Geotechnology and Applied Geotechnical Engineering Intertwined

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Introduction

This paper will illustrate how technology and applied engineering, with particular reference to geotechnical engineering, are intertwined and dependent on each other in the process of designing and building large construction projects. After describing the civil engineering procedure and the inter-relationships between technology and engineering, a few examples of projects wherein technology and engineering worked together for design/construction success will be cited from the author's experience. The paper is directed to undergraduate and graduate students in technology and engineering.

The Civil Engineering Process

The civil engineering process begins when a need arises, usually for the public good, such as a highway, airport, tunnel, building, dam, bridge, etc. Rehabilitation and/or reconstruction of existing facilities are also needed periodically to maintain facilities in service and extend their useful life. Sometimes there is the need to conduct forensic investigations and studies of failing facilities or collapsed structures. The process requires civil engineering specialists in structural, geotechnical and other engineering disciplines.

Successful engineering design depends on identifying the relevant engineering issues, including project constraints and limitations, obtaining design data, establishing engineering criteria, conducting appropriate engineering analyses, iterating and reiterating the design as improved understanding of the project and more information become available. With this information, analytical results, tempered with judgment, and prescriptions of the appropriate building codes, construction drawings and specifications are prepared for prospective bidders (construction contractors). At various stages, these construction documents are subject to value engineering and/or peer review by client staff and/or other consulting engineers, and adjustments to the design may be warranted for technical and/or financial reasons.

Equally important in this civil engineering process is the use of technology. For instance, technologically based laboratory or in-situ testing, and instrumentation and monitoring of the construction process are recommended to confirm critical design assumptions, or to verify engineering analyses, to detect unanticipated field conditions or incorrect construction procedures, and to gain still more relevant information in order to make adjustments that will correct or resolve construction issues.

Basis of Applied Geotechnical Engineering

The basis of geotechnical engineering is rooted in an understanding of geology and the principles of soil mechanics.[1,2] Knowledge of rock mechanics, flow of water through soils and the importance of drainage[3] is very important too.

Typically, the applied geotechnical engineering process is initiated by a study of the regional geology, followed by planning and implementing a subsurface investigation program consisting of the drilling of boreholes in order to identify the soil, rock and groundwater conditions. The borehole also permits an indirect measure of the density and shear strength of the soils by way of the Standard Penetration Test, which produces the number of blows per foot of penetration of a standard hammer to drive a standard split spoon sampler. There are many textbooks (Refs. 4-7), journals and conference proceedings on soil mechanics or foundation engineering for a description of the making of borings, the Standard Penetration Test (SPT), and methods for the recovery and testing of soil samples. The boreholes allow the geo-professional, be she or he a geologist, geotechnical engineer or geotechnologist, to determine the groundwater conditions (including artesian pressures if present), the soil and rock types and their engineering properties and indices. Soil engineering properties include water content, density, strength, compressibility, permeability, etc.

The soil/rock profile may be comprised of gravels, sands, silts, clays or mixtures thereof, including organics such as vegetation and peat or miscellaneous fill materials containing various degrees of soil, brick, glass, shells, timber and even old foundations, especially occurring in reclaimed lands, such as around Manhattan Island. If rock is encountered, the engineer would want to know if it is intact, fractured, weathered, decomposed, bedded, foliated, etc. Sometimes the soil and groundwater are contaminated and require disposal or mitigation before a new foundation can be constructed.

The boreholes also permit the retrieval of soil samples and rock core recoveries for laboratory testing purposes. Valuable in-situ tests such as the vane shear test, the pressuremeter and dilatometer tests, packer permeability tests, etc. may be carried out inside the borehole. The boreholes may be created by augering, rotary drilling, etc. with or without casing. In the latter case, bentonite slurry may be used to keep the borehole open. All of the soil boring and rock coring operations and methods of sample recovery and in-situ tests have specific advantages as well as disadvantages, which the geo-professionals must be aware of in order to obtain a valid illustration of the underground conditions.

