Construction Engineering Education: History and Challenge

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Abstract: Engineering has been defined as the vocation of guiding nature to produce something needed or desired. A historical review of the evolution of engineering and engineering education leads to the conclusion that sustainability in design and construction requires the engineer to approach nature with imagination and humility. As part of its *Engineer of 2020* initiative, the National Academy of Engineering in 2001 questioned how engineering education should evolve to prepare the profession for the future. From that work and efforts by ASCE, it is clear that an educational system that fails to provide engineers with a broad base of learning results in graduates ill-prepared to enter professional practice. The National Academy *Engineer of 2020* work and ASCE Policy Statement 465, "Academic Prerequisites for Licensure and Professional Practice," echo a call to adopt a new educational model. The new model seeks to strengthen the cognitive ability of engineers and leads them to practices that work in cooperation and harmony with nature for the benefit of society. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000273.

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Ingenium

A panel on engineering infrastructure diagramming and modeling convened by the National Research Council in 1986 struggled to define what constitutes engineering and who is an engineer (Panel on Infrastructure Diagramming and Modeling 1986). In wrestling with this characterization problem, the panel went back to the Latin word *ingenium*, which they explained as meaning natural talent or capacity. They noted that the words ingenuity and engine stem from ingenium. Finally, the Academy panel said "engineering is an activity of man—manipulating nature to produce something needed or desired."

Etymologically speaking, the word ingenium links nature and capacity, or more implicitly, the forces of nature and the practice of engineering. Latin speakers used the word *ingenium* in reference to nature in the context of something that forms and deforms; therefore, in relation to engineering, the word means the art of changing things. Tracking this ancient line of thought, the Italian philosopher Vico (Giovanni Battista Vico, 1668–1744) stated that originally ingenium meant acute or the ability to perceive subtle distinctions. He wrote in *On the Most Ancient Wisdom of the Italians* (Vico 1710) that "an acute wit penetrates more quickly and unites diverse things." For Vico, ingenium is an art of discovery, a synthetic means of "finding something new." This is a very different historical and philosophical reflection on engineering as compared to how engineers are now educated in the university.

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Outline of the Argument

The functions of engineering design and construction originated in man's need to survive, that is, in the need for food. To produce food, man had to learn to guide nature and produce artificial environments conducive to the requirements of plants that would yield fruits to meet the nutritional needs of the community. The more hostile the environment where the community resided, the more focused was man's attention to nature. This proposition is demonstrated by examining the engineering practices developed by the Inka civilization of South America. Such an examination quickly finds that engineering practices that work in harmony with nature serve to promote sustainability.

However, modern man in the industrialized world with a western mind has become separated from the rhythms of nature and the daily patterns of social life. "Nature and environment for the hyperurbanized populations of the modern world have been transformed into abstracted, increasingly romanticized ideals: one political cause among many, but no longer an experienced daily reality" (Kolata 1993). Therefore, the issue today is how to move engineering education from a pure mathematics-physics approach to manipulating nature to one that encourages engineering students to develop solutions that work with nature in a holistic and integrated manner.

Francis Bacon (1561–1626) made famous the aphorism "knowledge is power" (Bacon 1597), but John Newman (1801–1890) expounded "education is not mere knowledge." This concept that education is more than knowledge is why ASCE issued Policy Statement 465, "Academic Prerequisites for Licensure and Professional Practice." With this document and its accompanying body of knowledge, ASCE is moving the profession to acknowledge that the practice of engineering requires a higher degree of cognitive ability and that to develop the required cognitive ability, engineering education needs much more breadth and depth. Engineering solutions founded on mathematical theory must be examined based on practical experience, that is, an awareness of nature. This critically important effort by ASCE can only be understood from the perspective of how engineering education matriculated into the university. The movement from engineering knowledge garnered from nature to engineering taught in the university and now to the demand for higher cognitive achievement with more breadth before admittance to the practice of engineering are the arguments of this critique.

Bridges Built on the Principle of Tension

The origin of engineering lies in man's attention to nature. The ingenium—art of discovery—for bridges that work in tension as opposed to the compression ideas of the Romans is an example of early engineering education from nature.

The first suspension bridge in Great Britain opened in 1820. This was Capt. Samuel Brown's Union Bridge over the River Tweed with a deck span of 110 m (360 ft). Six years later, Thomas Telford completed his famous 176 m (579 ft) center span Menai Suspension Bridge. Both of these bridges used wrought iron chains (Tang 2010). In fact, it was wrought iron that made them possible because it is a material from the forge that is strong in tension (Billington 1983). In France, the engineer Marc Francois Seguin proved by tests that wire cable was twice as strong as the English iron eyebar-chains. He then proceeded to create the first suspension bridges on the European continent, where the arch bridge had been the standard since the days of the Roman Empire (Hagen 1966). In 1823 Seguin completed a wire-cable suspension bridge in Geneva, and in 1825 his second suspension bridge provided a crossing of the Rhône.

The idea of using suspension cables to create a bridge soon moved from Europe to the United States. In the United States, Charles Ellet defeated the steamboat interest and conquered the Ohio River with a suspension bridge at Wheeling, Virginia in 1849 (Rogers et al. 1996). He had 7 years earlier completed the 104.5 m (343 ft) span Fairmont Park Bridge in Philadelphia, which was the first wire suspension bridge in the United States for general traffic (Schodek 1987). John Roebling moved to the forefront of suspension bridge engineering when he replaced Ellet as designer and builder of the Niagara Suspension Bridge. Roebling completed his Niagara Suspension Bridge in 1855.

