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JOURNAL OF THE BOSTON SOCIETY OF CIVIL ENGINEERS SECTION/ASCE

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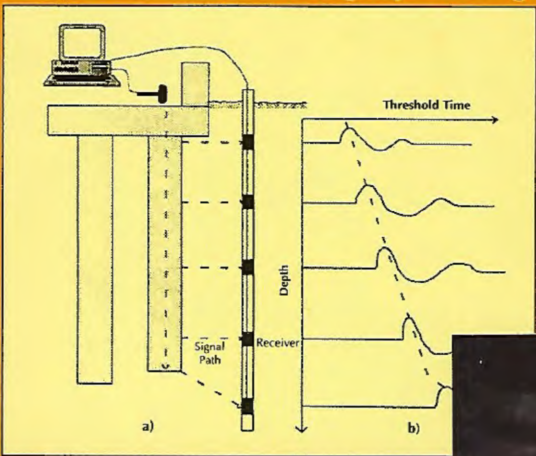
Deep Foundations Integrity Testing



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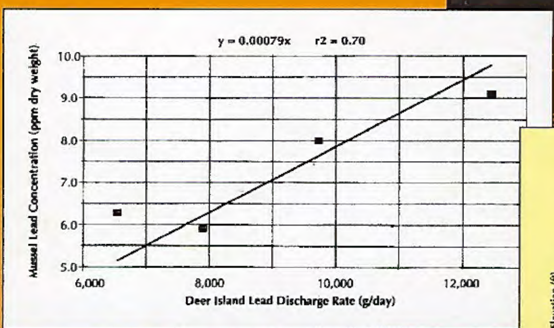

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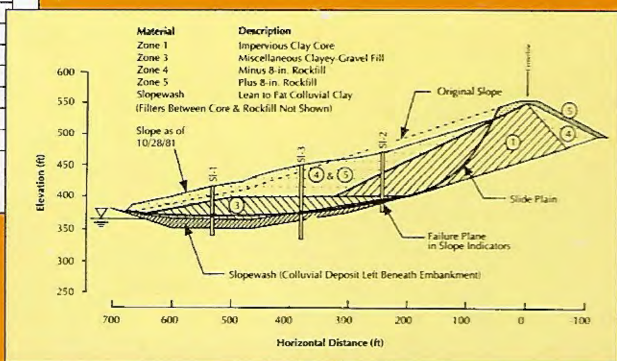

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The Role & Contributions of Hydraulic Testing Labs: Part I, Industrial Revolution to World War I

Hydraulic testing laboratories have played key roles in advancing the science, practice and teaching of fluid mechanics. One on-going laboratory has made far-reaching contributions in the field.

GEORGE E. HECKER, ALBERT G. FERRON & BRUCE J. PENNINO

Prior to the 19th century, water power in the United States was furnished mainly by undershot, overshot, breast and paddle wheels (see Figure 1). In the early 1800s, experimentation with different types of hydraulic wheels, still mostly constructed of wood, began. Flutter wheels, Barker's mills and tub mills were utilized in the various industries of the times. In the 1820s and 1830s, Claude Burdin and Benoit Fourneyron experimented with iron turbines, which culminated in a patent issued to Fourneyron for an outward-flow wheel (see Figure 2). Samuel Howd of Geneva, New York, patented an inward-flow wheel in 1838 and an outward-flow wheel in 1842. At the Lowell, Massachusetts, mills in the mid- to late 1840s, James Bicheno Francis and Uriah Boyden experimented with turbines and diffusers, initially using Howd and Boyden patents. Asa Swain, in 1857, and John McCormick, in 1870, improved the blades of the turbines that to this day bear the name of Francis (see Figure 2).

The Industrial Revolution in New England

Huge textile mills were being built in Lowell (in 1822) and Lawrence, Massachusetts (in 1845), Slatersville, Rhode Island, and Manchester, New Hampshire. A large complex of paper manufacturing companies was erected along the Connecticut River in Holyoke, Massachusetts, in the mid-1850s. These mills were greatly responsible for fostering the development of hydraulic engineering in the United States. Various types of wooden water wheels, up to 30 feet in diameter with 12-foot buckets, were

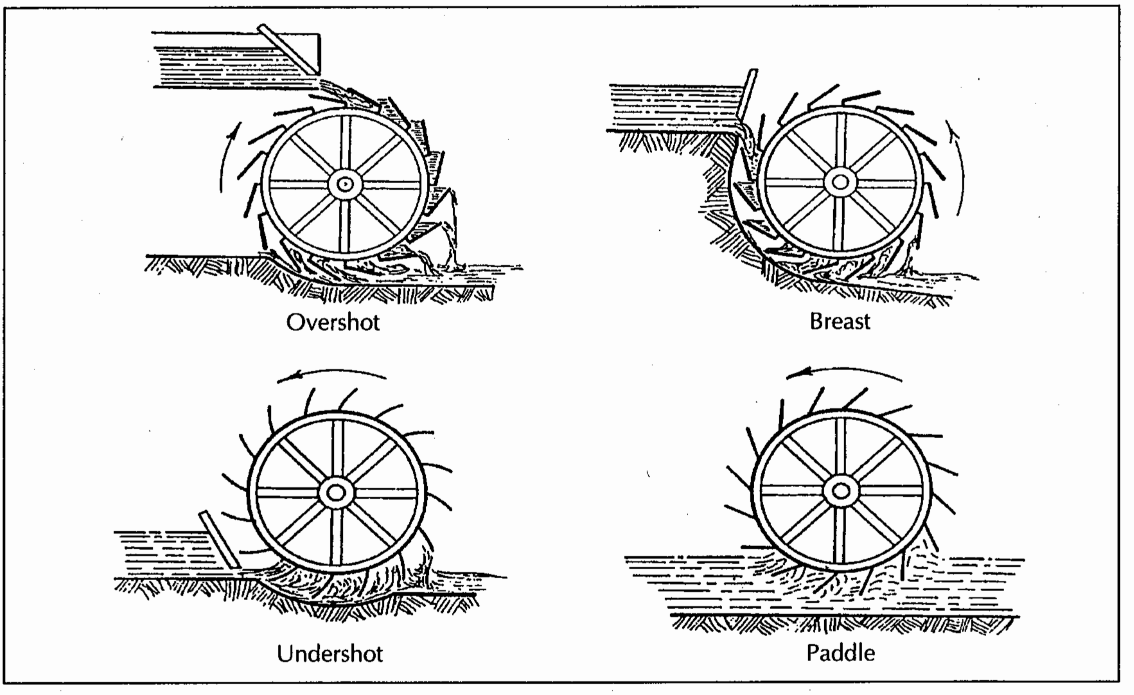

FIGURE 1. Early types of water wheels.

being used at this time). In 1828, the growth of Worcester, Massachusetts, was helped when the Blackstone Canal linking the city with Providence, Rhode Island, began operating.

Worcester was developing into an industrial city of mechanics. Immigrants were arriving in large numbers to work in developing wire/cable and the machine tool industries. In the 1830s, an expert mechanic, Icabod Washburn, was producing quality wire in Worcester and locomotives were being manufactured in Lowell. Also in Worcester, the nation's leading builder of stage coaches turned to railroad cars in 1837, quickly becoming again the nation's leader in that field. "High-speed" weaving machines and looms were being designed and manufactured in the city. From about the 1840s, many companies were supplying looms for fancy woolens to the mills in Lowell.

By the 1840s, the Industrial Revolution had truly arrived in Worcester. The city's population increased from 2,962 in 1820 to 7,497 in 1840, and 25,000 in 1860. By 1885, Worcester was a thriving industrial city of 63,000, with

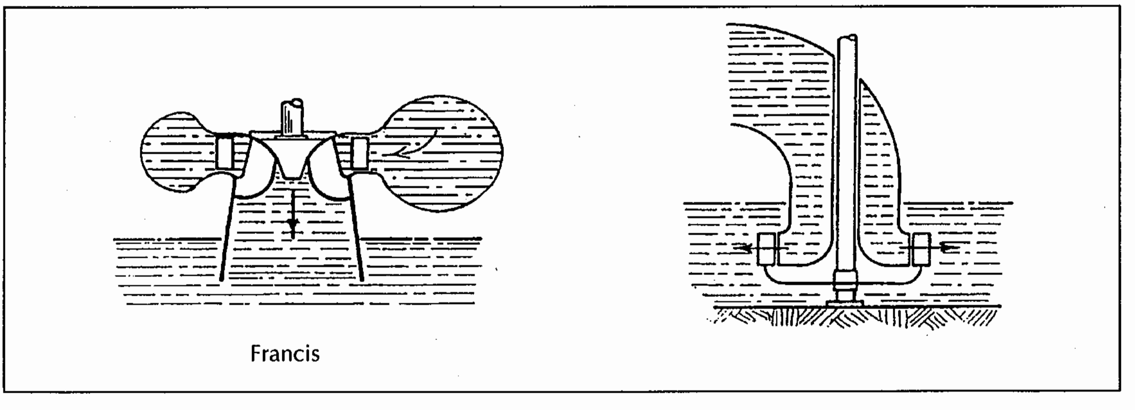

FIGURE 2. Early turbines.

722 industrial firms that supplied machinery and wire to industry. This population would increase 80 percent by 1898 to 103,000, when Worcester would be the third largest city in New England. However, economic growth slowed in 1893 when a financial "panic" occurred with a stock market crash; in the following year more than 400 banks in the United States failed.

Development of Hydraulic Engineering in New England

The growing industries in Worcester, Lowell, Lawrence and Holyoke needed a way to make more efficient use of their cheapest source of energy — water. Waterpower purveyors and users sought out the best engineering minds available to help them do so.

One pioneering hydraulic engineering writer and investigator in New England was Charles Storer Storrow (1809–1904). Born in Montréal, educated at Harvard, and trained in France, Storrow wrote the first American book on hydraulics.[1] He was retained by the Proprietors of the Locks and Canals (the Proprietors) on the Merrimack River at Lowell in 1835 to measure the quantity of water used by the mills. He later repeated the Lowell mill concept at the new mill city of Lawrence (downstream on the Merrimack) as Chief Engineer of the Essex Company.

In 1837, James Francis (1815–1892) was hired by the Proprietors at Lowell.[2] Francis worked on canals in England before coming to the United States in 1833 as assistant to George Washington Whistler (1800–1849), father of the artist, on the New York to Boston railroad. Whistler then took him to Lowell, where he later succeeded Whistler as canal superintendent and in 1845 became the Proprietors' principal engineer, remaining in that post for nearly 40 years. Among his major responsibilities at Lowell were measuring the flow to each mill so that costs could be properly and fairly assessed, and to determine the efficiency of the machinery that converted the flow to power.[2,3]

Francis' early, large-scale detailed experiments on improved turbines, weirs, stream gaging and related topics pioneered hydraulic engineering in the United States. They are described in his 1855 book, *The Lowell Hydraulic Experiments*.[3]

The development of textile mills in New England would also have a dramatic effect on another engineer starting his long career at about this time. Charles T. Main graduated from the Massachusetts Institute of Technology (MIT) in 1876 with a degree in Mechanical Engineering. After working as an assistant in MIT's Department of Mechanical Engineering for three years, Main became a construction engineer for the mills in Manchester, New Hampshire. By 1891, he was Superintendent of the Lower Pacific Mills. Over the years, Main engineered numerous hydroelectric projects, including the major developments on the St. Lawrence River at Massena and on the Niagara River at Niagara Falls.

By 1879 much was known about the measurement of water through hydraulic turbines. However, Clemens Herschel (see Figure 3) found that the Holyoke mills (which were mostly paper mills) used large amounts of water that remained unmeasured, thereby losing considerable income for his employer. Using Venturi's principle, he designed and tested a 12-inch and a 48-inch diameter meter. This type of meter that measured water flow more accurately was called a Venturi meter.

Engineering Education & Training

When the mills began to operate in America, people also saw the need for technical education. In 1861, MIT was founded by William Barton Rogers, a geologist. Its completion was delayed by the Civil War, and classes were first held on February 20, 1865.[4] Also in 1865, John Boynton, a tinware peddler, supplied the funding for a technical school in central Massachusetts. The school, initially known as the Worcester County Free Institute of Industrial Science, was built in Worcester and enrolled the first class in its three-year program in 1868. The institute was later renamed Worcester Polytechnic Institute (WPI) in 1887. Its initial teaching staff of five included George I. Alden (see Figure 4), instructor in theoretical and practical mechanics. Alden received his basic education at the newly created Lawrence Scientific School of Harvard, and was influenced by the early hydraulic work in Lowell and Lawrence.[2]

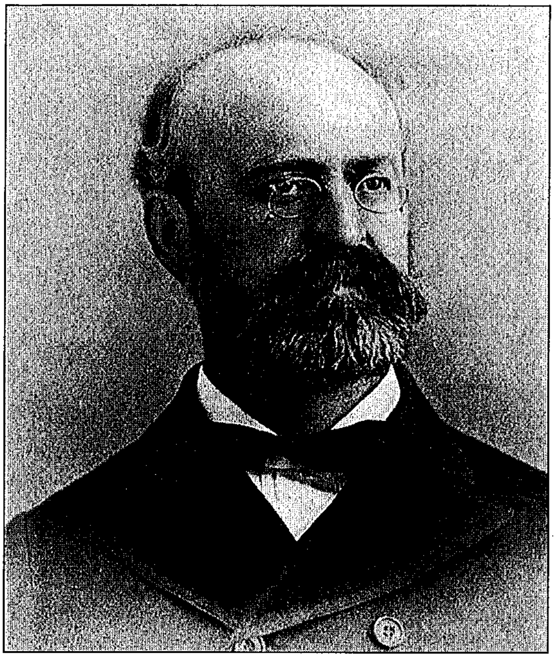

FIGURE 3. Clemens Herschel.

