a borehole
Geophone	Measure velocity of motion in 1 to 400 Hz range
Accelerometer	Measure acceleration of motion in 1 to 4,000 Hz range
Temperature	Measure temperature at the location of the sensor
Barometer	Measure atmospheric pressure
Automated Total Station	Measure position of multiple targets relative to fixed targets to about 1 mm
Global Positioning System	Measure position of one or more point relative to global reference system to about 1 mm
Seismographs	Measure dynamic motions resulting from shock loads such as blasting, pile driving and operation of heavy equipment

By adding a data logger to the sensor and a link to some external communications device, one can monitor a sensor anywhere via the Internet at relatively low cost. Electronic sensors are available for all of the measurements listed in Table 2. Figure 4 illustrates how my company uses these technologies to monitor sites anywhere in the world. These systems also provide alert messages to project personnel any time a measured value exceeds preset limits. These systems are complex with many opportunities for problems in the data flow. They must be made simple and reliable to the end user for them to be effective on a project. We now routinely simplify all data reports to the bare information necessary, but we maintain an extensive database of all data that is available to anyone willing to go deeper into the system. For performance monitoring systems we establish alert levels and required actions like the following:

GREEN	reading within acceptable zone – no action required
YELLOW	examine measuring system, investigate cause, evaluate trends, increase monitoring frequency, and consider additional instruments
ORANGE	meet, make changes where possible to mitigate damage to existing facilities, make ready corrective action plan
RED	stop work until corrective action is in place that will ensure this level is not reached in the future
BLUE	monitoring system is not functioning
BLACK	monitoring element is turned off, broken or removed

Modern performance monitoring systems allow us to closely track the actual performance of a facility during construction to detect unexpected performance early enough to take actions that reduce consequences from adverse performance. This proactive approach helps protect our work from unexpected poor performance, reduce delays to the project, and avoid expensive damage claims. A modern performance monitoring system that is effectively executed can save many times its cost. As an example the Central Artery/Tunnel project nearing completion in Boston required some of the most daring undertakings in underground construction ever attempted. The design engineers recognized that they faced enormous risks from adverse performance and designed a robust performance-monitoring program for the entire project. The monitoring program cost about $60 million dollars or 0.4% of the total project cost. Engineers working on the project experienced numerous instances where the monitoring program