Both Ellet and Roebling received their engineering education in Europe. Ellet had studied suspension bridges in France at the Ponts et Chaussées before attempting his record-setting 307 m (1,008.5 ft) Wheeling Bridge (Schodek 1987). Roebling received a formal engineering education at the Royal Polytechnic School in Berlin (Steinman 1957). Additionally, before he came to the United States, Roebling was exposed to the wire-cable suspension work of the French and Swiss in Europe.

Conquistadors

When Francisco Pizarro pushed his small band of conquistadors into the Andean mountains of Perú in 1533, they found a very different type of bridge from the old Roman river crossing of their homeland. Pizarro's secretary Pedro Sancho wrote that the first time these fearless men had to cross an Inka bridge they were terrified; "to someone unaccustomed to it, the crossing appears dangerous because the bridge sags with its long span…so that one in continually going down until the middle is reached and from there one climbs until the far bank; and when the bridge is being crossed it trembles very much" (Sancho 1917). Sancho was describing the astonishment and fear the Spaniards felt as they first encountered suspension bridges. From puna grass (*ichu*) braided to form cables, the Inkas had been constructing suspension bridges for at least 100 years before the Spaniards arrived. These native engineers, who lacked a written language, succeeded in building roads and other lasting structures on the steep and unstable mountain slopes of the Andes that experience catastrophic flooding from El Niño rains. The Andes are also a land of constant tectonic creep, where the continental plate passing over the sea floor Nazca plate at a rate of 9–15 cm (3–6 in.) annually creates approximately 10 major seismic events each year.

After the conquest, Spanish builders failed to account for the physical environment of western South America, and soon many of their buildings and bridges of stone and brick crumbled. The Inka and other peoples of Perú, however, often used quincha construction techniques for common dwellings. Quincha is a wall constructed by interlacing small vertical and horizontal elements of wood or reeds to form a mesh. The mesh, typically finished with a covering of mud, provides a flexible wall (Carbajal et al. 2005). This type of wall construction was used because of its ability to withstand the stress of seismic movements. For ceremonial building, constructed of stone, the Inka built walls with a 5–6° batter for stability (Wright 2000). These native engineers had a better fundamental understanding of how the forces of nature act on structures then many modern engineers. Their bridging solution was superbly suited for the vertical topography of the Andes with deep defiles confining roaring torrents of water. The roaring torrents of water from El Niño rains destroyed previous western South American civilizations, but the engineering knowledge of the Inka seems to have been built on a remembrance of those events.

Nature, the First University

The Swiss naturalist Johann Jakob von Tschudi spent five years exploring Perú in the late 1830s and early 1840s. In his published observations, he describes several Inka suspension bridges; however, his most interesting remarks regard the genesis of the idea. Tschudi writes, "In the construction of these crude bridges, I observed that the Indians, in their simplicity, always faithfully copy their great instructress, nature" (Tschudi 1854). He specifically made reference to the vegetation he observed on the eastern side of the Andes that fastened itself to neighboring plants to form "a kind of suspension bridge." Other writers have offered the proposition that the idea of a suspension bridge came from man watching monkeys create suspension bridges with their own bodies (Jenison 1948). The exact truth will probably never be known, but it is apparent that nature was the primary instructor of the first engineers.

The faculty of man's first university were the raw forces of nature, and for early man, there was only one field of study—farming. At this university, man sought knowledge about plant cultivation, and the award of the Doctor of Philosophy came by learning to work with the forces of nature. It has been estimated that the early inhabitants of western South America cultivated roughly the same number of plant species as civilizations in Europe or Asia (Cook 1925). The significance of this success is better appreciated when it is considered that the accomplishment was on a land mass composed of a narrow coastal desert backed by mountains rising to over 4,570 m (15,000 ft) and in climates that varied from tropical to polar. To support their agricultural needs, it was necessary to create flat well-watered soil in the vertical environment of the Andes or irrigation systems in the narrow river valleys that cross the coastal deserts.

To provide tillable land, Inka farmers created 600,000 ha (1,480,000 acres) (National Research Council 1989) of staircased

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terraces on steep mountain slopes, as shown in Fig. 1. Reaching up the mountains for hundreds of meters, these terraces allowed Andean farmers to use all the microenvironments and engage in diverse vertical farming. This achievement rested upon knowledge of soil mechanics and hydraulics that permitted them to build thousands of terrace-supporting retaining walls. To attain farming success required builders who united diverse knowledge about how water flows, soils drain, and the properties of available building materials. These master builders, or engineers, took time to closely observe nature and then form a treaty with reality to coax nature to do what it is willing to do and nothing more. In retrospect, their work presents a holistic approach to engineering with a devotion to sustainability.

Some of the greatest global challenges facing the engineering community today involve reducing the impact of the built environment on the natural environment. Unlike many modern engineering works that initiate these problems, the Inka engineers adapted their structures to the natural environment while preserving harmony with the land. Moray, located on table land high in the Andes of Perú, is an outstanding example of how the Inka used nature and the physical environment as supporting components of their work. Instead of filling and leveling the natural sink holes at Moray, the Inka stabilized the side walls of the depressions and created a religious ceremonial site with agricultural terraces (Fig. 2). Each level of the terraced sinkholes is suitable for plants with different moisture and temperature requirements. These engineers had an insightful knowledge of nature, and through ingenium, they produced sustainable solutions to the challenges imposed by the physical environment of western South America.

Fig. 1. Terraced farm land in the Andean peaks of Perú (image by C. Schexnayder)

Fig. 2. Terraced sunk holes at Moray, Perú (image by C. Schexnayder)

Shaping of Engineering Education in the United States

The practice of engineering in the United States as it emerged after George Washington's Revolutionary War victory at Yorktown, Virginia in 1781 was shaped by two distinct traditions. First, there was the French theoretical tradition that came from their government-supported works and schools. In 1676, the Corps du génie was established in the French Army. Eighty-one years later, the French government recognized the need for formal engineer training and created the École des ponts et chaussées (school of roads and bridges). The development of these engineering schools culminated in 1794 with the École Polytechnique. That nstitution, with its emphasis on scientific and mathematical principles, laid the foundation for formal theoretical and mathematical-based engineering education.