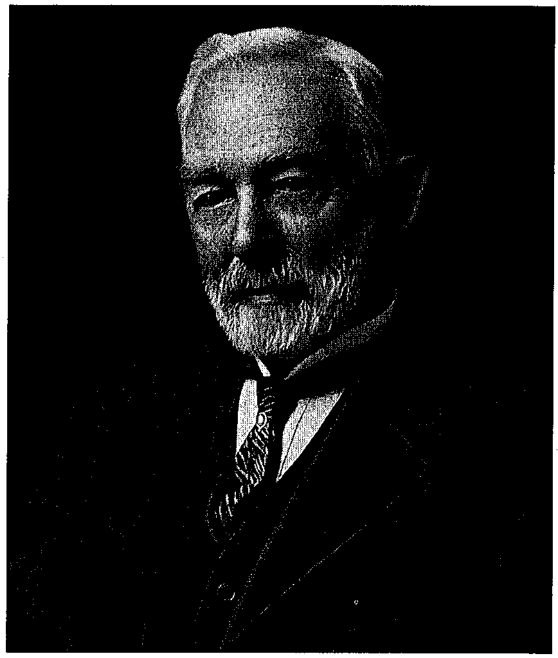

FIGURE 4. George I. Alden

Birth of a Hydraulic Testing Laboratory

Alden was an astute engineer and apparently well read on the new technologies of his time. During his first two decades at WPI, he became aware of the hydraulic developments of Francis in Lowell and those of two of Francis' former colleagues who had taken positions around 1879 at the Holyoke Water Power Company. One of these engineers, Clemens Herschel, invented the Venturi meter; while the other, James Emerson, was responsible for building a turbine test facility of 200-cubic-feet-per-second capacity under an 18-foot head. This early hydraulic facility (known as the Holyoke Testing Flume) was utilized for obtaining the efficiency of 139 water wheels located in nearby factories, most of which were in the paper industry. When its reputation spread, the testing flume was utilized by many turbine manufacturers and users of the day. As turbines became larger and the value of water and head was fully appreciated, the efficiency of the "wheels" became a major selling point. At this time, the different aspects of efficiency were just starting to be appreciated and defined.

During the period from about 1870 to 1890, great strides were made to improve the efficiency of water-powered machinery due to the increase in manufactured goods utilizing limited water supplies. Also, the invention of electricity by Thomas Edison and the ability to produce this electricity by waterpower further inspired Alden to formulate plans for facilities at WPI that would be at the cutting edge of technology. The institute's interest in waterpower in the late 1880s was probably stimulated by the appearance of electric utilities in the eastern United States during that time. These companies required engineers knowledgeable in hydraulics.

Alden proposed that WPI should build engineering facilities, a turbine that could also be used for testing and instruction, and a hydraulic laboratory. With these facilities, Alden envisioned testing relatively large equipment, something not normally associated with technical school laboratories. Alden was invited on June 8, 1893, to the home of U.S. Senator George F. Hoar, a WPI trustee, to present his ideas before a trustee committee meeting. The committee ended up recommending that the institute build the facilities and asked the school to acquire the use or ownership of some neighboring waterpower sites for making tests of hydraulic machinery.

Later that year at an alumni dinner, Alden presented the proposed facilities for WPI. Alden indicated that a water-mill power site existed in Chaffinville, a village of Holden, a town just to the north of Worcester. Stephen Salisbury III, a prominent local industrialist as well as a WPI trustee and benefactor, was in attendance and questioned Alden as to the exact location of this site. Salisbury then indicated that he was the owner and would be glad to give the school the property for a test facility. The Holden site obtained water from a 200-acre pond, and two smaller 2-acre and 4-acre ponds were on the site, which was located five miles from the school.

The hydraulic laboratory at WPI, established in 1894, was the third hydraulic laboratory established at an American school and the second at an American engineering school. Prior to 1883, the University of California, under Frederick Hesse, established the first hydraulic teaching laboratory. In 1887, Mansfield Merriam built a similar laboratory at Lehigh University. Merriam was famous for his textbook *Treatise on Hydraulics*, which was first published in 1889 and had subsequently gone into ten editions.[5] Cornell University followed WPI with a laboratory in 1899. As the importance of hydraulics grew, many of the U.S. engineering schools added laboratories in the early 1900s to supplement classroom instruction. Another notable laboratory founded about this time was at the State University of Iowa.

Site History

WPI's Hydraulic Laboratory was located on a stream whose flowage rights were acquired by John Bigelow in 1726. At that time, this section of Massachusetts was called Worcester North Half or North Worcester, and it was highly forested. Since the area had been recently opened for development, Bigelow erected a water-powered sawmill to produce lumber for the new inhabitants' houses and other necessary buildings.

Besides running the sawmill, Bigelow was active in local politics. In 1740, armed with a petition signed by 25 people, he approached the Massachusetts Legislature to have this section of Worcester incorporated as a separate town. On May 4, 1741, after two petitions, Governor Belcher signed the act creating a new town called Holden.

There is little record of Bigelow's activities, but in 1753 his property was acquired by Benjamin Flagg who built a sawmill of his own. The present dams located on Lincoln and Shrewsbury Streets were erected by Bigelow and Flagg to impound the water necessary to power their mills. Unfortunately, the impoundments flooded valuable hay meadows in an area where cultivable land was scarce. This situation led to a compromise with local farmers whereby the ponds were drained in the spring and re-flooded in the late fall. As more land was cleared, the farmers relaxed their rights to the meadow hay, and in the 1770s the ponds were allowed to remain full all year. Following the War for Independence, a grist mill (see Figure 5) was built and operated in conjunction with the sawmills. The owner was Samuel Chickering, a blacksmith who ran his shop on the site and leased the mills.

All this development in Holden was taking place when England was experiencing the Industrial Revolution and unrest was brewing in the Colonies. Isaiah Tomas, a Boston printer, began publishing his rebel newspaper, *The Massachusett's Spy*, from Worcester in 1775. John Kay's flying shuttle (1733), James Watt's steam engine (1769), Richard Arkwright's spinning frame (1769), James Hargroaves's spinning jenny (1770), Samuel Crompton's mule (1779) and Edmund Cartwright's power loom (1783) were the main factors in promoting increased production in the textile industries. These inventions were indirectly responsible for the creation of the laboratory and its early involvement in testing turbines used to power textile machinery.

The Embargo Act of 1807 caused great hardships in the new American states, and caused Americans to look into increased production of goods such as textiles, paper and metal. Water was a readily available source of power and all water sites became important, even those in Holden. At this time, Holden, as most of New England, was a self-sufficient, agricultural-based community that benefitted by close

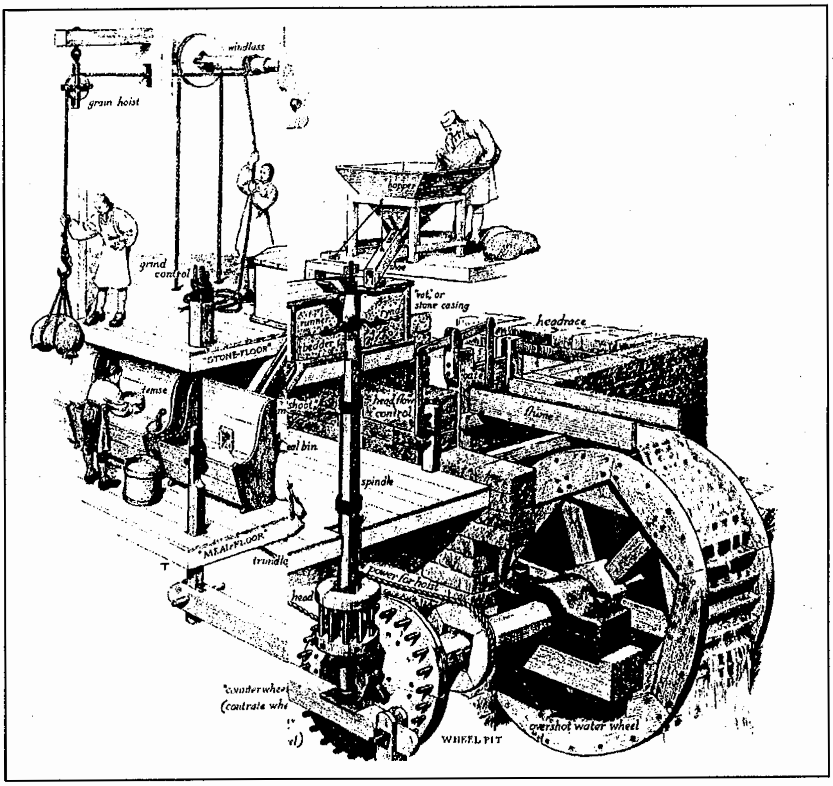

FIGURE 5. A typical grist mill.

proximity to a growing city — in this case, Worcester.

In 1817, Royal H. Chaffin acquired the Holden site of the future laboratory (see Figure 6), with sawmill, lumberyard and gristmill. Chaffin added wool dyeing and yarn coloring operations. In 1819, John Parks acquired the sawmill and lumberyard along with a water privilege reading "for said sawmill when there shall be more than is needed at the grist mill." Chaffin, located downstream and perhaps uncomfortable with this situation, eventually reacquired complete control of the site. His son Alfred occupied part of it, manufacturing woolen goods used in prison uniforms, and later became sole owner of the entire site and its water rights. The neighborhood of the site, including the mill ponds, was referred to as Chaffinville and is shown as such on maps from the 1870s.

During this pre-electric period, mills like those at Chaffinville frequently experienced destructive fires due to the combination of hazardous lighting and heating systems and highly flammable cotton, wool and flour dust. Alfred Chaffin had built a grist mill in 1870 only to see it demolished by fire. It was rebuilt, only to burn again in 1890. Subsequently, the site changed hands several times. The names of Daniel Hesselton, Lewis Rivers and John Shewbrook appear on deeds of various parts of the property. Shewbrook had converted the grist mill to a shoddy mill used to process woolen cloth into wool yarn. Later in the 1890s this mill, too, suffered a disastrous fire.

The deeds of the Holden site in the late 1800s record Stephen Salisbury III as the mortgage holder for all the proprietors of this site. The Salisbury family was a prominent Worcester industrial family in the 1800s, and the three Stephen Salisbury's had been long associated with WPI. The oldest known photograph, circa 1894, of the site is shown in Figure 7. It was taken standing on the south side of Shrewsbury Street, looking approximately east toward the "red barn" in the background. (This barn still exists on the site.) The new pipe being installed under Shrewsbury Street runs to the original laboratory.

Initial Layout

The first laboratory structure, built on the site of Chaffin's old woolen mill, was a wood frame building, 90 feet by 40 feet, erected in the summer and fall of 1894 (see Figure 8). This site had enough water at a head of 30 feet to produce 75 horsepower. A horizontal control gate was built at the exit of Pond No. 2 (see Figure 6), and a 40-inch riveted steel pipe approximately 400 feet long was installed from

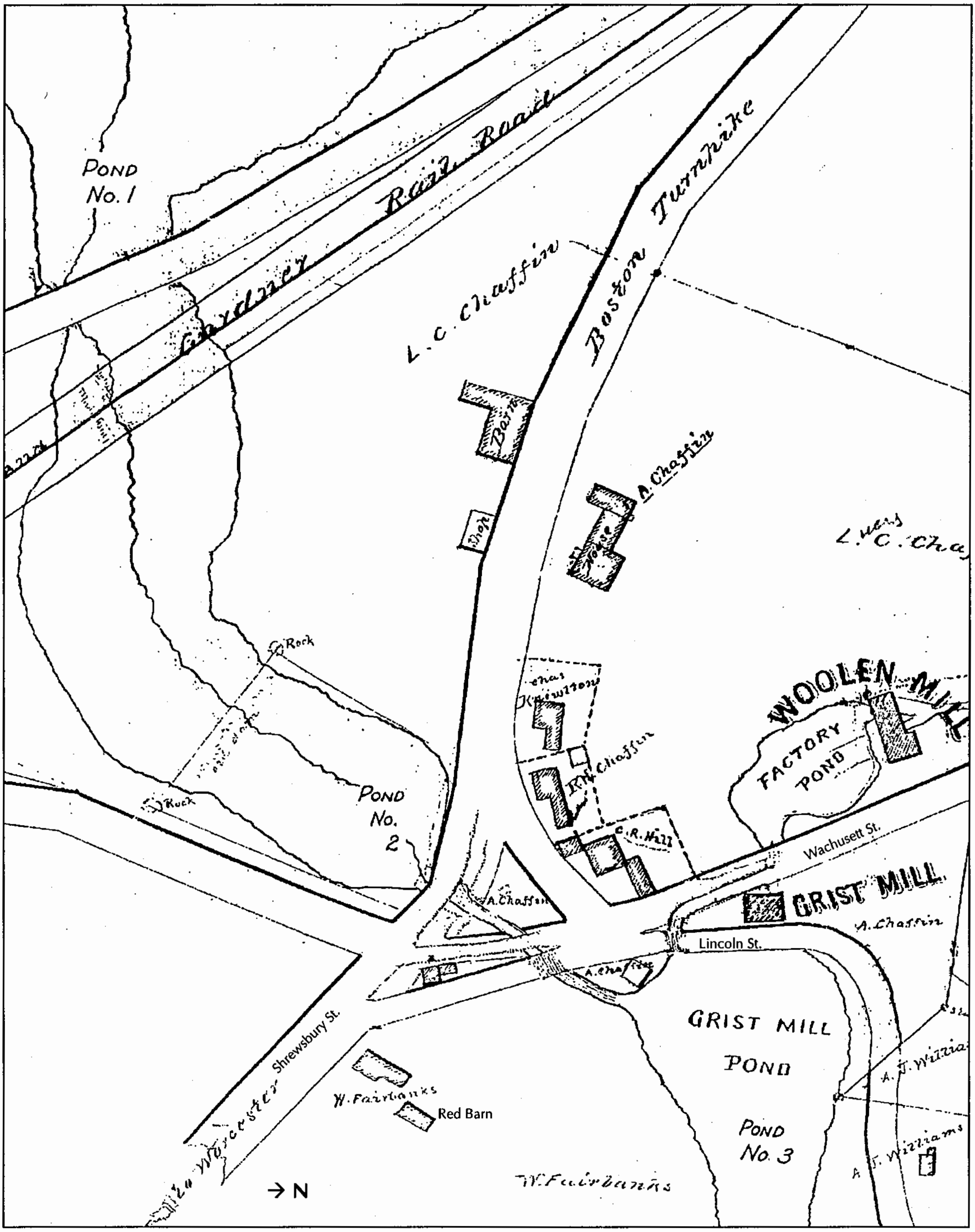

FIGURE 6. Chaffin's map, 1873.