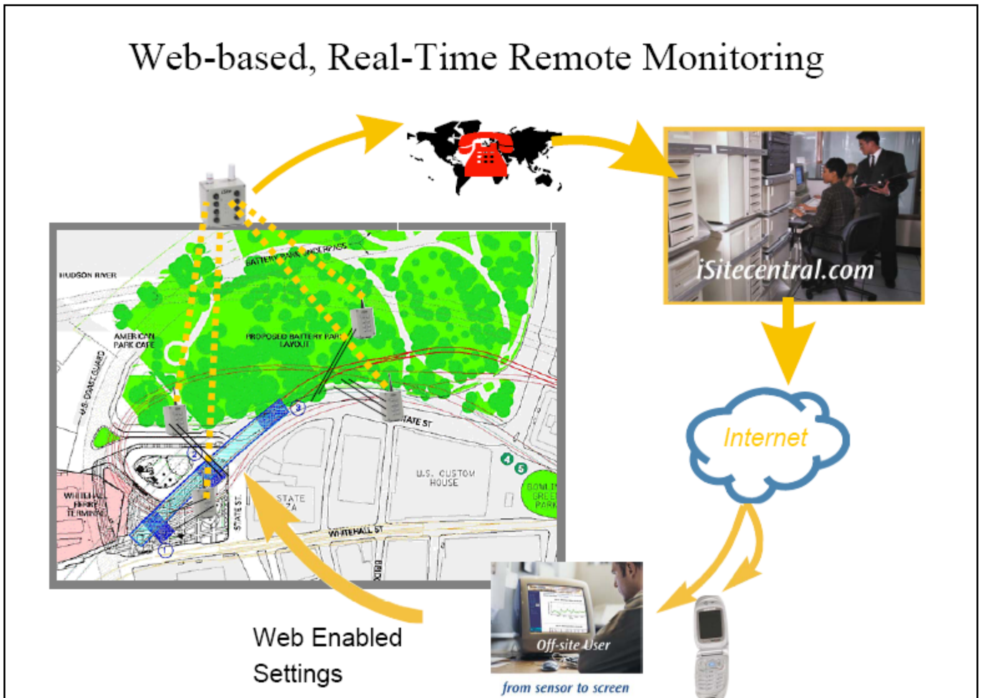

Figure 4: Geocomp's Web-based Remote Monitoring System

showed problems and deficiencies in time for corrective action to be taken. Estimates have been made which show that the performance-monitoring program for the project helped avoid as much as $500 million dollars in costs from damages and delays that could have resulted were no monitoring systems in place. (FHWA, 2007).

Performance monitoring systems are complicated and tend to not work well if they are not maintained and supported by an experienced and motivated team of professionals. Effective and reliable systems require all elements to work non-stop. This can only be achieved with systems that include much redundancy.

Modern performance monitoring systems provide geoengineers with major opportunities to deliver more value to our clients. They provide a high tech implementation of the Observational Method (Peck, 1969). From my perspective, the role of performance monitoring on infrastructure projects is to save owners money. These savings result from the benefits that an effective performance monitoring system can provide. These benefits include avoiding surprising behavior, reducing the likelihood of undesirable performance and providing early warnings of unexpected performance so that remedial actions can be taken to reduce the undesirable consequences. These benefits reduce the potential for delays to the project from unexpected performance. They reduce the possibilities that construction will adversely affect neighboring people and facilities. They also reduce the opportunities for claims arising from unexpected performance.

On projects that involve uncertainties about the existing conditions, new construction methods or materials, low margins of safety, high consequences of adverse performance, or tight restrictions, performance monitoring can provide benefits that may be several times the cost of the monitoring program. As an example the Central Artery/Tunnel project in Boston required some of the most daring undertakings in underground construction ever attempted. The design engineers recognized that they faced enormous risks from adverse performance and designed a robust performance-monitoring program for the entire project.

The challenge limiting our use of these modern performance-monitoring systems are the same as discussed for lab testing: the difficulty the geo-profession has communicating value to its clients. We have a difficult time explaining how performance measurements will save our client money. Usually their impression will be the opposite – performance monitoring takes time and costs money, so why bother? Besides these systems never worked in the past so why should we use them on this job? We need an effective response to these nay Sayers.

LOOKING AHEAD

This brief review of our profession's capabilities for testing and performance monitoring has shown that we have very powerful tools to help our clients succeed in the risky world of underground construction. The factor that most inhibits our ability to apply these tools effectively to each project is common. It is our inability to demonstrate to clients the value added by using these tools. Geoengineers tend to become so entangled in the technical jargon of our work that we have difficulty effectively communicating with the non-specialists. For our profession to survive and thrive we must change how we deliver our services. We must understand the project in a broader sense than before and be prepared to identify and seize opportunities during the early stages of its life. We must become a player during the planning and permitting processes of the project so that we can develop a broader understanding of the context and drivers of the project. We must see the big picture and manage the details. By being involved early and responding in terms of the value we can provide, we have a much better opportunity to expand our role in the project. We can become "geo-engineers" in the broader sense of the word, rather than be constrained by the limiting connotation of "geotechnical engineers".

We must also upscale the value of the products of geoengineering through more effective use of the capabilities and technologies currently available. A key requirement for this to work is for geoengineers to become more effective at communicating the value they provide to the project. Geoengineers working with a broader understanding of the project drivers can communicate the benefits of their work to reducing risk, avoiding delays, minimizing claims and saving the client money.

We must embrace and enhance our ability to make decisions with limited and uncertain information. Geotechnical engineers do this all the time through a process we call "applying our engineering judgment." This is a powerful but misunderstood skill that geoengineers should development more completely for our client's and our own benefit. Engineering judgment in its best form is the efficient application of critical thinking skills. Continual development of critical thinking skills is essential to improving our ability to provide clients with high value. The interested reader can refer to Marr (2006a) and Marr (2006b) for more discussion on the relationship between engineering judgment and critical thinking.