Second, in England, technical project supervision was employed primarily by private commercial interest. British engineers worked on civilian projects that supported the industrial expansion of the country and hence the origin of the term "civil engineer." These practitioners learned their profession through apprenticeship-type training. The British engineer approached problems in a practical and empirical manner. Some have even said that British engineers were suspicious of mathematical and theoretical methods (Cardwell 1972). In the United States, the engineering school of the Erie Canal followed the British model. Benjamin Wright, Canvass White, and James Geddes learned their engineering by self-education and trial-and-error experimentation. Most 19th century American engineers were trained in this practical manner. They began under a master practitioner as an axman or chainman on a survey crew laying out canals or railroads. Slowly by absorbing practical knowledge they worked their way up to assistant engineer and later as engineer on another project. There were some, however, such as Loammi Baldwin Jr., Samuel M. Felton, John W. Brooks, and Thomas Doane, the great canal and railroad engineers from Boston, who first received a classical education in the university before venturing into the field to learn engineering. The quality and breadth of that combined educational process gave that select group the ability to successfully push railroads across Massachusetts and New York, on to Chicago, and halfway across Iowa before the Civil War.

University and Engineering Education

Formal engineering education in the United States developed very differently from the manner in which medicine or law became part of the university, and that difference still affects the structure of the knowledge base of those that enter the engineering profession. Medicine and law founded and controlled their own educational institutions independent of colleges. Lawrence Grayson pointed to this fact and how it impacted engineering education in a critical manner. He noted that "Almost from the beginning engineering education in the United States was in all essential aspects a form of collegiate education, instituted and directed by educators, rather than practitioners" (Grayson 1977). The primary factor that caused this difference in educational approach was that colleges and universities began offering engineering degrees before professional engineering societies came into being. Therefore, the profession

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had almost no voice in the content of engineering curriculum offered in the university.

Early Engineering Schools

The United States Military Academy at West Point, New York is usually honored as the first engineering school in the United States. It was established on March 16, 1802; however, for the first 10 years there was no systematic curriculum of any type. Finally, President Monroe appointed Sylvanus Thayer superintendent in 1817. Thayer had graduated from Dartmouth College before entering West Point and graduating with the class of 1808. He was then sent to France and received a formal engineering education at the École Polytechnique. Bringing that experience back to West Point, he established an engineering program modeled on the French theoretical and mathematical-based approach.

The forerunner of Vermont's Norwich University was established in 1819 by Capt. Alden Partridge. Partridge had attended Dartmouth College for three years but did not graduate before he entered West Point. After graduation from the Academy, he was commissioned a First Lieutenant and served as professor of mathematics and then engineering at West Point (Grayson 1977). In 1834, Norwich University was organized from Partridge's original American Literary, Scientific, and Military Academy with a department of civil engineering. Its first engineering degree was awarded in 1837. This was the first civilian technically oriented university because it went beyond the typical classical-college curriculum of the time.

Stephen Van Rensselaer, understanding the importance of education, started the Rensselaer School in 1824. His initial creation had a 1-year curriculum, and there was no mention of engineering. Finally, in 1835 the school began to offer a 1-year course in civil engineering. The academic program did not vary from this limited offering until 1842, when Benjamin Franklin Greene assumed leadership of the school. Green, who had made a study of European technical schools, changed the school into Rensselaer Polytechnic Institute in 1849 (Grayson 1977). His creation limited the school's offering to two degrees, one in architecture and the other in engineering. Rensselaer Polytechnic, like West Point, was modeled after the Écoles of France, and both schools required three years of French because of their dependence on French technical publications.

Early in 1847, a committee of the Harvard Corporation issued a report on the establishment of a scientific school within Harvard College. This occurred a full year before the Boston Society of Civil Engineers came into existence, so practicing professionals had no unified voice in the discussion at Harvard. The corporation's report failed to answer the question of how the humanities fit into a scientific school. Some assumed "a completely scientific curriculum, with no languages or history," but others viewed languages and rhetoric as an essential part of the curriculum (Stratton 2005) This debate about breadth still occupies those charged with designing engineering curriculum. The discussions at Harvard continued into 1848, but in that year, Abbott Lawrence, a leader in the textile industry of New England, offered Harvard $50,000 in support of a scientific school. Such a donation in the 1840s was an unprecedented amount. The offer was accepted, but curriculum questions continued to plague the faculty and leaders of the Harvard Corporation.

Edward Everett, who had been confirmed as president of Harvard two years before in February 1846, had to preside over these tensions between cliques and scientific rivalries. Everett had entered Harvard at age 13 and graduated in 1811 with high honors. Four years later, he was appointed to a professorship that allowed him to take a Ph.D. at the University of Göttingen in Germany. During the scientific curriculum debates, he championed the idea from the German university of a curriculum beyond the baccalaureate. This was an idea that ASCE now espouses in Policy Statement 465—to enter the practice of civil engineering at the professional level should include academic course work beyond the bachelor's degree (Lynch 2009).

At this time, Everett was opposed by one distinguished professor at Harvard dedicated exclusively to the idea that only pure science had a place in the university. "He scorned the teaching of practical science or those subjects designed to qualify students for active pursuits of life" (Stratton 2005). These attitudes of scorn at Harvard lead to the creation of the Massachusetts Institute of Technology (MIT) in 1861 by those who thought differently about engineering education.