the gate to the building to supply water for testing. A 30-foot-high tower was erected onto the building to provide access to glass tubing from piezometers located in the steel pipe and the flow measuring device (a Venturi meter). This building, enlarged and modified several times, is still used for flow meter calibration and other types of testing.

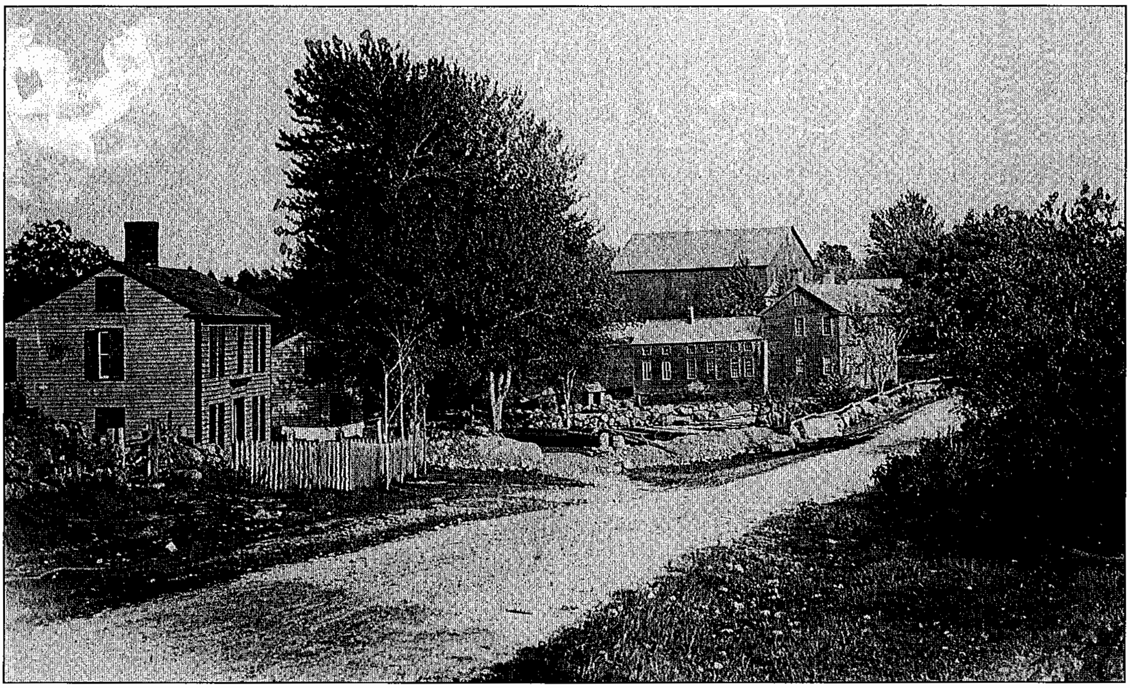

FIGURE 7. Hydraulic Laboratory site, circa 1890.

Testing Equipment

Clemens Herschel's Venturi Meter. The first piece of equipment for the new hydraulic laboratory was a 36-inch by 16-inch Venturi meter designed by Clemens Herschel for the 1893 Columbian Exposition in Chicago and the largest in the world at that time. A pamphlet published for the exposition indicated that the meter was the first commercial Venturi meter ever built. After the exposition, the meter and its automatic recorder were purchased by Stephen Salisbury III at a cost of $500 and donated to WPI. This Venturi meter is shown in its original laboratory location in Figure 9. Taps for velocity traversing and the U-tube connected to a probe should be noted. In the background is an early recorder or controller.

An interesting story exists concerning the performance of the meter at the Columbian Exposition. The meter had been installed in series with a piston pump to measure the total water supply to the exposition. It was common in those days to measure large water flows using piston pumps. Knowing the piston displacement and the rotational velocity of the pump, it was possible to obtain the flow rate, assuming the leakage was insignificant. This technique was well accepted as being a very accurate method to measure relatively large flows. Therefore, at the end of the exposition, the records of both the Venturi meter and the piston pump were compared. A discrepancy of approximately 20 percent was found. After much thought and deliberation, the discrepancy was attributed to the fact that the Venturi meter was relatively new, its theory having been presented by Herschel in a 1887 paper, and that there was the possibility that there was a flaw in the theory. Herschel could not believe that the testing he had performed at the Holyoke Water Power Company and later at the East Jersey Water Company could have produced data whose results, when applied to the exposition meter, would result in a 20 percent error. After all, the test meters and the exposition meter were of approximately the same size. Herschel, therefore, sent one of his engineers to Chicago to investigate the inconsistency between the two devices. Among the investigations the engineer pursued was a walking inspection of the site. One of the things he discovered was a manhole cover located between the piston pump and the Venturi meter. Upon removing

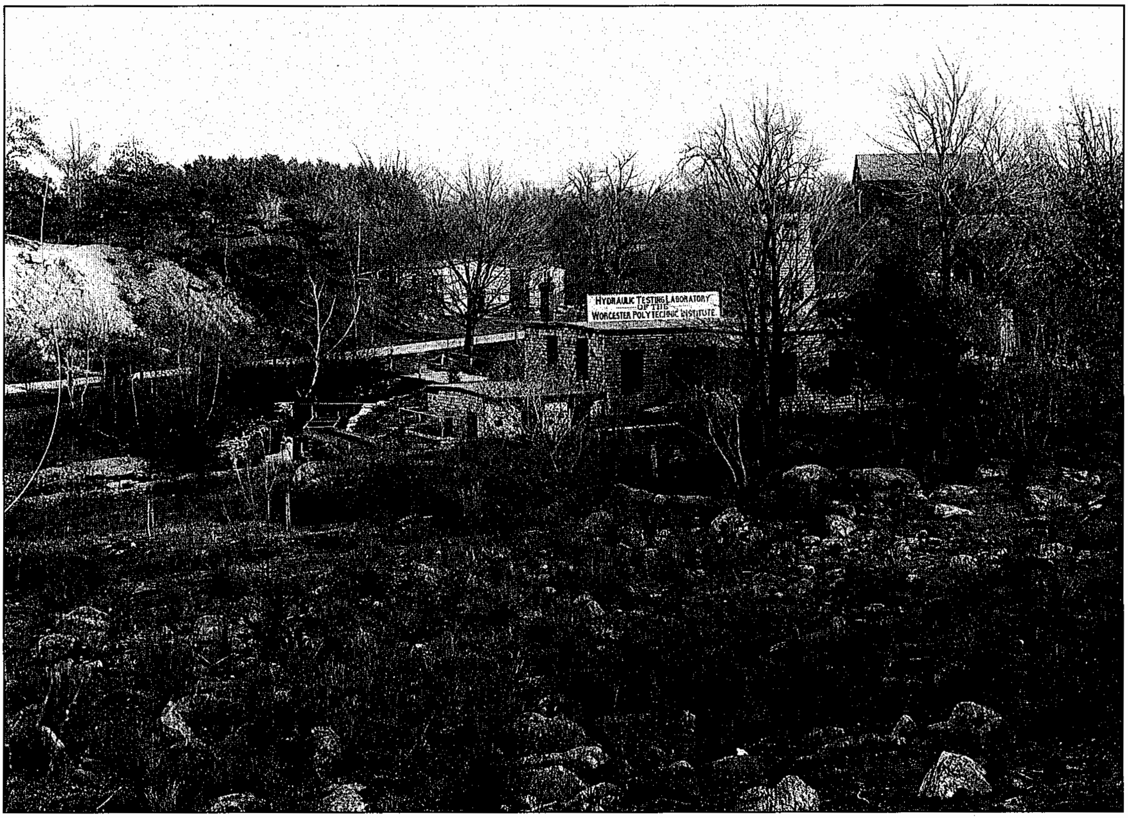

FIGURE 8. Original buildings and water supply channels in 1907.

the cover, he noticed that a 12-inch line containing a valve had been installed onto the side of the main pipe. Climbing down the manhole, he discovered the valve to be wide open. Further research traced the 12-inch line to a slaughter house. As the result of the investigation, the operators of the exposition decided to obtain the difference between the flow indicated by the piston pump and the Venturi meter and to charge the slaughter house for the use of this amount of water.

Absorption Dynamometer. Another piece of apparatus for the laboratory was an absorption dynamometer invented, designed and commercially sold by Alden, and described in the *ASME Transactions of 1890*.[6] Dynamometers that were used to measure torque had attracted the attention of inventors in the mid-1800s, who saw a need to measure power output and obtain the efficiency of various types of mechanical machinery used in the expanding mills of the United States. Alden experimented for some time with dynamometers before coming up with a design (see Figure 10) that for many years was utilized in testing automotive and train engines, hydraulic turbines and other numerous rotating mechanical equipment.[6]

The WPI student newspaper, in its January 15, 1892 issue, described the dynamometer as follows:

"The apparatus is designed for three purposes: to maintain an uniform load upon an engine under experimentation or test, to accurately measure the useful power developed by the engine, and to automatically regulate the rate at which energy is absorbed.

"This dynamometer is essentially a friction brake with comparatively large rubbing surfaces, thus giving a low intensity of pressure at any one point. Pressure is produced by water from a main, and enough water is allowed to pass to absorb the heat due to the absorbed energy. The rubbing surfaces are finished smooth and run in a bath of oil.

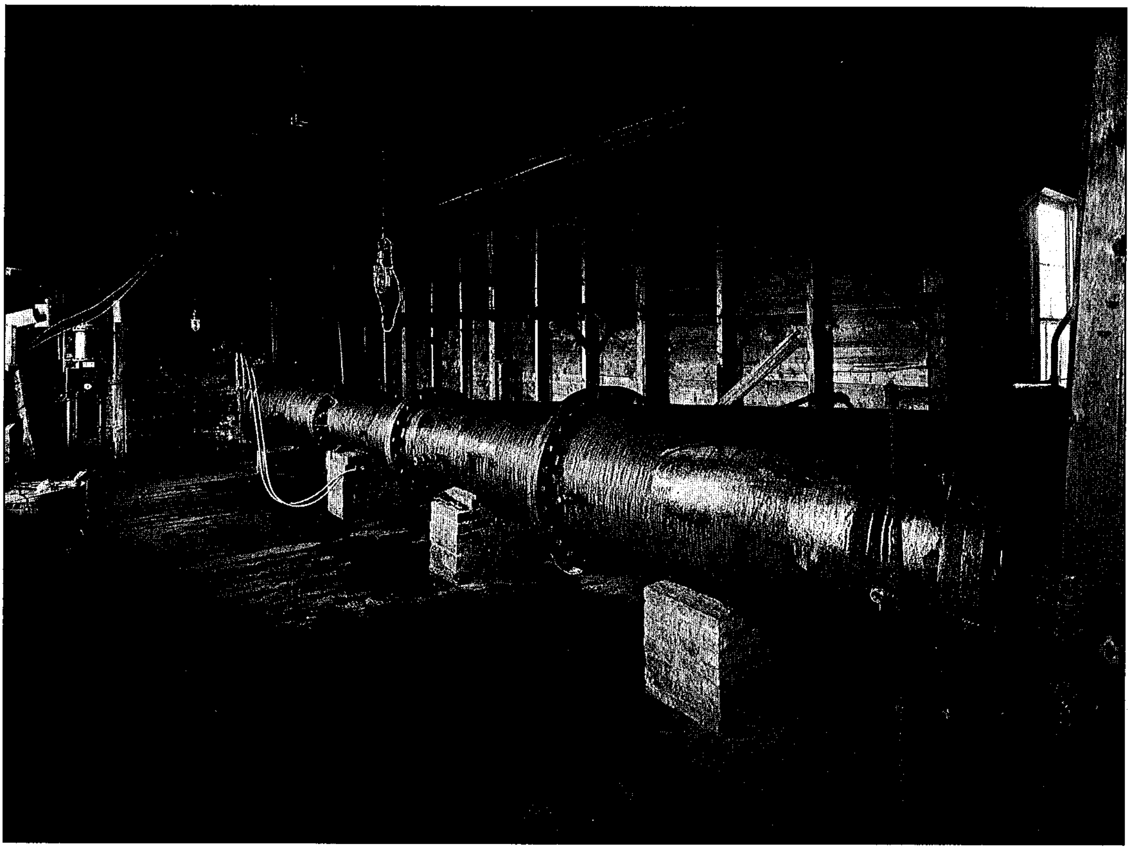

FIGURE 9. Herschel's Venturi meter installed in the laboratory with velocity traversing probe.