If sufficient information is obtained from the borings and the laboratory and in-situ tests, then a generalized soil layered profile may be developed. Idealized sections, including design parameters, may then be drawn for conducting soil mechanics analyses in order to assess soil bearing capacity in support of individual footings or large structural mats, estimate magnitudes and rates of settlements and evaluate slope stability. Other considerations addressed by soil mechanics are the lateral or inclined earth pressures acting on retaining walls, allowable loads and required depths of pile foundations, seepage analyses, geotechnical earthquake engineering, seismic liquefaction assessments, etc. For large projects in earthquake zones, the geotechnical engineer will consult with an engineering seismologist.

A geotechnical engineering report summarizing the regional and local geology, the findings of the subsurface investigation, including results of the laboratory and in-situ tests, assignment of design parameters, design criteria, the outcomes of the various analyses that were performed, conclusions and recommendations for design, construction drawings and specifications are typically provided in the report. Also included may be recommendations for monitoring construction for compliance with the design intent and the construction documents in order to successfully build the intended project without subsequent failures or functional deficiencies, as well as preventing damage to any existing adjacent structures.

Many civil engineering problems involve an interaction between soils and structures. Therefore, geotechnical engineers, which include tunnel specialists, dam construction experts, and geostructural or foundation design engineers, should also have a basic knowledge of structural design-analysis, and an understanding of the behavior of structures in response to soil and rock loadings.

Principles of Soil Mechanics

A few principles and laws of soil mechanics may be described as follows:

The Strength of Soils

The strength of soils is comprised of its shear strength and its cohesion. The available shear strength, τ, of a dry granular, cohesionless soil (i.e., gravel, sand, coarse silt) on any plane of the soil is a function of the normal stress, σ_n, acting on that plane multiplied by the tangent of the soil's angle of internal friction, φ, or $\tau = \sigma_n \tan\varphi$. The available strength of a cohesive material (clay, fine silt) resides in its cohesion, c. The strength of a soil containing both cohesionless and cohesive materials is given by the equation $\tau = \sigma_n \tan\varphi + c$, which is referred to as the Mohr-Coulomb failure criterion.

Concept of Effective Stress

Since water may exist in the voids or pores of soils, pore-water pressures that exceed the hydrostatic pressure result in excess hydrostatic pressures or simply excess-water pressure. Excess water pressures reduce the net normal stress on all shear planes (since water pressures act equally in all directions). This reduction in normal stresses decreases shear strength of the soil, making it more vulnerable to failure under loads that induce shearing stresses in the soil. This is the concept of effective stress and it governs the strength response of soils to loading, whether the loading is externally applied such as by a building or bridge or arises from its own body forces as may arise around the excavation of a tunnel.

An important example of the concept of effective stress is displayed during earthquake ground shaking wherein deposits of fine sands are especially susceptible to seismic liquefaction, a state in which the pore-water pressures build up, thereby reducing the effective normal stresses and consequently the effective shear strength of the soil. As the shear strength approaches zero, the soil approaches a condition of liquefaction, which has been responsible for the failure of embankments, foundations, quay walls, etc.

Darcy's Law

In most soil mechanics analyses Darcy's law, which is known from the field of mechanics of hydraulics, is sufficiently applicable to the flow of water through soil media to result in satisfactory solutions for engineering purposes. Darcy's law may be stated as velocity, v, is proportional to the hydraulic gradient, i, or v = f(i) or v = ki, where k is the coefficient of permeability. For quantity of flow q = kiA, where A is the cross-sectional area. Since the values of permeability for coarse gravels to sands, silts and clays range from 10^{-1} to 10^{-9} cm/sec, an accurate determination of realistic k values is important in the estimation of reasonable solutions to problems involving flow nets and seepage analyses such as for dewatering of excavations, slope stability analyses of dams, etc..

Other mainstays of soil mechanics are the Theory of Consolidation, Rankine's Active and Passive State's of Earth Pressures (subsequently extended by Coulomb) and Terzaghi's Bearing Capacity Equation (subsequently extended by Meyerhoff and others), presentations of which may be found in geotechnical engineering and foundation design textbooks[4,5,6,7].