A few other institutions developed engineering schools in the following years, but it was not until 1862 with the signing of the Morrill Act that the number of engineering schools truly expanded. The Morrill Act donated to the states public lands that could be sold for the purpose of using the proceeds to benefit colleges of agriculture and the mechanic arts. In Massachusetts, the state divided the funds from the Morrill Act land sales between the organized but not operating MIT and a new agricultural college. MIT admitted its first students in 1865.

Kansas took advantage of the act in 1863 and Vermont in 1866, but the Civil War delayed establishment of colleges in other states. Four states, Connecticut, New Jersey, New York, and Rhode Island, used the grant to endow schools in existing private institutions. The receiving institutions were Yale, Rutgers, Cornell, and Brown. Eighteen states used their grants to endow existing state institutions. Other states established separate agriculture and mechanical colleges, and Virginia founded a specialized polytechnic institute.

Professional Engineers Organization

Over the decades while these engineering schools were coming into existence, practicing civil engineers struggled to form a professional organization. The initial movement toward the formation of a national association of engineers sprang from Augusta, Georgia in 1838. John Edgar Thomson, who was then chief engineer for the Georgia Railroad, was probably the instigator of this plea to form an engineering association (Schexnayder 2007). That attempt went no further than a single meeting in Baltimore the following year. Subsequently James Laurie, an engineer practicing in New York City, revived the idea in 1853. He succeeded in holding semimonthly meetings for a little over a year, but those were never attended by more than six gentlemen. Again, the effort failed because of apathy, but Laurie persisted and in 1867 the American Society of Civil Engineers was organized. Still the society languished until 1877, when it was finally incorporated. Three years after the incorporation of ASCE, there were 21 engineering colleges in existence (Layton 1971) and all had been created with only minimum input from practicing professions.

The Morrill Act stimulated the rapid expansion of engineering education and established the linkage of state support for higher education. Furthermore, it caused the concept of "engineering as an integral part of a four year college program to become more deeply rooted" (McGivern 1960). Nevertheless, the practicing profession and ASCE had played no part in the formation of these schools. Many developed in the context of the disputes that had taken place at Harvard in the 1840s. As an example of what happened in one case, Texas A&M University appointed a doctor of divinity as chair of its chemistry, natural science, and agriculture school.

Political forces have also tried to dictate curriculum and requirements for academic degrees. These efforts go back to the famous

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Dartmouth College case that Daniel Webster argued before John Marshall's Supreme Court in 1818. In the case, the issue was whether New Hampshire could take over Dartmouth College by changing the structure of its governance. Webster was successful in protecting the college because it was a corporation holding a royal charter. Marshall's court ruled the charter was a contract that created a private, not a public, corporation and, therefore, was not subject to the state's regulatory power (Remini 1997). This defense did not protect public colleges from political pressures.

Webster had protected the university from the political forces. But his good friend Edward Everett as president of Harvard could not influence the structure of engineering education over the opposition of the faculty. However, with a professional organization finally coalescing, practitioners began to voice their thoughts about the educational process. A paper published in the ASCE *Transactions* of 1875 authored by Thomas Clarke proposed that those aspiring to be engineers attend college and then go into the field to learn the practice of the profession (McGivern 1960).

National Studies on Engineering Education

Two detailed studies of engineering education have recently been undertaken by foremost engineering organizations in the United States. The impetus for both studies was the obvious need for major changes in engineering education to meet the challenges of producing engineering professionals for the 21st century. The studies by the National Academy of Engineering (NAE) and ASCE broadly recognized that engineering education must be reformed; otherwise, American engineers will be ill-prepared to meet the challenges of a global economy and competition.

Engineer of 2020 Studies

The NAE study, *The Engineer of 2020*, was initiated in 2000. Phase I focused on the nature of engineering practice in the future (NAE 2004), and Phase II focused on changes needed in engineering education if future challenges are to be met (NAE 2005). The Phase I study committee looked at the technological and societal, global, and professional contexts of engineering practice. In seeking to predict future needs, the academy committee used a scenario-based approach. The four scenarios that focused the dialogue were (1) the next scientific revolution—an optimistic future; (2) a biotechnology revolution—political and societal implications; (3) the natural world—events originating beyond man's control; and (4) global changes—conflict and globalization. The final report expressed bold optimism while specifically endorsing efforts to improve engineering through appreciation of the

- Impact of engineering on sociocultural systems;
- Linkage between professionalism, technical knowledge, social and historical awareness and traditions;
- Need for experts well grounded not only in mathematics and science, but also in humanities, social sciences, and economics;
- Importance of a focus on sustainable development; and
- Requirement to be proactive in educating engineers to address technological and societal challenges in the future.

These points, sociocultural, historical awareness, humanities, sustainable, and societal challenges, are not in any specific order of importance, and NAE made many other points. Nevertheless the message harkens back to the foundation of Inka engineering, an appreciation of nature and the forces of nature. Moreover, the points can be traced to the discussion at Harvard in the 1840s when the idea of a scientific school was first broached.

The attributes needed by the engineer of 2020 include strong analytical skills, practical ingenuity, creativity, communication, business and management skills, leadership, high ethical standards, professionalism, dynamism, agility, resilience, flexibility, and above all lifelong learning. In summary, the NAE report stated

> "He or she will aspire to have the ingenuity of Lillian Gilbreth, the problem-solving capabilities of Gordon Moore, the scientific insight of Albert Einstein, the creativity of Pablo Picasso, the determination of the Wright brothers, the leadership abilities of Bill Gates, the conscience of Eleanor Roosevelt, the vision of Martin Luther King, and the curiosity and wonder of our grandchildren."