Automatic regulation is secured by a slight angular motion of the brake which operates the valve controlling the water supply, and hence the pressure.

"The brake consists of a disc keyed to the crank-shaft of the engine. The disc is finished smooth except for one or more radial grooves in each face. The disc is surrounded by a cast iron shell consisting of two pieces bolted to a ring of the thickness of the disc. Two copper plates, concave toward the shell, bear against the disc and form with the shell two water-tight compartment, the copper being "spun" out into a cavity in the iron and held in place by driven rings. One chamber communicates both with the main and the other chamber. A chamber filled with oil lubricates the disc by means of the radial grooves. The shaft revolves in bearings in the shell which carries an arm carrying weights. Angular motion of the arm is limited by stops.

"The automatic valve consists of two brass tubes, one fitted inside the other, but free to revolve therein. Each tube has slots nearly parallel to its axis, one is connected with the supply, the other rigidly with the brake. A flexible tube encloses the whole. The valve is so adjusted that a small angular motion of the brake varies the water passage through the slots and the apertures into the chamber being constant, the pressure is thus regulated.

"The operation of the brake is this: The oil chamber is filled and sufficient weight to give the required load is hung on the arm. The engine is then started and speeded up. Water is then admitted to the automatic valve in any suitable manner, and thence to the chambers. The pressure of the water forces the copper plates against the disc, thus causing sufficient friction to lift the weight arm. This motion operates the automatic valve, checking the flow of water to the brake, and regulating the moment of friction on the disc to the moment of the weights on the arm."

Other Laboratory Equipment. Erected inside the laboratory was an 18-inch horizontal Hercules turbine built by the Holyoke Machine Company of Worcester (see Figure 11). The wheel was mounted 18 feet below the level of Pond No. 2 and had a draft tube 12 feet long. It was located immediately downstream of the Venturi meter, which was used to measure the flow through the turbine. The water discharged from the turbine was then directed over two 10-foot weirs located in the tail race. These weirs served to measure the flow a second time and, thus, check the Venturi measurement. Figure 12 shows an early weir, circa 1907, used to measure flow from Pond No. 3 in the background. Note that the side edges were beveled and a flow distributor was used.

The test laboratory also included a 12-inch water meter, valued at $1,250, which was a gift from the mayor of Worcester, Phinehas Ball.

A copper-lined wooden weighing tank built on a 50,000-pound Fairbanks scale was also installed in the laboratory (see Figure 13). The scale had been acquired by WPI shortly after the Centennial Exposition held in Philadelphia in 1876. It had served on a strength-testing machine in another WPI laboratory and had seen other duties before coming to Holden. The scale was reputed to be so sensitive that it could detect a silver fifty-cent piece placed on its platform. The tank and scale were almost immediately incorporated into use for student experiments and to determine flow for efficiency tests. Thus, very early on, flow measurement was a major focus of the laboratory since weight and time could be easily and accurately measured.

The last piece of equipment for the new laboratory was a large hydraulic ram (see Figure 14) that was used to supply water to an air pressure tank that furnished pressure to the meter that was used to operate the friction dynamometer.

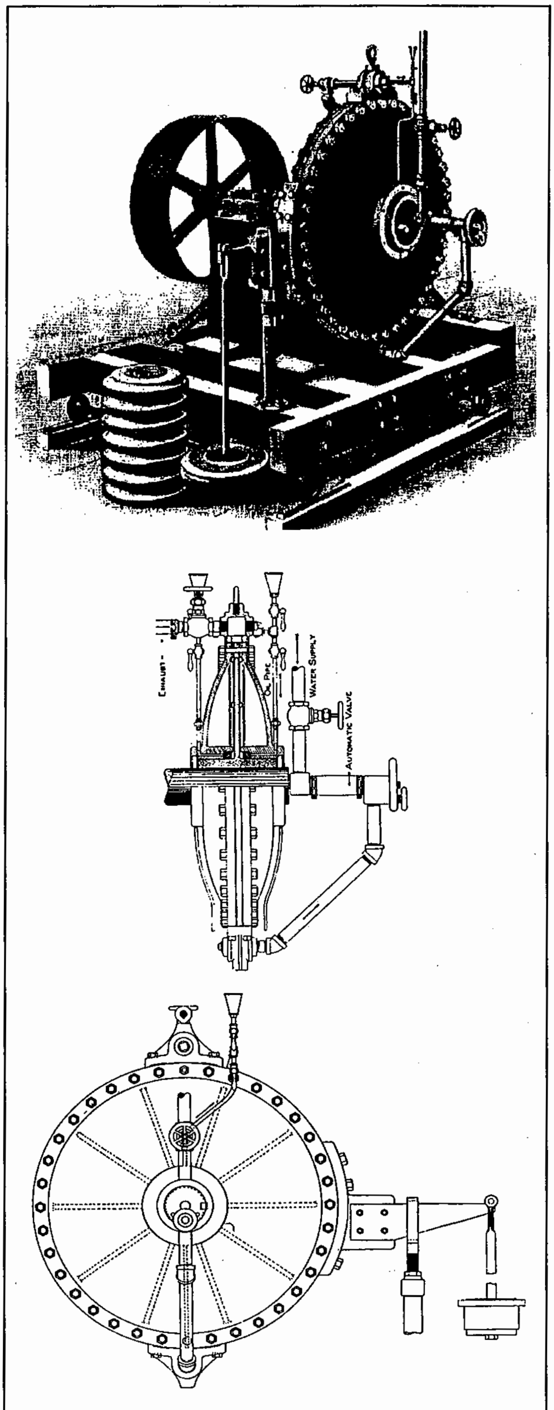

FIGURE 10. The Alden dynamometer.

Early Use of the Lab

The control gate from Pond No. 2 was opened for the first time in December 1894 and allowed water to enter the test facility. On May 8, 1895, Professor William W. Bird took two divisions of senior WPI students to the Hydraulic Laboratory to perform the first student experiment at the facility. The May 18, 1895, issue of the student newspaper detailed the testing:

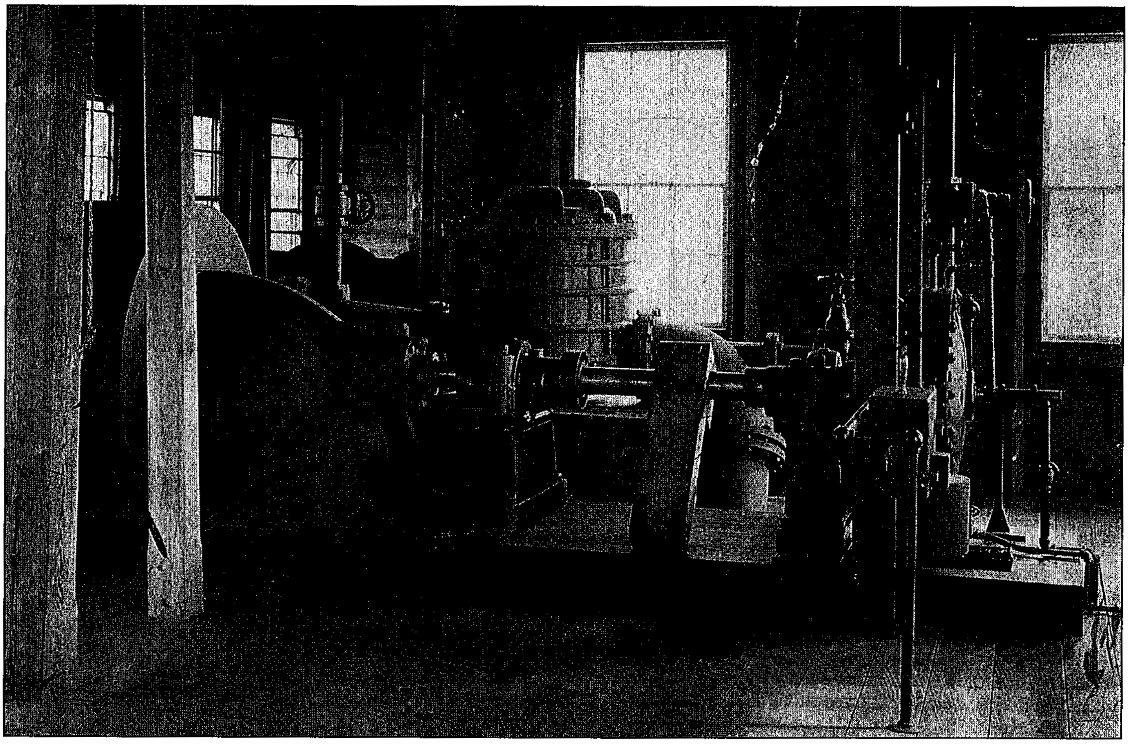

FIGURE 11. The Hercules turbine with the Alden dynamometer.

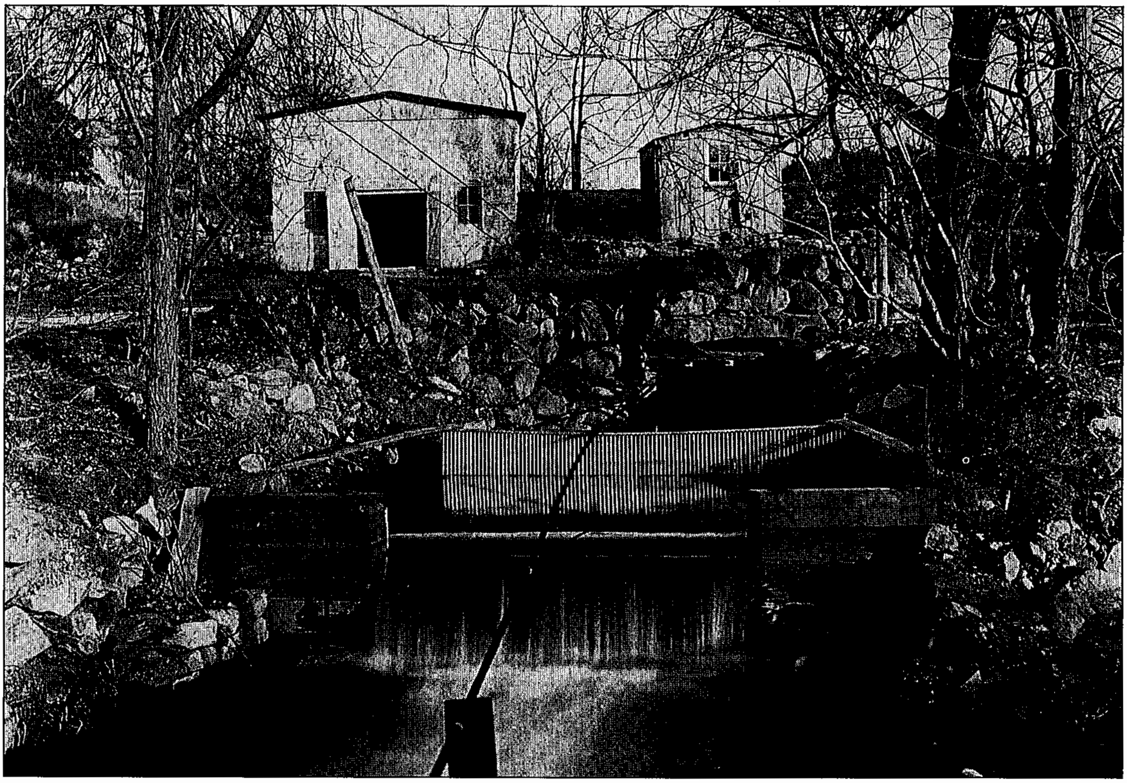

FIGURE 12. An early sharp-edged weir with an approach flow distributor (1907).

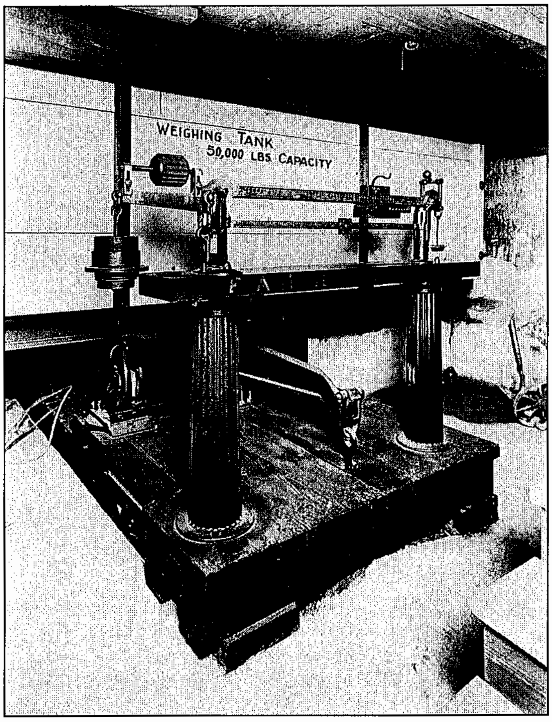

FIGURE 13. The Fairbanks scale.