Role of Technology

The word "geotechnology" may be used where technology is applied to support or advance the purposes of geotechnical and geoenvironmental engineering. This technology makes it possible for geotechnical engineering to be applied to solutions of foundation design and construction. It does this by providing the physical tools necessary to explore below ground, conduct in-situ field tests and retrieve soil and rock samples for laboratory testing. It makes geotechnical engineering feasible and practical to apply, by various means of measurement and quantification, even if the values so obtained are approximate at times. The factual information it provides assists in reducing the uncertainties in geotechnical engineering practice.

Subsurface investigation and soil/rock laboratory testing programs

This includes a subsurface investigation, including the making of boreholes, retrieval of soil samples for laboratory evaluation, detection of the groundwater table location, etc. The technology is comprised of various methods of drilling and sample recovery. The soil samples are then tested for various engineering properties such as water content, strength, permeability, grain sizes, index properties of clays, soil classification, compressibility and consolidation parameters. These properties are obtained from specially designed laboratory testing machines and procedures, and it is most important that the tests are set-up and conducted by certified soil engineering technologists with the assistance of qualified technicians. The devices to carry out the tests have evolved over time by the mutual contributions of engineers and technologists, improving on each other's ideas. In all of these technological advances, practicality, reliability, accuracy and precision are essential to obtaining meaningful results.

The technology that allows us to carry out laboratory testing or field monitoring of construction is based on the use of an impressive array of instruments, machines, devices and apparatus, which were developed in turn on principles from the fields of mechanical, electrical and hydraulic engineering. The engineering sciences of physics and chemistry also have a role. In order to evaluate engineering properties or the response of soils to loads, test equipment such as the consolidometer used to obtain compression design parameters, sieve series for grain size analysis, direct shear box for strength of sands, triaxial compression test cells for clays and pore pressure measuring devices are required. Sophisticated data acquisition systems are often involved.

In-situ testing of geotechnical/foundation construction

For large construction projects, it is usually not sufficient to limit the application of geotechnology to the subsurface investigation and laboratory testing programs. Assumptions made during design regarding soil strength, soil properties, design parameters, soil behavior predictions, foundation installations and ground improvement techniques require verification and validation via in-situ testing. Observations during construction monitoring are recommended to determine whether design and or construction methods require modification. These tests may include the following:

- Controlled inspection/testing of foundation installations
- Confirmation of subgrade conditions under foundation footings
- Subgrade and in-place embankment density testing
- Compression, uplift and lateral load testing of foundation piles
- Dynamic pile driving measurements[8] of effective hammer energies, driving stresses, possible pile damage, pile capacities, set-up and relaxation[9] of pile capacities
- Confirmation of requisite pile driving resistance during production driving
- Quality of rock to support drilled shafts and drilled-in rock socketed caissons
- Pile integrity testing and cross-hole sonic testing of concrete quality
- Cone penetration testing to confirm specific soil improvements, such as from vibro-compaction of loose sands, vibro-replacement (“stone column”) of clays, dynamic consolidation or heavy tamping of poor soils and refuse sites
- Monitoring of foundation construction operations for vibration and noise levels in order to prevent possible settlement or damage to adjacent structures
- Monitoring deep excavations for vertical and horizontal movements of structural shoring[10]
- Monitoring staged embankment construction for preconsolidating and stabilizing soft soils being treated by surcharging and sand drains or wick drains
- Settlement observations are obtained by surveying settlement platforms or deep settlement points. Increases and dissipation of pore-water pressure is monitored with various types of pore pressure devices from simple standpipes to pneumatic methods, horizontal movements by inclinometers, rotations by tiltmeters and crack growth by crackmeters.

The development, function, and response of these geotechnical measuring devices and monitoring instruments are themselves based on principles of engineering[11].