It could be taken as a prodding that an engineer grounded solely in mathematics, chemistry, and physics will not be capable of seeing things as a whole and producing solutions to the problems of the future. Awareness of languages, history, and literature, the liberal arts, opens the mind (Newman 1891) and develops a student's rational thought. The NAE report followed Newman's argument from a century before; rational thought is a critical component of engineering. The need is for a Renaissance type of engineer; an engineer whose education and expertise span a wide range of fields beyond the foundational subjects of engineering. Engineering schools must be open to new teaching and training approaches.

Phase II of the NAE study examined engineering education, in the broadest context, and sought to address the question of what the academy needs to do to enrich the education of engineers who will practice in 2020. The study acknowledged past interventions, but it was sobered by the fact that these interventions did not result in systematic change. It found that they were only isolated instances of success in individual programs. The report then went further and stated that "the disconnect between the system of engineering education and the practice of engineering appears to be accelerating." A poll of the pubic indicated that 54% believed that scientists were held in "very great prestige," whereas only 34% indicated the same for engineers (National Science Board 2002).

The NAE Phase II study recommendations included the following:

- The B.S. degree should be considered a preengineering or as an "engineer in training" degree;
- ABET should permit engineering programs to be accredited at both the B.S. and master's level so the master's degree can be recognized as the engineering "professional" degree;
- Institutions should take advantage of the flexibility inherent in ABET accreditation criteria in developing curricula, and students should be introduced to the "essence" of engineering early in their undergraduate careers;
- In addition to producing engineers who have been taught the advances in core knowledge and are capable of defining and solving problems in the short term, institutions must teach students how to be lifelong learners (a tough assignment); and
- Engineering educators should introduce interdisciplinary learning in the undergraduate curriculum and explore the use of case studies as a learning tool to introduce and explain engineering successes and failures.

American Society of Civil Engineers

The ASCE's Board of Direction adopted Policy Statement (PS) 465 in 2001. PS 465 boldly counseled the need to reconstruct the academic foundation of professional practice. The underlying rationale for this recommendation was the awareness that "a bachelor's degree is becoming inadequate for licensure and practice of civil engineering at the professional level—that a new model for civil engineering education is needed to prepare practitioners for increasing complex work in which they will be engaged in the 21st century" (Task Committee on the Academic Prerequisites for Professional Practice 2002).

Recognizing the need for change, PS 465 explained that to prepare engineers for the challenges of the future there must be "…appropriate engineering education and experience requirements as a prerequisite for licensure." Those who formulated PS 465 were aware that the profession's principal means of changing the way civil engineering is practiced lies in reforming the manner in which tomorrow's civil engineers are prepared, through education and early experience, to enter professional practice (ASCE 2007).

To support implementation of PS 465, ASCE defined a body of knowledge (BOK) for entry into the practice of civil engineering at the professional level (ASCE 2004, 2008). Using Bloom's *Taxonomy* (Bloom 1956), an ASCE committee described outcomes for which minimum levels of cognitive achievement were specified. Bloom and his coauthors described a hierarchy of cognitive ability starting with (1) knowledge, the ability to recall previously learned material; (2) comprehension, the ability to grasp the meaning of material; (3) application, the ability to use material in a new situation; (4) analysis, the ability to ascertain the components of the material; (5) synthesis, the ability to reorganize the material to form something new; and finally (6) evaluate, the ability to judge the reorganized material. A practicing engineer needs more than the ability to remember previously learned material (i.e., knowledge). An engineer must possess a much higher degree of cognitive ability that allows application of knowledge to new situations. Bloom's work is more than a half century old, yet many engineering students still encounter courses in the university requiring aptitude at only the lowest possible level, that is, the recall of information.

Together the profession and academics must push to change engineering curricula. It is vitally important that students be mentored at developing the three upper levels of cognitive ability. Failing to rise to this challenge will fulfill Leonhard Bernold's prediction that "college education will be replaced by much cheaper Internet-based engineering programs that look a lot like the lecture-oriented teaching of today" (Bernold 2005).

The failure of many engineers to apply knowledge at higher cognitive levels is demonstrated by tragic news stories every day; from bridge collapses, to tunnel liner failures, to inadequate hurricane protection, to crane collapses. To focus on a specific example, the Big Blue crane accident at the Brewer's Miller Park stadium project in Milwaukee on July 14, 1999 (Shapiro 2003) is a representative illustration of the need to enhance engineering education. The accident involved a 1,361 t maximum lifting capacity crane hoisting a 363 t steel roof section. During the lift the crane collapsed, killing three construction workers.

The upper levels of Bloom's taxonomy are analysis, synthesis, and evaluation. The terrible Milwaukee crane accident summarized here from the perspective of a practicing engineer brings the needs of construction engineering education into clear focus:

- Did the project engineers do analysis considering the loads imposed by the roof section on the crane under wind effects? It seems that no one criticized, examined, or tested conditions against even the known loads.
- Did the engineers synthesize the loading conditions—play "what if" considering differing reach requirements, different wind conditions from different directions, the crane not being perfectly level, effect of acceleration and deceleration during the swing, and effect of combinations of these possibilities?
- To supposedly speed the schedule, the roof sections were designed to the maximum capacity of the crane. Those sections could have been designed in smaller sections and the risk would have been reduced significantly. This consideration goes to evaluation. Where was the comparison of risk or where was the evaluation?