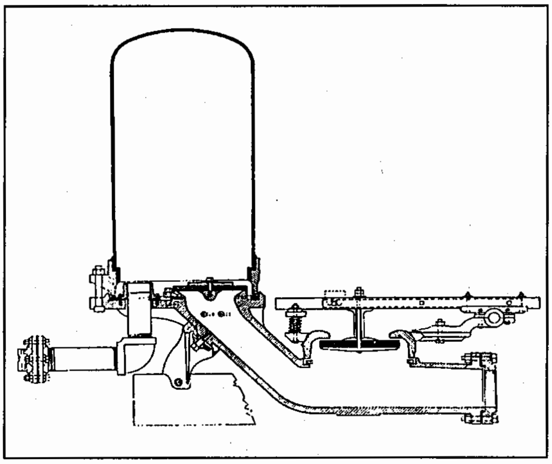

FIGURE 14. A hydraulic ram.

"The work consisted in determining the efficiency of the 18-inch Hercules Wheel at different speeds, with different gate openings, and finding what speed gives the best efficiency. Each division makes eight tests, two on each gate, the gate openings ranging from 0.3 to full gate, and the horsepower developed from 15 to 75. In making these tests each student has the care of some special piece of apparatus, or the reading of one of the gauges, and in the subsequent test has a different assignment, so that in the several tests, he becomes familiar with all parts of the plant.

"The quantity of water used is measured before entering the wheel by the Venturi meter, and again measured, after passing through the wheel, on a ten foot weir, two hook gauges being used, one on either side. The head on the wheel is measured in columns in the tower, while the power developed is shown by the weight on the brake and the number of revolutions. The tests made were not as exact as could be desired, but as the students become more familiar, better results may be expected."

WPI took great pride in being able to advertise that their students were being trained on a full-sized turbine, using state-of-the-art instrumentation. It is hard to believe that this hydraulic facility, including equipment and instruments, was estimated to have cost $12,000.

The early accumulation of equipment and instrumentation set the pattern for the future. The laboratory staff became adept at acquiring, fixing, enhancing or building their own equipment and test facilities. This "can-do" attitude extended to relatively large tasks and test facilities. Also, being directly associated with industry led the laboratory early on to applied fluids engineering — *i.e.*, hydraulics. The early interest in efficiency and hydropower led to a continuous relationship with the U.S. power industry, particularly hydropower.

Hydraulic Instruction

A driving force behind the success of the Hydraulic Laboratory was Charles M. Allen (see Figure 15). As a senior at WPI in 1894, he chose as his thesis to test a 3-foot, 6-inch diameter overshot waterwheel he designed and constructed on his parent's property in Walpole, Massachusetts. The wheel produced about 0.5 horsepower and was used to pump water, saw wood and turn the crank of an ice cream maker. (As it turns out, this thesis was a prelude to Allen's lifetime work.) The test apparatus consisted of an Alden absorption

FIGURE 15. Charles M. Allen

dynamometer to measure the power output, a 2-foot sharp-edged weir to measure the flow and a hook gauge to measure the head.

In June 1894 after his graduation, Allen was hired as an assistant in the Department of Mechanical Engineering at WPI "at a salary of $100 for the year; it being understood that he is to give half of each day to the service of the Institute while he occupies the other half in study and investigations." It appears from the records that although Allen received promotions and salary increases during his stay at WPI, his half-time teaching schedule persisted throughout his 55-year career. In 1895, Allen's annual salary was increased to $700, and in 1896 to $900.

From 1895 to 1900 the Hydraulic Laboratory was utilized for student instruction and for tests performed by a variety of the teaching staff in both the Mechanical and Civil Engineering Departments. Transportation to the laboratory was by steam railroad, horse-drawn buggies or barges, bicycles or shanks mare (walking) up the track from Worcester's Greendale section. By 1903, an electric car line was built to Holden and was used by students along with the automobile, which had started to appear at about the same time.

The WPI catalog outlining course work in 1895 indicated that students were required to:

- Obtain the efficiency of the Hercules turbine;
- Measure flows with rectangular weirs, Venturi meters and water meters;
- Test a hydraulic ram; and,
- Measure the head loss in the approach piping to the turbine.

An apparataus for student testing is shown in Figure 16.

Early senior theses at the laboratory during its first five years covered a variety of tests involving the hydraulic ram and the determination of discharge coefficients for different weir types. Some of the early investigations involved turbine draft tubes. Although records of these tests have not been found, an article in the school newspaper indicated that:

> "On Friday, November 8th, Col. James Francis, Chief Engineer of Locks and Canals on the Merrimack River at Lowell, with his chief engineer, Mr. Safford, inspected the hydraulic plant at Chaffin. Prof. Alden, assisted by C. M. Allen, '94, explained the machinery, some of which was run for a short time. They were particularly interested in the dynamometer and methods used in experimenting with draught tubes."

This visit was quite an honor for the laboratory, considering Francis' many contributions in the field of hydraulics and hydraulic turbines. At Lowell, both Francis and Uriah Boyden had done considerable work in maximizing water turbine power output by use of draft tubes that conveyed the water from the turbine exit to the tailrace.

At this time and for some years to come, Allen would be primarily concerned with classroom instruction and turbine testing. Surveying instruction also was conducted on the laboratory grounds.

In 1895 WPI decided to establish a Chair of Hydraulic and Steam Engineering. To fill that position, WPI hired Sidney A. Reeve, an edito-

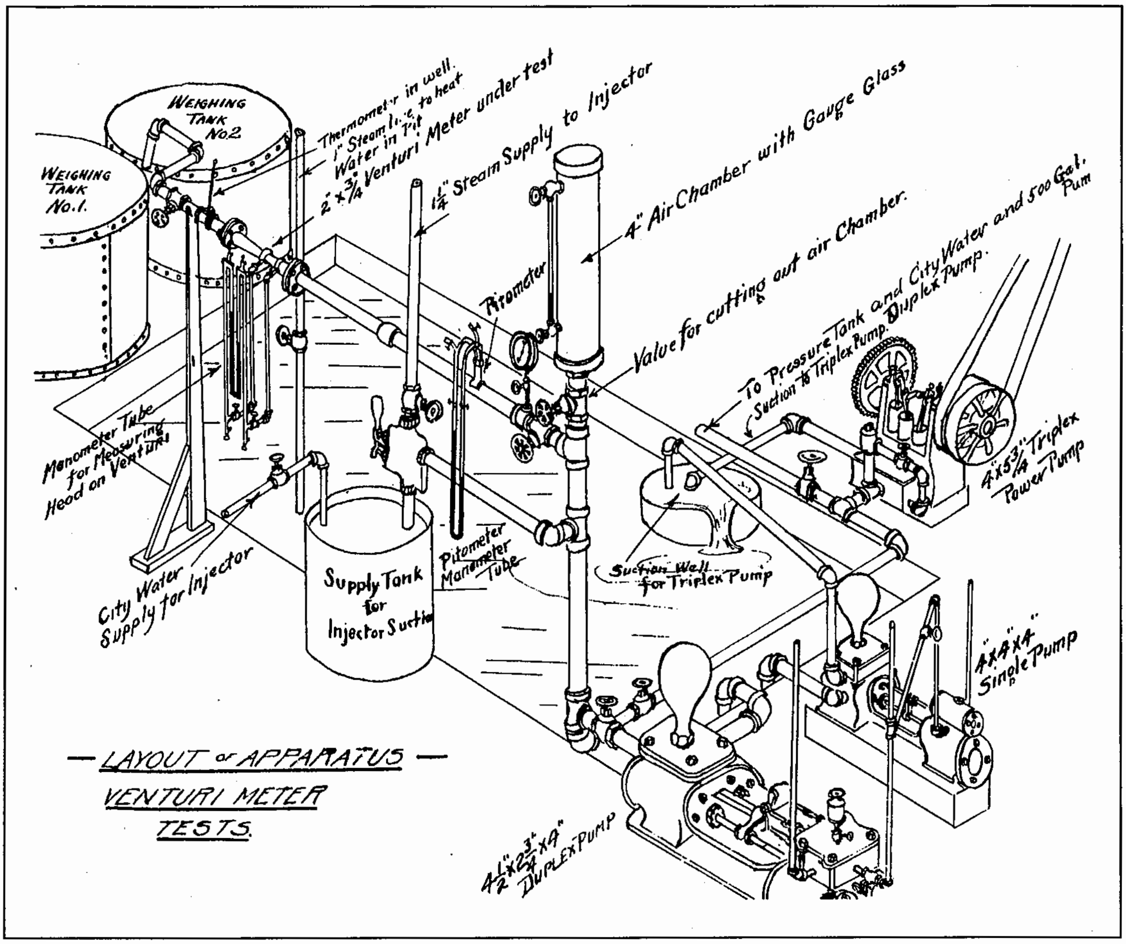

FIGURE 16. Student testing apparatus.

rial writer on *The Progressive Age*, a publication devoted to the gas industry. Reeve was a recognized authority on gas engines.

In the spring of 1896, Alden, disillusioned with proposed philosophical changes in engineering education at WPI, announced his resignation from the school effective July 1, 1896. Although Alden, who had twice served as chief officer of the school between presidential terms, left WPI, his interest in the Hydraulic Laboratory, which he had founded and headed, continued with frequent financial and technical support throughout his lifetime.

In 1898, Reeve was promoted to full professor and was named to head the newly created Department of Hydraulic and Steam Engineering, which included the Hydraulic Laboratory. He remained in that capacity until his resignation in 1906. At that time, Allen was named Professor of Experimental Engineering and officially became the Head of the Hydraulic Laboratory, a position he had held unofficially during Reeve's tenure. During his stay at WPI, Reeve showed very little interest in the field of hydraulics and the operation of the laboratory. In fact, it was mentioned in one of the student publications that due to his lack of interest, Reeve relinquished his teaching duties in the hydraulic course to Allen in the middle of a term.

During the initial five-year period of the hydraulic laboratory's existence, Allen worked toward his master's degree and did testing in the area of gears, pulleys, belting, pumps and draft tubes. The master's examination given by Alden to Allen in shown in Table 1. These areas of research showed Allen's multi-faceted interests, curiosity and creativity. Further proof of Allen's versatility was an article in the 1897 *WPI Journal* written by himself and Reeve on "The Crushing Strength of Concrete."[7]

In 1899 Allen obtained his master's degree. His master's thesis, "The Design and Construction of an Oarsman's Indicator," was inspired by his brother, who was captain of the Yale rowing team. (It is interesting to note that many years later one of Allen's research activities at the Hydraulic Laboratory involved the testing of a rowing tank that would be used to train Yale University crews.) As a fallout from his thesis, Allen designed an adjustable foot-stretcher rig for shell boats.

Dynamometer Testing

Most of the early research and testing at the laboratory involved the use of the Alden absorption dynamometer in determining the efficiency of different devices such as pumps, gears, pulleys belting, motors, etc.

The 1890s were the beginning of the American automotive industry. Pioneers Charles and Frank Duryea, Elwood Haynes, Henry Ford, Ransom Olds and Alexander Winton started an industry that became one of the largest in the United States. Allen, always being at the forefront of new technology, envisioned the use of the dynamometer in measuring and improving the efficiency of automobile engines, and wrote to various motor companies soliciting sales of the Alden dynamometer.

The Alden dynamometer was also popular in the early 1900s with many technical schools throughout the country. MIT, Georgia Institute of Technology, Iowa State, Kansas, Tufts, Colorado, Leland Stanford, Maine and other schools either bought dynamometers or plans for dynamometers. The University of Illinois bought one of the largest dynamometers built in its day for use in a large locomotive engine testing facility.

Besides teaching at WPI and conducting research at the hydraulic laboratory, Allen was involved in numerous field tests of water turbines in the early 1900s. The rental of the test apparatus in those days was $250 per test. Allen's charges were $25 per day plus expenses. Transportation in those days was not always as convenient as today. As an example, Allen was given these instructions to inspect a potential test site in Maine:

"Go to Portland, Maine, in the evening. Stay overnight and take the train on the Maine Central Railroad to White Rock. At White Rock take the stage to North Gorham and from there to the powerhouse if you request it. It will be a long cold ride and you should be well prepared."

TABLE 1.
Hydraulics Master's Examination Questions Given by Alden to Allen (June 1894)

1. What is the theoretical velocity of a liquid flowing into a vacuum under a head of 144 feet?

2. How many cubic feet would theoretically flow in one minute through an area one-twelfth of a square foot?

3. What causes would in practice modify this theoretical flow? About how much would it be reduced?

4. Find the theoretical flow through a rectangular notch depth, *h,* and breadth, *b,* upper edge of notch at surface of liquid.

5. If 200 cubic feet of water flow per minute through a vessel where its sectional area is one-seventy-second of a square foot, and the hydrostatic head is 12 feet, what is the kinetic and what is the potential energy of a quantity of the water whose weight is *w* as it passes this section?