Example Projects

Several projects listed below from the author's experience demonstrate the intertwining of geotechnology and applied engineering:

- New Staten Island Ferry Terminal in Lower Manhattan
  Cross hole sonic logging and pile integrity testing were recommended to assess quality of tremied concrete for drilled-in-rock-socketed caissons.
- JFK International Airport - Terminal 4
  Compression, uplift and lateral load pile tests; pile integrity tests, controlled inspection of driven piling, including dynamic measurements during pile driving.
- La Guardia Airport
  Pile load tests on two dog-legged piles, inclinometer used on all piles to obtain post-driven pile curvature. By comparison of curvature on production piles with successfully load tested dog-legged piles, acceptance envelope of production piles was substantially increased, and rejected piles were minimized.
- Goose Creek Bridge Replacement along Wantagh Parkway
  Cone penetration testing for subsurface investigation and for verification of improved soil densities by the installation of stone columns.
- Rehabilitation of partially failed man-made foundation island to support major transmission tower in the Delaware River
  Engineering solution required underwater placement of 50-foot high rock buttress placed on varved subsoils to prevent further movement of sheet-pile cellular cofferdam around the island. A nearby gas transmission pipeline was monitored for vertical and lateral displacements as the buttress was built. Underwater divers used technology to make corrosion measurements and metallurgists used their technology to assist in the determination of the cause and manner of failure of the cofferdam.
- Keehi Interchange on Interstate Route H-1, Honolulu, Hawaii
  Subsurface investigation of under-consolidated soft compressible silty clay (locally, "muck") by way of borings, cone penetration testing, laboratory tests, field test programs, monitoring of staged embankment construction, including pore pressure measurements, settlement points and inclinometers.
- Japan Airlines Cargo Facility at JFK International Airport (JFKIA)
  Monitoring major utility line for displacements during the driving of nearby timber piles through steel sleeves to minimize vibrations from the impact of the driving hammer.
- Jamaica Station of LIRR and AirTrain of JFKIA
  Real time monitoring of tied-back retaining wall of deep excavation with in-place inclinometer measurements automatically recorded and transmitted to remote desktop computers.

An Example of a Major Advance in Geotechnology

The advent of earth reinforcement technology[12,13] about 40 years ago, ushered in over time the application of man-made materials such as galvanized metal strips and subsequently geosynthetics. Henri Vidal, the inventor of Reinforced Earth, thought of reinforcing sand based on simple observations he made at the beach, where while making sand piles he observed that interlacing some fibers into the sand piles seemed to allow steeper slopes to stand than those without fibers. From that simple engineering idea, he spent years in research and testing in order to develop the technology to build Reinforced Earth walls that were safe, competitive and aesthetically pleasing when compared with conventional concrete walls.

Today there are numerous geotechnical and geoenvironmental applications for geosynthetics, such as synthetic filter fabrics, which allow drainage while retaining fine sands and silty clays in-place. These filter fabrics may be used in lieu of thick, costly layers of graded granular filters for the same purpose. Other geosynthetics are used to reinforce weak or loose soils to support construction equipment or permit construction of steep reinforced soil slopes or mechanically stabilized earth walls (MSEW). Geosynthetics are also used as subgrade-stabilizing geotextiles, reinforcing geogrids or waste containment impermeable geomembranes. These applications require the adoption of new tests to evaluate such geosynthetic engineering properties as grab tensile strength, puncture strength, burst strength, permittivity, ultra-violet sensitivity, etc. These tests constitute the supporting geotechnology necessary for the geotechnical engineer to specify the appropriate material for the application at-hand.

Applied Engineering and Technology Personified

Karl Terzaghi (1883-1963) is known as “the father of soil mechanics”. This honorable attribution did not happen by accident. Dr. Terzaghi was a man with great respect for geology and an intuition for the influence of geology on construction works.[14] By hard work and years of perseverance, and with analytical insight, he rigorously and painstakingly formulated the early mechanics of soils, and he recognized the need for and the value of testing in the laboratory to confirm theories and enhance his understanding of soil behavior. He complemented this with observations in the field before, during and after construction. Thus, he evolved from a student of geology to a teacher of soil mechanics, a developer of laboratory tests, and to a practicing engineer of great judgment, and yet always a willing technologist.