Professors with extensive industry experience are more likely to assign open-ended problems and projects that include teamwork and writing. Such problems cause students to analyze, synthesize, and evaluate. Open-ended problems that emphasize the three upper levels of cognitive ability require more time to develop. In addition, the professor must assess student work in a subjective manner because these problems have no single best answer. The grading process is part of the learning process because it is necessary to explain the ramifications of ideas. This is not a grading procedure with which most professors or students are comfortable. Construction professionals who have been actively engaged in real projects where they held positions of responsibility and decision making have experience accepting responsibility for decisions and can be very good at presenting and appraising open-ended problems.

The presence of professors with extensive industry experience can radically change how engineering schools prepare students for industry careers and satisfy the ABET Professional Component Criterion 4, particularly the (b) component to "provide a bridge between mathematics and basic sciences on the one hand and engineering practice on the other" (ABET, Inc. 2006). The diversity of backgrounds and experiences that professors of practice bring to a program is the best method for moving construction engineering education to higher levels of cognitive achievement, as recommended in the ASCE's body of knowledge documents.

Professor of Practice

At doctoral (D)/research universities (RU) classified as very high research activity (VH), high research activity (H), and doctoral/research universities (under the new Carnegie classification definitions, RU/VH, RU/H, and DRU), it is accepted that tenure-track faculty develop into recognized academic scholars. In an era of reduced research funding from both the private and public sectors and an increased emphasis on research at almost all universities, the result is more competition for less resources. This, in turn, means more demands on faculty. The reality is that given the research expectations, few, if any, faculty are able to totally focus on curricula, new education pedagogy and innovation, connecting practice and application to education, and proactively advising and mentoring students. All programs of construction engineering have an opportunity to broaden their pool of talent and resources for educating tomorrow's engineers while recognizing the importance of implementing ideas contained in the ASCE body of knowledge.

The utilization of Professors of Practice (Gappa 1996) is not new; there are currently active positions at a number of universities in the United States, especially positions in the sciences. Professors of Practice can be found at Carnegie Mellon University, University of Colorado, Duke University, Georgia Institute of Technology, George Washington University, Harvard University, Lehigh University, MIT, Syracuse University, and Worcester Polytechnic Institute. Noteworthy is the similarity among virtually all such programs regarding non-tenure-track status, strength in teaching, and a focus on professional practice based on extensive experience and knowledge in the world of practice. At the same time, each of these universities use Professors of Practice in a variety of programs, therefore it is clear that the positions are adaptable to pure construction engineering, to construction engineering and management, and to construction technology degrees.

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Georgia Institute of Technology

Georgia Tech has a number of eminently qualified academic, business, or government leaders who have made major impacts on fields and disciplines important to Tech's programs. Tech requires that these professors

- Be distinguished academicians and practitioners who have had a major impact on fields important to Georgia Tech's teaching and research programs;
- Have substantial experience, normally at least 10–15 years, and a national/international reputation for excellence;
- Have rich and extensive backgrounds in fields and disciplines related to the school or college of appointment at Georgia Tech; and
- Serve as liaisons between industry or government and Georgia Tech in identifying teaching and research opportunities that support the public interest and societal needs.

Carnegie Mellon University

At Carnegie Mellon the Professor of Practice stipulations are the following:

- Be a successful and effective professional in the given field. At least 10 years of professional practice is normally expected.
- Be an effective teacher of the profession. As evidence of effective teaching, one can present other professionals that have learned from the candidate, written or oral presentations that educate, teaching records from professional or academic organizations.
- Understand research that applies to the profession. The person should be able to evaluate research results, devise applications of the research, and teach the results to students. The person need not have a research track record comparable to regular faculty.

Massachusetts Institute of Technology

MIT seeks professionals who will bring specialized knowledge to support particular thrust areas of the institution.

- Appointments to the rank of Professor of the Practice are made only to practitioners who have developed a high level of expertise in fields of particular importance to the MIT academic program and who also demonstrate a deep commitment to teaching and research. Responsibilities include, but are not limited to, teaching, and conducting and supervising research. Each appointee should teach at least the major part of one subject per academic year, may be the instructor in charge of subjects of instruction, may supervise theses with departmental permission, and may be principal investigator on research projects.
- Professors of the practice are academic instructional staff positions and may be full or part time, paid or unpaid. In cases where departments wish to commit to multiple-year appointments such appointments may be for two or more years, but not more than 10 years, and must be approved by the dean, the school council, and the Academic Council. These appointments, which may be renewed indefinitely, are subject to a 5-year review by the School council and a 10-year review by both the school council and the Academic Council.

Advantages

University Professor of Practice positions are increasing. Professors of Practice are typically better teachers than researchers and many would rather spend more time in the classroom than doing research. Normally, they need only the field's entry degree and 10–15 years of work experience. The length that Professors of Practice remain at a university depends how long they are needed. Typically contracts are for not more than 5 years. Usually the number of Professors of Practice in a department is limited to a percentage of the total faculty. Their duties are typically specified by the dean/chair of their department. Although Professors of Practice are typically known for teaching, they can also be valuable in applied research, and are usually excellent at service and outreach, or a combination of both.

Controversy

The use of Professors of Practice has, however, caused controversy. The American Association of University Professors (AAUP) and faculty unions at some universities have questioned administrators as to the intent of hiring nontenured professors. There is concern that the use of such individuals is a measure aimed at diluting or abolishing tenure. AAUP believes that contingent faculty, the general grouping in which Professors of Practice are categorized, undermines academic freedom, academic quality, and professional standards. These are very real concerns and the use of Professors of Practice must be such that they enhance the academic experience of the student, raise the cognitive achievement of the student, and prepare the future generation of engineers to practice in the challenging and complex but rewarding world of the 21st century.