6. What is the construction and action of a Venturi meter?

7. Deduce the formula for the quantity of water that will flow through a given meter.

8. Explain the formula:

$$\frac{\theta}{g} u(v-u) / (1-\beta) = p_x$$

9. What two values of *u* make the second member equal to 0? Why should this be so?

10. Substitute in the last formula the values of *u* and of β which make the result a maximum and explain the resulting formula.

Note: The equation is reconstructed from an unclear original.

This trip today, in the comfort of a modern automobile, would take no more than four hours.

David Gallup & Propeller Testing

In 1902, David Gallup, a 1901 WPI graduate, was appointed as an instructor in the Mechanical Engineering Department. Although there is no record that Gallup had any interest in hydraulics, he worked with Allen, as attested by his signature that appeared on many curve sheets found in the Allen reports of the early 1900s. Gallup was fascinated and interested in automobiles and, especially, automobile engines. During his stay at WPI, he gained national recognition for his work, and his engine testing plant in the Mechanical Engineering Department was visited and used by many automotive engineers of the growing automobile industry.

Gallup had read about the December 17, 1903, flights of Orville and Wilbur Wright in a heavier-than-air machine conducted in Kitty Hawk, North Carolina. Due to his interest and his realization that aviation was in its infancy and provided new challenges to engineering, Gallup proposed testing nine hand-carved wooden propellers on a rotating platform. As he wrote in a July 1911 *Aeronautics* article:[8]

> "The purpose of the investigation is to determine if possible the proper design of a propeller to give the most efficient results, taking into consideration the varying factors, such as speed, pitch, and diameter. . . It must not be understood that the stationary type of test is considered of much value, for it is very evident that the conditions existing, such as circulation over and over a given quantity of atmosphere, are very different from those met with by a propeller on an aeroplane which is going through the air."

Rotating booms, earlier called "whirling arms," had been around since 1740 when Benjamin Robbins in England built one to study the air resistance of projectile forms. In the early 1750s, another Englishman, John Smeaton, used one for windmill tests. Jean Charles Borda of France tested various shapes in water using a whirling arm in the 1760s.

Such a rotating test platform, secretly funded by Alden, had been built at the Hydraulic Laboratory in 1908 in Pond No. 2 that fed the main laboratory. The facility was called the Circular Current-Meter Rating Station and is shown in Figure 17. Allen, with two of his students, had designed a 42-foot wooden testing arm balanced by a 21-foot arm loaded with counterweights (stones). The bottom of the shaft was supported by a hole drilled in a submerged rock located 45 feet from shore and the top supports were guy wires attached to deadmen anchored on the shoreline. The rotating boom was powered by a 24-inch Hercules water wheel located under Shrewsbury Street. The power was transmitted to the boom by a series of pulleys and a rope drive. The maximum speed (at the boom end) was 10 feet per second.

The original purpose of the rotating boom was to test hydraulic equipment, especially current meters. Testing of such meters in those days was usually performed in towing tanks. The circular test facility was chosen over a towing tank because the former was much less expensive to construct, allowed longer test runs and enabled larger objects to be tested without experiencing boundary effects from channel sides. It is interesting to note that testing large objects was a continuation of the original testing concepts of the laboratory.

In 1911, the wooden boom was replaced by an 84-foot diameter steel boom (see Figure 18). The same shaft configuration, rope and pulley drive (see Figure 19), and waterwheel power were used on the refurbished boom. The steel was erected in the dead of winter so that the ice could be used as an erection platform. Ice also made it easy to slide the heavy steel members to the boom. This thinking was all in keeping with Allen's philosophy of doing things as easily as possible and with the least expenditure of money and energy. With the reconstructed boom in place, Gallup installed a 75-horsepower electric motor at the center of the boom and transmitted its power through a long shaft and angle drive to propellers mounted at the end of the boom. The thrust of the propeller caused the boom assembly to rotate while a

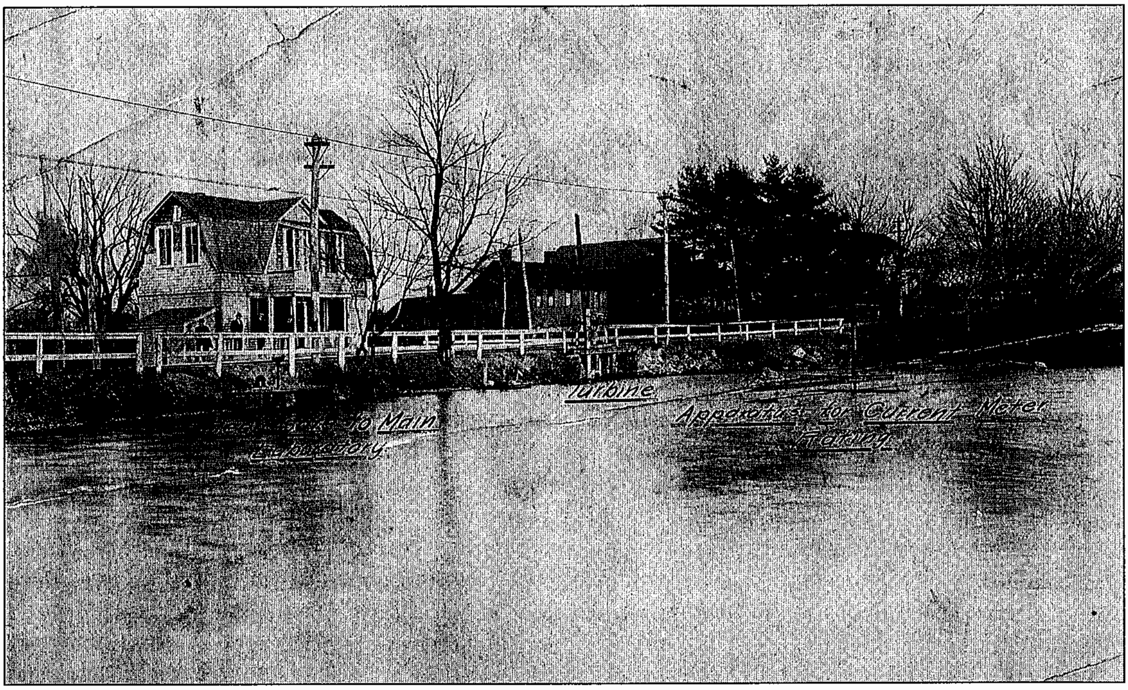

FIGURE 17. The Circular Current-Meter Rating Station (wooden boom).

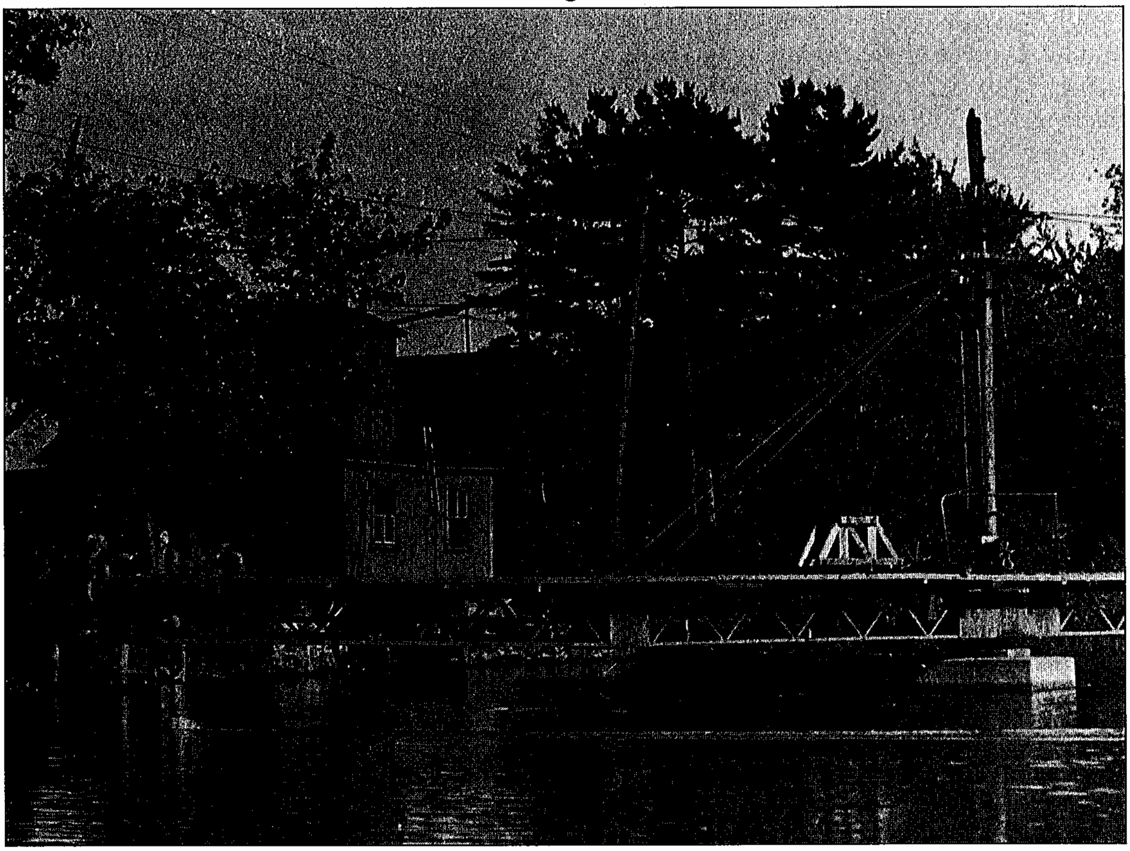

FIGURE 18. Rotating steel boom (circa 1920).

drag device in the water was used to calculate the power dissipated. Tests on nine different propellers, ranging from 6 to 7 feet in diameter, were conducted by Gallup and his students. Thrust ranged from 5 to 47 horsepower, and propeller speeds ranged from 550 to 1,300 rpm.

Testing on the same propellers had also been performed on a stationary platform erected in the Worcester Armory. In spite of the relatively similar results of both types of tests, controversy existed as to the reliability of the tests on the rotating boom. Some claimed that propellers tested on rotating booms were unreliable because the propeller encountered turbulence from its own wake after the first revolution of the boom, and, therefore, it did not see air identical to that encountered by heavier-than-air machines. To resolve this conflict, Gallup and some of his senior thesis students organized tests using a gasoline engine, mounted on an ice boat in the winter (see Figure 20) and on a pontoon boat in the summer, to turn various test propellers. The straight-line tests were conducted on Worcester's Lake Quinsigamond and gave results similar to those achieved on the rotating boom. (It was said that some of the students encountered numerous thrills during testing at the lake, especially in the summer when the boat had a tendency to "nose over" at higher speeds.)

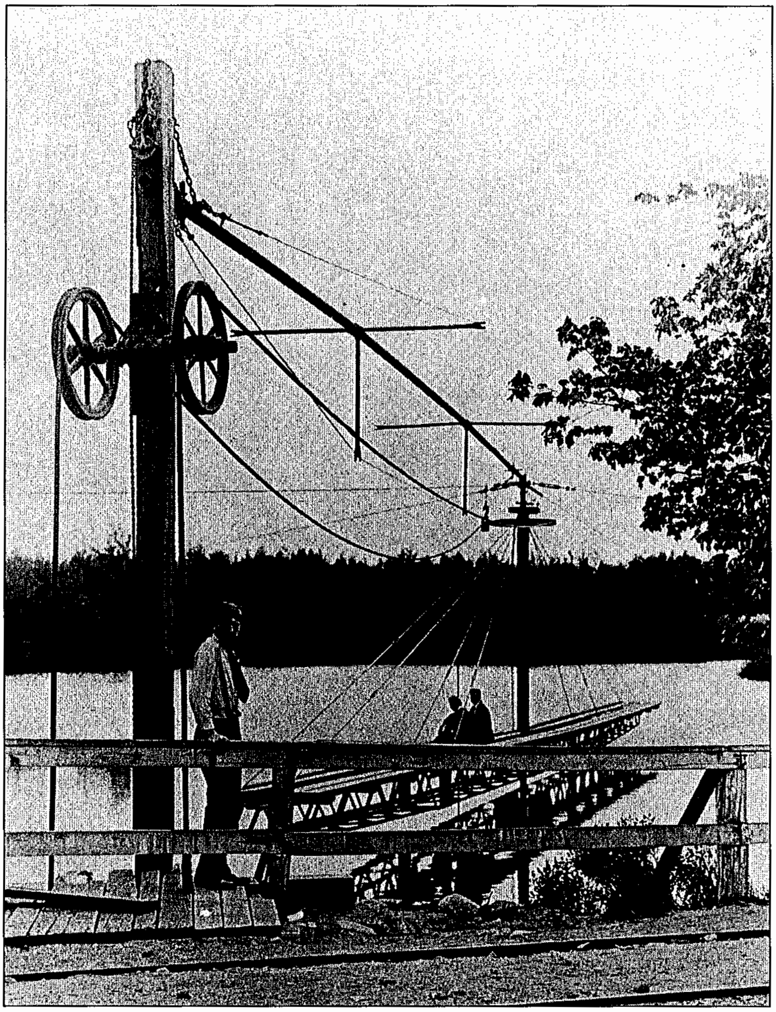

FIGURE 19. Rope drive for steel boom (circa 1920).