Many other geo-professionals have since followed in his vein, such as his long-time associate, Dr. Ralph B. Peck,[15] who combined geology, soil mechanics, geotechnology and engineering into thoughtful approaches to the solution of problems enabling the creation of major projects in civil and construction engineering.

Closure

The process begins with engineering, but in order to safely apply that engineering economically to needed projects of society, the use of technology is essential, and that technology is itself based on engineering principles. Without applied engineering there would be little need for technology and without technology, engineering would not advance [except by unconfirmed theories (one would have to hope) and by trial and error].

Another type of “geotechnology” relates to applying technology to various aspects of the world at large as well as endeavors in the outer space surrounding our planet, such as satellite systems, space shuttles, geo-positioning, etc. One can study astronautical science and engineering, but at some point a rocket has to leave Earth, and that requires technology. And the development of that technology in turn depends on science and engineering.

Thus we see that technology and applied engineering are so intertwined and interrelated we often take their relationship and dependence on one another without noticing where one starts or the other ends, and that, perhaps, is as it should be when they are perfect together.

Bibliography / References

[1] Terzaghi, K., Peck, R.B. and Mesri, G. (1996) *Soil Mechanics in Engineering Practice*, Third Edition, John Wiley and Sons, New York, p. 71 and p. 213.

[2] Lambe, T.W. and Whitman, R.V. (1969) *Soil Mechanics*, John Wiley and Sons, Inc., New York.

[3] Cedergren, H.R. (1977) *Seepage, Drainage, and Flow Nets*, Second Edition, John Wiley & Sons, New York.

[4] Bowles, J.E. (1982) *Foundation Analysis and Design*, Third Edition, McGraw-Hill, Inc., New York.

[5] Coduto, D.P. (1998) *Geotechnical Engineering: Principles and Practices*, Prentice Hall, Upper Saddle River, New Jersey.

[6] Coduto, D.P. (2001) *Foundation Design: Principles and Practices*, Prentice Hall, Upper Saddle River, NJ.

[7] Holtz, R.D. and Kovacs, W.D. (1981, 2006, Second Edition) *An Introduction to Geotechnical Engineering*, Prentice Hall, Englewood Cliffs, NJ.

[8] Goble, G.G., Rausche, F., and Likins, G.E., Jr. (1980) *The Analysis of Pile Driving – A State of the Art*, Proceedings of the International Seminar on the Application of Stress-Wave Theory on Piles, Stockholm, June 4-5, 1980.

[9] York, D.L., Brusey, W.G., Clemente, F.M., and Law, S.K. (1994) *Setup and Relaxation in Glacial Sand*, Journal of Geotechnical Engineering, Vol. 120, Issue No. 9, American Society of Civil Engineers, pp. 1498-1513.

[10] American Society for Testing and Materials, 1974, *Performance Monitoring for Geotechnical Construction*, Special Technical Publication STP 584, L.I. Stern and C.J. Dunnicliff, symposium co-chairmen.

[11] Dunnicliff, J. (1993) *Geotechnical Instrumentation for Monitoring Field Performance*, Wiley-Interscience.

[12] Vidal, M.V. (1979) *The Development and Future of Reinforced Earth*, Proceedings of Symposium on Earth Reinforcement, ASCE Annual Convention, Pittsburgh, April 27, 1978, pp. 1-61.

[13] Lee, Kenneth L. (1979) *Mechanisms, Analysis and Design of Reinforced Earth*, State-of-the-Art Report, Proceedings of Symposium on Earth Reinforcement, ASCE Annual Convention, Pittsburgh, April 27, 1978, pp. 62-76.

[14] Bjerrum, L., Casagrande, A. et al (1960) *From Theory to Practice in Soil Mechanic, Selections from the Papers of Karl Terzaghi*, John Wiley & Sons.

[15] Dunnicliff, J. and Deere, D.U., Editors (1984) *Judgment in Geotechnical Engineering: The Professional Legacy of Ralph B. Peck*, John Wiley & Sons, NY.

Biography

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