Construction Engineering

The war that the United States plunged into in 1917 caused the Army to greatly expand its engineering capability, but the need was primarily for railway engineers, and these were drawn from the experienced men working for railroads across the country. The situation was very different 22 years later as the Battle of Britain raged over English cites. The "Destroyers for Bases Agreement" that President Franklin D. Roosevelt negotiated in 1940 granted the United States the right to construct a string of air bases on British territories in the Atlantic Ocean. From that point on, the need for engineering expertise in construction of facilities expanded astronomically, and as a result, the Army began establishing its own schools focused on instruction of construction practice. Those schools would lead to recognition of the need for establishing construction engineering academic programs.

Within the university, construction engineering as a separate discipline had its birth after World War II when R. L. Peurifoy (1902–1995) began teaching it at Texas A&M in 1946. Peurifoy had served as principal specialist in engineering education for the U.S. Office of Education during the war and came to recognize the need for a concentration in construction. His work aimed explicitly to bring a greater level of specificity and precision to construction engineering. These labors continued into and through the 1950s and formed the foundations of what today is described as construction engineering education (Halpin 2007). The Texas A&M program was soon joined by programs at Stanford University, MIT, the University of Mississippi, North Carolina State University, and the University of Michigan. By the early 1960s the discipline had matured and graduate programs evolved at Illinois, Michigan, Purdue, and Stanford.

As at Harvard a century before, with the proposal for a scientific school, the development of construction engineering as a separate academic discipline was challenged by many engineering schools because construction was and is still viewed by many as a business or commercial endeavor rather than an engineering activity. "In some academic circles, establishing construction as an academic discipline was vigorously opposed" (Halpin 2007). Even with that opposition, construction engineering has over the past 60 years matured significantly as an academic discipline. The opposition and debate that has relentlessly plagued construction engineering is really a mirror of the questions facing all civil engineers, specifically, how should the preparation for the practice be structured.

To achieve recognition in the university environment, construction engineering requires a research agenda. In 1968, acceptance of construction engineering was, therefore, aided tremendously when the U.S. Army Corps of Engineers establishment its Construction Engineering Research Laboratory adjacent to the University of Illinois. Soon thereafter the National Science Foundation began funding construction research, and later in the 1970s, the Energy Research and Development Agency of the federal government funded construction research at Georgia Institute of Technology, Ohio State University, the University of Texas, and at Pennsylvania State University (Halpin 2007).

Accreditation of Programs

ASCE was one of the seven engineering societies that came together in 1932 to found and organize the Engineers' Council for Professional Development (ECPD). ECPD was the predecessor to ABET, Inc., the recognized accreditor for college or university programs in engineering and technology in the United States. Actual evaluation of engineering degree programs began in 1936. With increased responsibility for program evaluation, ECPD changed its name in 1980 to the Accreditation Board for Engineering and Technology, which was shortened to ABET, Inc. in 2005.

Construction engineering as a unique academic discipline has its foundation based on the fundamentals of civil engineering—statics, fluid mechanics, geotechnical engineering, and structural analysis and design. For a construction engineering program to receive ABET accreditation requires that the program demonstrate that graduates have an understanding of construction processes, methods, materials, systems, equipment, to include planning, scheduling, safety, cost analysis, and cost control. This requirement is in addition to proficiency in the supporting subjects of mathematics, chemistry, and physics, and an understanding of management topics and legal issues. ABET guidance sets forth the requirement that faculty must include at least one member who has had full-time experience and decision-making responsibilities in the construction industry (ABET, Inc. 2006).

Professional Licensure

The title Professional Engineer (PE) implies that one holds paramount the safety, health, and welfare of the public [World Federation of Engineering Organizations (WFEO) 2001]. The process of licensure is the decisive career step that raises a technically trained person to the status of professional engineer with all of the implicit responsibilities that go with the authority to make critical decisions affecting the public. Every state has its own specific requirements for licensure as a professional engineer. Nevertheless, some uniformity results from the fact that all state licensure boards are members of the National Council of Examiners for Engineering and Surveying (NCEES), and the council seeks to promote uniformity of U.S. licensure processes. The first step toward licensure is the Fundamentals of Engineering (FE) exam. By NCEES model rules, a candidate is eligible to sit for the FE during the senior year of enrollment in an engineering program (NCEES 2009). This is an 8 h exam broken into two parts. The first part, 4 h, covers the primary knowledge base of engineering mathematics, chemistry, physics, statics, and introductory design. The second part can be taken either as a general exam or in a major specialty area. There is no specialty FE exam for construction, so individuals must take either the general exam or one in civil engineering.

Once individuals successfully pass the FE exam and have satisfactorily fulfilled the application requirements of the jurisdiction (usually a specified work duration under a professional engineer), they can take the PE exam. The civil engineering PE exam is also structured in two parts. The first part is a breadth exam, and the second part is a depth exam with the examinee choosing questions from one of five specialty areas, which now includes construction. The inclusion of construction with geotechnical, structural, transportation, and water resources/environmental engineering as a specialty area for the PE exam has only been achieved in the last decade.

The Construction Engineering Education Committee of ASCE was organized in 1995, and it immediately undertook the task of advancing construction engineering as a recognized specialty area under the NCEES model rules. After 8 years of work, NCEES agreed to assess the modification of the specialty areas of the civil engineering PE exam to include a construction engineering module (Johnson 2007). At that point it was necessary to conduct a Professional Activities and Knowledge Study (PAKS), which is the first step in developing a PE exam. A PAKS asks two questions:

- What does the newly licensed civil engineer do?
- What does the newly licensed civil engineer need to know to perform those tasks?

The PAKS results were approved by the NCEES board of directors in 2005, and development of the construction engineering PE exam began immediately. Although the primary purpose of the PAKS was to validate construction as a separate specialty discipline within civil engineering, it also provided a better understanding of the knowledge base needed by construction engineers. The PAKS results should therefore be of value to construction engineering education community and to industry in identifying critical subject matter for inclusion in courses and curriculums (Johnson 2007).