Throughout its lifetime, the rotating boom has been used to calibrate current meters. During World War I, Major Victor E. Edwards (an 1883 WPI graduate) used the boom to conduct drag tests on artillery shells. These studies proved to be valuable in his subsequent studies of artillery shell ballistics at the Aberdeen Proving Grounds in Maryland. Students also used current meters in available flow channels (see Figure 21).

Hydroelectric Power

Besides the great strides being made in the automotive, aviation and petroleum industries, the turn of the century saw the use of water turbines changing from driving machinery via belt and gear drives to driving electric generators. Arguably, the first hydroelectric station had been placed in operation at Appleton, Wisconsin, in 1882. Power transmission using step-up and step-down transformers had been achieved in Great Barrington, Massachusetts, in 1886. "Large-scale" hydropower saw its

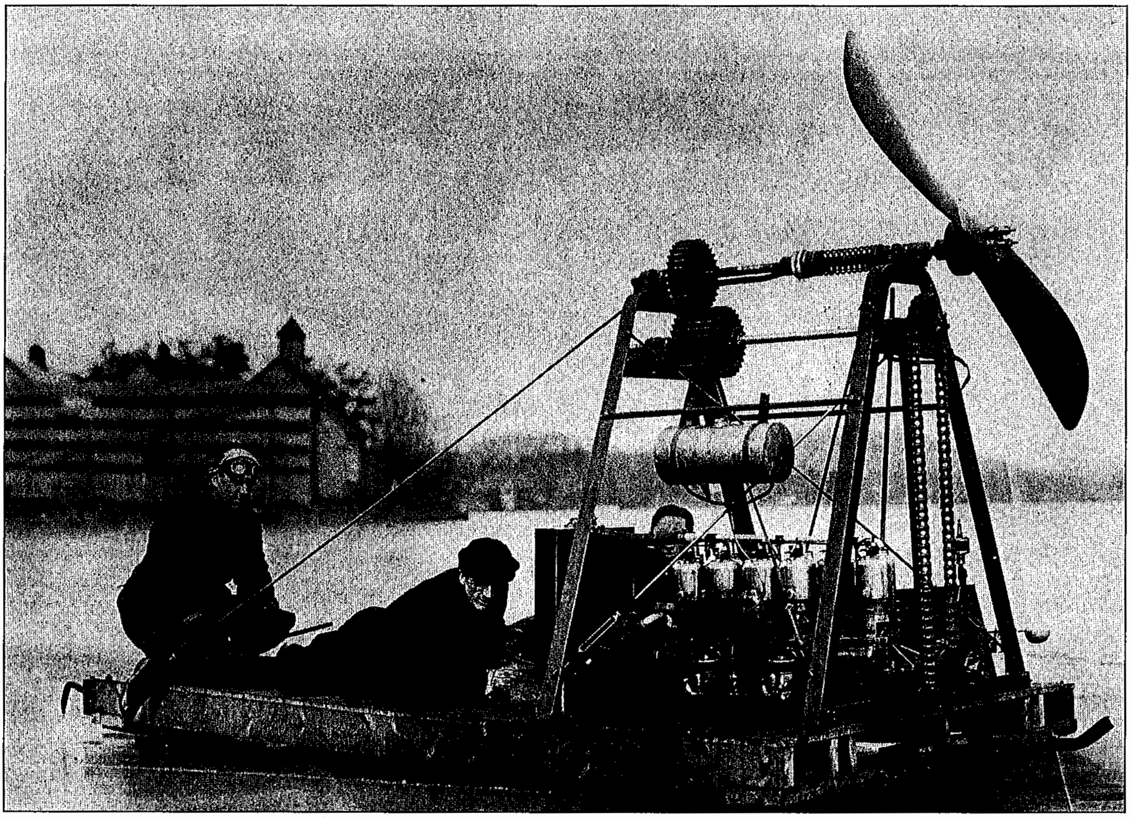

FIGURE 20. Testing propellers using an ice boat (circa 1915).

birth in the Niagara Falls development in 1895. Around the same time the transmission of power on small grids began. By 1900, electric transmission was at 40,000 volts and would increase to 110,000 volts by 1923.

Field testing of hydro turbines used both for power and electric production increased at that time. Allen's creative mind saw the need to accurately measure the flow of water during these tests. Based on the results of the Holyoke flume tests and the head on the turbine, he invented a flow recorder (see Figure 22) that gave continuous flow readings.

By 1910, Allen had conducted almost one hundred tests on hydro turbines and had published an ASME paper in 1910 on the "Testing of Water Wheels After Installation."[9] His turbine testing experience ranged from tests at the famous Holyoke turbine test flume, at hydroelectric power plants throughout the Northeast and at paper mills in Maine. At this time, the relatively low flows were measured using current meters or weirs. His concern for installed water-wheel efficiency was always on his mind. He frequently mentioned the term "fair setting" in his writings on installed turbines. In his mind, "fair setting" meant there was more to proper turbine operation than testing the turbine in the Holyoke Test Flume. Minimizing approach head losses, efficient draft tubes, regular wheel inspection, clean racks, efficient gate operation and all other "hydraulic common sense" plant characteristics taken for granted today encompassed his concept of "fair setting." He frequently showed plant operators and owners the misconceptions they had relative to efficiency when operating wheels at wide open gate or maximum speed to produce maximum power.

The size of hydroelectric turbines in the early 1900s increased exponentially due to the high demand from electric-intensive industries, such as chemical and steel. Urban centers were increasing in size, and electricity for lighting homes and streets was in great demand. In the 1890s, unit sizes were in the 500

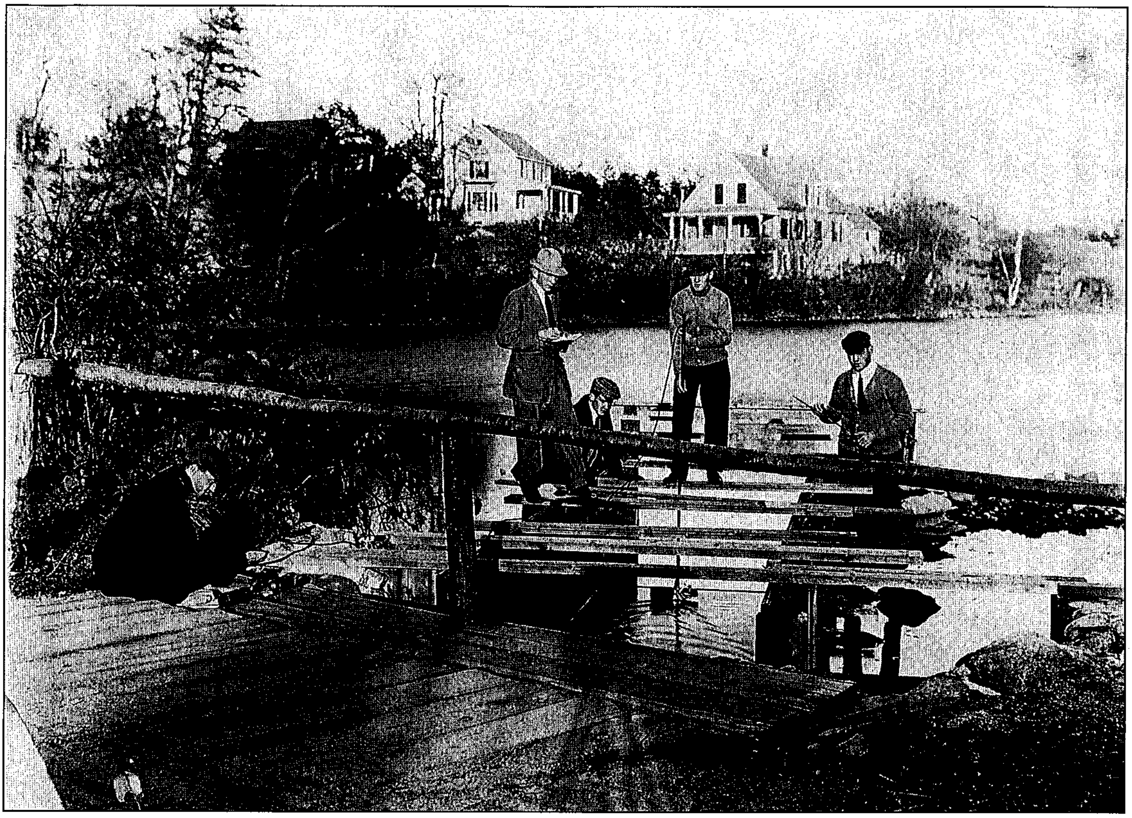

FIGURE 21. Students measuring current (1911).

horsepower range. By 1901, 10,000-horsepower units were being considered for Niagara, and ten years later the figure approached 20,000 horsepower. Another decade later, units 140 times the size of the 1890 units were being considered.

Besides the need for electric power, the power of hydro turbines increased due to technical advances in turbine designs. The work started in the late 1800s by Francis in Lowell (and Pelton and Doble on the West Coast) was continued. Blade designs were improved and efficiencies increased. As the steel industry grew, construction techniques also improved. All these factors and the relatively low cost of hydropower contributed to the sizable growth in this industry.

Although it may seem that Allen was doing mostly field tests, the laboratory building was being utilized fully for student activities, and for testing by Allen and his staff and other WPI faculty. By 1908, the facility was considered too small, and a "low head lab" (the Water Wheel Testing Laboratory) was built across the street from the existing facility. Built with funds supplied by Alden, this new building was erected on the site of the old grist mill. It was 70 feet long by 15 feet high and 36 feet wide for half its length and 24 feet wide for the other half. A portion of the building was used for a machine and repair shop. The building contained a large copper-lined wooden flume in the basement where two vertical 15-inch Hercules water wheels were used to power a jack shaft motivating a combined rope and belt drive apparatus.

Alden Hydraulic Laboratory & Early Field Testing

Allen approached research in an applied manner that would be followed by the laboratory during its existence. The other qualities that set the tone for the laboratory were his variety of work (demonstrating his grasp of engineering fundamentals), his Yankee thrift and the loyalty of his clients (showing the respect he earned in his work).

For example, in 1906, Allen was contacted by a paper manufacturer in Millinocket, Maine, to test turbines used to power grinders that reduce wooden logs to pulp. The company was so satisfied with Allen's work, he tested 13 turbines for this company during his career. Some of the later tests involved turbines used to produce electricity.

Early field testing was not limited to turbines. The large use of water in paper manufacturing and its accurate metering for the purpose of billing were problems that had been studied by Herschel in the late 1800s at the Holyoke Power Company. In 1908, the same company hired Allen to measure the flow rate in different diameter pipes. The tests were made at seven different paper mills by using a pitometer, invented by Edward Shaw Cole in 1896, and traversing pipes ranging from 8 inches to 24 inches in diameter. Some of the tests were to check the accuracy of flow meters, while others were checks on hydraulic turbines used to power machinery. These tests also indicated the fact that Allen remained current with the technology of his time.

On October 16, 1908, Herschel visited the Hydraulic Laboratory. During the tour he noticed many valved pipe fittings sticking out of the downstream end of his Venturi meter (see Figure 9). He asked, "What have you got on my meter, a bunch of parasites?" Allen replied by inquiring if Herschel knew what went on inside the pipe. Herschel's reply was that the water velocity slows down as the pipe diameter increases. Allen assured him this was true for the average velocity. "But what about the velocity distribution across the pipe diameter?" asked Allen. Herschel replied, "I don't know." At which time, Allen informed Herschel of the velocity traverse data that had been obtained downstream from the Venturi meter's smallest diameter.

Allen followed in Herschel's footsteps, testing in the Holyoke paper mills. He also did work for the Proprietors of Locks and Canals in Lowell where James Francis had performed pioneer studies on turbines and basic hydraulics some six decades earlier. At one of the largest textile mills of its time, Allen tested a 72-inch Swain turbine.

From 1900 to World War I, Allen conducted some one hundred and fifty different field tests on various types of equipment. He was held in high esteem as a hydraulic engineer, and his services were highly sought after throughout the United States and Canada. His testing covered all six New England states, New York, Pennsylvania, North Carolina, Georgia and Alabama, in addition to the Canadian provinces of Ontario, Nova Scotia and numerous locations in Québec. During the same time period, he carried his teaching load at WPI, guided research at the Hydraulic Laboratory (which included seventy-eight senior theses). His reputation, and that of the Hydraulic Laboratory, were growing as was his knowledge of the multitude of turbines and hydraulic equipment he tested.

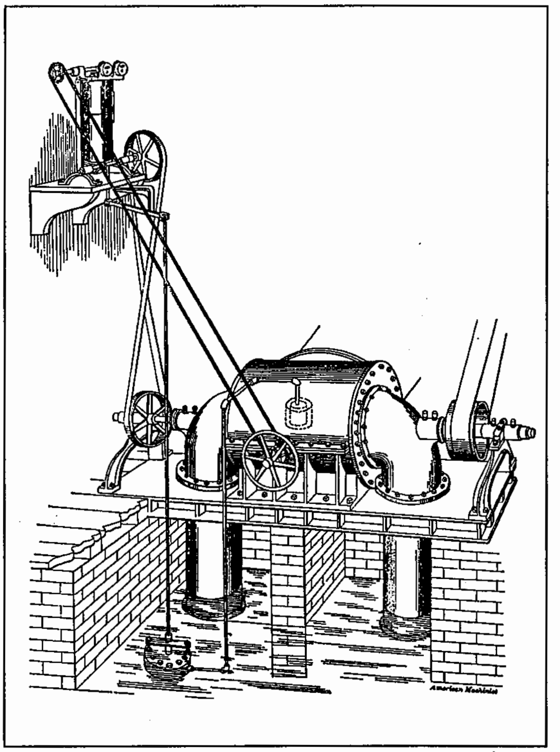

FIGURE 22. A double-cylinder flow recorder connected to a turbine.