One very effective means to demonstrate value to clients is through the use of the language of risk, i.e. risk assessment, risk management and risk mitigation. Quantified risks provide understandable benchmarks for us to communicate options and value to clients. Clients understand the language of risk much better than they understand the language of geotechnical engineering. Clients want to know if their project will be successful. They have no way to interpret the meaning of a conclusion like "a calculated factor of safety of 1.24 using shear strength measured in a $CK_0U(L)$ triaxial test." The language of risk allows us to demonstrate to clients how using our tools for testing and measuring performance deliver value to them. A statement like the following is much more useful to most clients:

"The probability of a damaging geotechnical failure during construction is estimated at 5%. By completing a more comprehensive site investigation and testing program we expect to reduce this amount to about 1%. By using a real-time monitoring system we can further reduce this probability by one order of magnitude to 0.1%."

Huge opportunities exist for civil engineers in the foreseeable future to help address issues the world population faces, issues such as:

- Providing fresh water, food and shelter to everyone
- Managing wastes
- Supporting economic development
- Managing, upgrading and integrating legacy facilities
- Sustaining our resources
- Adjusting to global climate change
- Reducing risks from geohazards (earthquakes, landslides, volcanoes, storms)
- Working in a more complex society comprised of multiple interest groups with competing agendas.
- Providing solutions in shorter delivery time with least life-cycle cost.
- Providing solutions that integrate social, economic, political, environmental, scientific and technical issues.

Geotechnical engineers have the opportunity to make major contributions in addressing all of these issues. To be successful in this new millennium, the geoengineer will have to develop stronger skills to:

- Effectively apply the tools already available including those described in this paper.
- Communicate with own peers, clients and the public.
- Have a willingness to get "down and dirty" to get the work done.
- Deal with lots of conflicting information where time is short.
- Separate good data/information from bad data/information.
- Make decisions in an uncertain world.
- Balance good engineering and competitive forces.
- Embrace and adapt new technologies from other areas such as biotechnology, MEMS systems, nanotechnology, cyber infrastructure and high tech materials.
- Understand that dealing with clients, stakeholders, coworkers, public officials and the public are just as important to the success of a project as is a state-of-the-art analysis with voluminous sensitivity studies
- Be a competitive professional with a working understanding of applicable principles of business and law.
- Understand and apply risk management to clients' projects and one's own business.
- Better understand and apply refined skills for use of engineering judgment.
- Cope with stresses of business, demanding clients, conflicting objectives, multiculturalism and expanded demands of a modern family.

Our universities must play a major roll in identifying and developing students with these stronger skills and retooling graduate engineers to take a broader role in the geo-profession.

CONCLUSIONS

Geoenginering is a fascinating field of practice that will continue to challenge all of us to provide our clients with best value in a world filled with uncertainties. We have entered the new millennium with many powerful tools at our disposal to test soil and rock in the laboratory and in the field and to measure just about every meaningful indicator of performance in real time. The opportunities produced with this new equipment are tremendous for the geoengineer.

The challenge hindering broader use of these tools is primarily the difficulty the geo-profession has communicating value to its clients. We have a difficult time explaining how a better machine performing a more sophisticated test helps our client save money. We have difficulty explaining how installing instruments and measuring performance bring value to the project beyond satisfying the intellectual curiosity of the geotechniacl engineer. We must figure out how we demonstrate and communicate the value of our unique services to our clients.

One very effective means to demonstrate value to clients is through the use of the language of risk, i.e. risk assessment, risk management and risk mitigation. Quantified risks provide understandable benchmarks for us to communicate options and value to clients. Clients understand the language of risk much better than they understand the language of geotechnical engineering. Geotechnical engineers are well equipment to identify and work with uncertainty that produces risk. Risk assessment and risk management represent large opportunities for the geo-community.

The geo-engineer of the new millennium must have a much broader range of skills in succeed in the global economy. Our universities must play a major roll in identifying and developing students with these stronger skills and retooling graduate engineers to take a broader role in the geo-profession.

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