Thanks to the efforts of the Construction Engineering Education Committee, individuals can now take the first part of the PE as a breadth exam in construction engineering and the second part of the PE as a depth exam in construction engineering. This has only been possible since April 2008.

Challenges

There is a critical need for a better educational vision to support the development of construction engineers that are prepared to meet the challenges of the 21st century. At its root, construction engineering is the series of technical activities throughout the project delivery process that influence design, support construction means and methods decisions, create a safe and productive construction environment, and seek to avoid and solve the engineering issues associated with project delivery. These typical activities are understood, but the challenge is to successfully accomplish each while attempting to execute "giga" projects, such as the third lane of the Panama Canal, or projects in urban environments, such as the World Trade Center, while keeping the city functioning. Understanding of the critical role construction engineering plays in delivering these projects to provide societal benefits and to improve the sustainability of the built environment is imperative. That understanding must be joined with a new construction education process that prepares engineers to understand the connections between disparate components and integrate them into successful delivery of a new generation of complex projects squeezed within existing infrastructure.

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Fig. 3. Interoceanic Highway construction in the Peruvian Andes (image by C. Schexnayder)

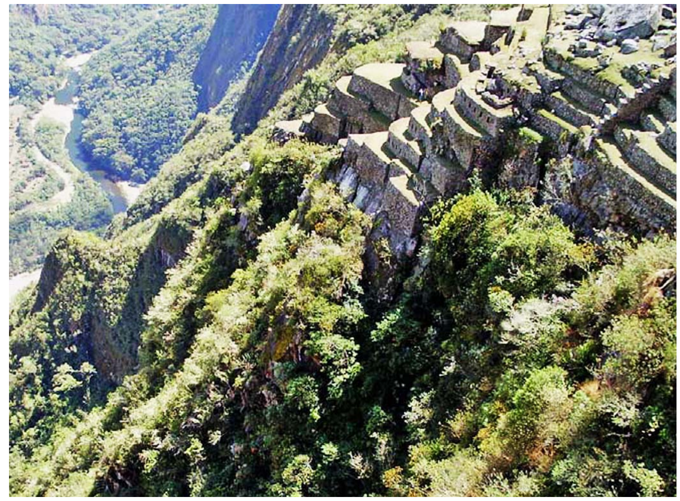

Fig. 4. Inka-constructed foundations at Machu Picchu (image by C. Schexnayder)

Final Thoughts

Engineering is light and this light can transform chaos into cosmos. The Inka engineers understood light because the foundation of their engineering education was agriculture. To be successful in growing plants, it is necessary to have an understanding of the amount of daylight each type of plant needs. Light is also warmth. To position a field to receive the light and warmth of the sun affects the success of plant growth. Are construction engineers of today attuned to nature? Does the engineering education process provide a graduate with an appreciation of how light affects their work and finished structures?

When MacDonald Construction Company and Pittsburgh-Des Moines Steel Company were trying to close the Gateway Arch on the waterfront in St. Louis, the light of the sun affected the expansion of east and west sides differently. This caused problems when the builders attempted to place the closing steel section at the top of the 192 m (630 ft) arch. They had to resort to working early in the day, and even then it was necessary to have the fire department deploy and spray the east surface with water to moderate the temperature difference. With the challenges of shifting populations to urban areas and limited resources, an appreciation of very slight natural differences can provide the basis for successful sustainable solutions to engineering challenges.

Engineering is water. Water can be destruction and death, as with a flood, but water is primarily life. The Inka engineers understood water because the foundation of their education was agriculture. Life, plant, animal, and man, comes forth from water. Clean water refreshes and renews. Inka engineers succeeded because they learned to work with water instead of trying to control it with brute force. James B. Eads, builder of the bridge that bears his name in St. Louis, understood water, and with that understanding he successfully opened the Mississippi River channel into the Gulf of Mexico in 1870. Instead of working to dredge a channel he used jetties that drew the river to the work of creating a ship channel.

Engineering is air. The artificial movement of air provides ventilation in modern buildings—the heating, ventilating, and air conditioning (HVAC) system. The Inka engineers understood the natural air flow provided by nature. They constructed their food storage building based on such knowledge. Taking advantage of the microclimates of the Andes, root crops (potatoes) were stored in buildings erected at specific elevations on the mountains. Additionally, these structures were oriented with the prevailing wind and had windows (doors) on both their uphill and downhill sides. The principle function of such architectural features was temperature control (Morris 1992).

Engineering is earth. Today geotechnical engineers are struggling to construct the Interoceanic Highway over the Andes of Perú (Fig. 3). The primary problem is to keep the road from sliding down the side of mountains that are being constantly pushed up by the movement of the Nasca plate under the continental plate. Inka engineers faced a similar challenge at Machu Picchu. Nearly everyone has seen the poster pictures of Machu Picchu, but to appreciate the skill of the Inka engineers it is necessary to step to the side and look at the foundations that have keep those magnificent structures atop the mountain (Fig. 4). In 1912, four centuries after the Inka Empire expired to the Conquistadors, Hiram Bingham began to reclaim Machu Picchu. He found the well-built Inka walls still intact even after those centuries of neglect. It might be said that the Inka engineers gathered strength from the very earth that produced them and thereby claimed their empire.

Can today's engineer gather strength from the earth? Do our university-trained engineers appreciate how to work with nature—light, water, air, and earth? Understanding how past achievements were accomplished can aid in the formulation of thoughtful solutions to current engineering challenges, particularly if the engineer remembers that success goes to those who approach nature with imagination, respect, and humility.

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