Two decades after its start, it was obvious that the WPI Hydraulic Laboratory was a success in terms of its practical academics and the impressive contributions made by its staff, particularly Allen, in the area of applied research and field testing. The laboratory had become famous and on May 1915, in honor of the laboratory's founder and benefactor, the WPI Trus-

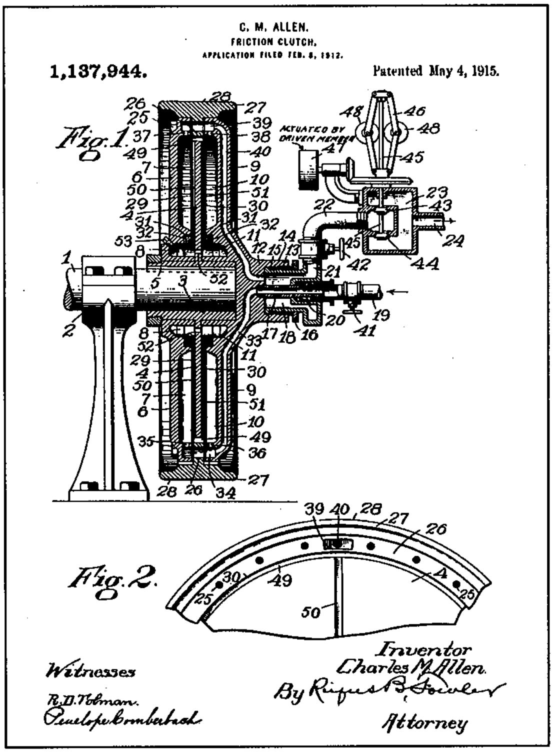

FIGURE 23. Allen's clutch.

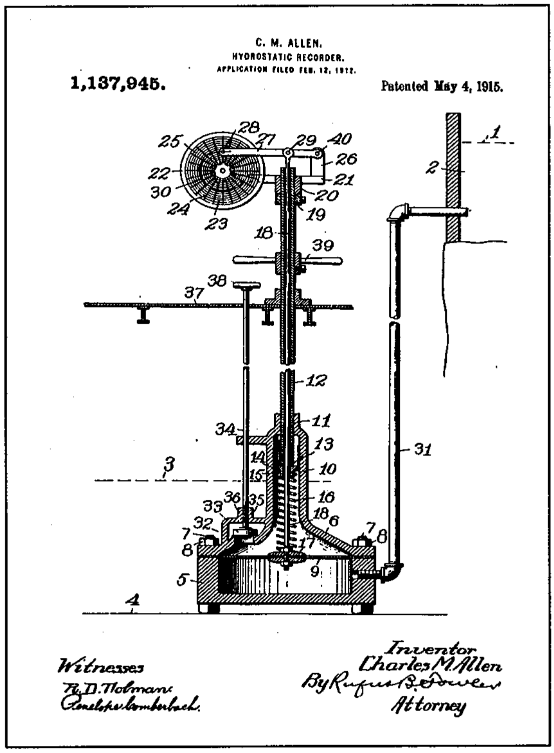

FIGURE 24. Allen's hydrostatic recorder.

tees voted to change the name of the laboratory to the Alden Hydraulic Laboratory.

In the same year, Allen received two patents from the U.S. Patent Office. One was for a clutch (see Figure 23) operated by hydraulic power. This device resembled the Alden dynamometer where the applied pressure to the plate in the dynamometer was regulated by a balanced valve actuated by a centrifugal flyball governor. The other patent was for a hydrostatic recorder (see Figure 24) to be used to record pressure variations on a flat rotating paper chart.

Growth of Cities, Industry & Electric Power

As the United States entered the new century, it was becoming an industrial giant. When Teddy Roosevelt was elected President in 1904, he expressed concern about electric power monopolies and the waste of what was thought of as unlimited natural resources. The first Reclamation Act was passed in 1902 and amended in 1906 to provide for the sale of electricity from federal projects for municipal purposes. Dams were reaching new heights, causing various hydraulic challenges in the areas of outlet controls, erosion below spillways and flood prediction.

In 1902, the Bureau of Reclamation was formed, and Roosevelt Dam in Arizona and Pathfinder Dam in Wyoming were well under construction. On the Susquehanna River, Holtwood Dam would be completed about 1910. Holtwood is notable because it is a very substantial eastern dam across a major river. This overflow dam had a downstream protective apron, but there was no stilling basin, the lack of which would cause erosion problems over the years. Also, there was apparently little consideration for migrating fish passage.

Larger water impoundments and transmission works for water supply were under active planning or construction. Flood control works were implemented in areas such as New Orleans, where the Sewerage and Water Board was formed in 1899.[10] A. Baldwin Wood, a remarkable engineer, was hired and worked 55 years for the Water Board, developing many inventions that eventually helped alleviate flooding problems. His high-capacity pumps for lifting water over the levees are notable.

In the early 1900s, threats to public health such as yellow fever, cholera and typhoid fever were concerns, and these concerns involved both water supply and disposal of sewage.

By 1914, Worcester's population had grown to 166,000. Arguably, more machine tool builders, machinists, mechanics and metal tradesmen were in Worcester and its suburbs than anywhere else in the United States. A partial list of products from Worcester and Worcester County included steam engines, railroad steam engines, saws, steam pumps, optical goods, cutlery, shuttles, gauges, drills and woodworking equipment. Other products included corsets, envelopes, railroad cars, grinding products, textiles and textile machinery, insurance-related businesses and lunch-car diners.

These developments set the stage for the activities of the WPI Hydraulic Laboratory through World War I.

GEORGE HECKER *was appointed Director of the Alden Research Laboratory (ARL) in 1975, when it was part of WPI, and became President in 1986 when ARL was separately incorporated. Prior to joining ARL in 1971, he worked for Stone & Webster in Boston and for the Tennessee Valley Authority before that. With more than 35 years of experience in solving flow problems using physical models, analyses and field studies, he has published widely and has served on many national professional committees. He has degrees from Yale and the Massachusetts Institute of Technology.*

ALBERT G. FERRON *was employed at ARL for 35 years. He also was an Adjunct Associate Professor of Mechanical Engineering at WPI. Upon his retirement from ARL in 1992, he was Vice President of the Flow Meter Calibration Section. Currently, he is employed at the University of Massachusetts Medical School in Worcester, continues as an Adjunct Associate Professor in WPI's Department of Civil & Environmental Engineering and is active in many community projects.*

BRUCE J. PENNINO *is Professor of Civil Engineering Technology at Springfield Technical Community College. Formerly, he was a Research Engineer at ARL for many years. He has a B.S.C.E. from Bucknell University and a M.S.C.E. from Colorado State University. He has over 30 years of civil and hydraulic engineering experience, and is a registered professional engineer in Massachusetts.*

REFERENCES

1. Storrow, C.S., *A Treatise on Water Works for Conveying and Distributing Supplies of Water; With Tables and Examples*, Hilliard, Gray & Co., Boston, 1835.

2. Rouse, H., *Hydraulics in the United States, 1776-1976*, Institute of Hydraulic Research of the University of Iowa, 1976.

3. Francis, J.B., *The Lowell Hydraulic Experiments*, Little, Brown, New York, 1855.

4. Aldrich, H.P., Jr., & Seeler, K.A., "The New Technology," *Journal of the Boston Society of Civil Engineers*, Vol. 68, No. 2, 1982.

5. Merriman, M., *Treatise on Hydraulics*, J. Wiley & Sons, New York, 1889.

6. Alden, G.I., "An Automatic Absorption Dynamometer," *Transactions of ASME*, Vol. 11, 1890.

7. "The Crushing Strength of Concrete," *Journal of the Worcester Polytechnic Institute*, Worcester, Mass., Vol. 1, No. 1, 1897. (No authors were given, but Charles M. Allen and Sidney A. Reeve are mentioned in the text and conducted the tests.)

8. Gallup, D., in *Aeronautics*, July 1911.

9. Allen, C.M., "Testing of Water Wheels After Installation," *Transactions of ASME*, Vol. 32, 1910.

10. Junger, S., "The Pumps of New Orleans," *American Heritage Encyclopedia of Invention and Technology*, Vol. 8, No. 2, Fall 1992.

The Role of Engineers in Creating an Environmentally Sustainable Future

An ever-expanding world population demands that engineers discover ways to sustainably manage both interaction with other humans as well as human interaction with the environment.

ANTHONY D. CORTESE

Civil engineering has played a critical role in increasing the quality of life over the last 50 years. From developing better water supplies, municipal sewer systems, wastewater treatment plants to the design of buildings to protect us from natural hazards and provide health care, to improved agriculture through water resource development and distribution projects to rapid and dramatic changes in transportation systems, civil engineers have developed the basic infrastructure on which modern society depends. Historically, civil engineers were the first practitioners of the engineering profession, and civil engineers continue to be dedicated to technology development for the common good and the general public.

Basic public works projects have helped reduced the death rate dramatically, which is one of the principal reasons that world population has been able to grow so dramatically in the last 150 years. Improvements in transportation also have enabled the rapid migration of large numbers of people all over the world and increased the volume of raw materials and finished products in international trade 800 times in the last century. Also, economic output has increased over 20 times, fossil fuel production 30 times and industrial production 100 times in the last century. Along with this phenomenal growth have come some undesirable environmental, health and social impacts, particularly in the last half century.

The Need for a New Human Perspective

In the last five decades, the population of the world has more than doubled to 5.9 billion people and the world's economic output has increased fivefold. This astonishing growth has no parallel in history and is altering the face of the earth and the composition of the atmosphere. Pollution of air and water, accumulation of wastes, destruction of forests, erosion of soils, depletion of fisheries and damage to the stratospheric ozone layer threaten the survival of humans and thousands of other living species. We are conducting an uncontrolled experiment unprecedented in scope and scale that represents the reversal of the "natural" evolution that produced clean air and water as well as increasingly complex and diverse ecosystems — systems that made human evolution possible.

These changes are the result of unsustainable and inequitable patterns of production and consumption, and are likely to accelerate with the addition of 81 million people to the planet each year. In *Changing Course: A Global Business Perspective on Development and the Environment*, Stephan Schmidheiny, chairman of the Business Council for Sustainable Development, points out that we are a society living off its natural capital, not its income.[1] We are acting like a planet in liquidation. Schmidheiny calls this behavior bad business.

These trends prompted the United Nations (UN) Conference on Environment and Development in Rio in 1992, from which emerged a declaration of action, "Agenda 21," and some treaties and conventions designed to move society on a path for sustainable living.[2] Also recognizing that these trends placed humankind at a profound crossroads, scientists around the globe (including 102 Nobel laureates) signed the *World Scientists' Warning to Humanity* in 1992, which reads in part:[3]

> "Human beings and the natural environment are on a collision course. Human activities inflict harsh and often irreversible damage on the environment and on critical resources. If not checked, many of our current practices put at serious risk the future that we wish for human society and the plant and animal kingdoms, and may so alter the living world that it will be unable to sustain life in the manner that we know. Fundamental changes are urgent if we are to avoid the collision our present course will bring about.
>
> "WARNING. We, the undersigned, senior members of the world's scientific community, hereby warn all humanity of what lies ahead. A great change in our stewardship of the earth and the life on it is required, if vast human misery is to be avoided and our global home on this planet is not to be irretrievably mutilated."

Despite these warnings and the rhetoric of commitment to address environmental problems, since the Rio Conference in 1992 all of the world's living systems have continued to decline. Moreover, the degradation of natural systems is likely to accelerate due to the high annual growth rate of human population unless strategies to meet human needs are made more sustainable and just.

Current strategies to meet human needs are not sustainable. Eighty percent of the world's resources are being consumed by 20 percent of the world's population. The world's poorest 20 percent earn 1.4 percent of the world's income. According to the UN, the income ratio of the richest 20 percent to the poorest 20 percent was 28:1 in 1960; it rose to 74:1 in 1994. For 30 percent of the world's population, poor sanitation, malnutrition and air pollution are still the major causes of illness and death. The rural poor will increasingly migrate and be transformed into an urban poor, and environmental, health and social problems will multiply. It is forecast that by the year 2005 more people will live in urban than in rural areas for the first time in history.

In the United States, air pollution is believed to kill more people than automobile accidents — more than 60,000 premature deaths per year according to the Environmental Protection Agency (EPA). By the time population growth stabilizes in the twenty-first century, a five- to sevenfold increase in the consumption of energy and goods will be needed just to raise the consumption level in the developing world to that in the industrialized world. Agricultural production must increase threefold in the next forty years for all humans to have adequate nutrition even though we are already appropriating the most productive 40 percent of the land-based biomass for human purposes. Simply to maintain the current unhealthy levels of pollution and waste loadings will require an 80 to 90 percent reduction in pollution generated per unit of economic output. This reduction cannot be achieved by building more waste treatment plants or air pollution control devices.

The world will need an unprecedented two billion jobs in the next twenty to thirty years to employ the current 1 billion underemployed and unemployed people as well as any new job seekers that will enter the market. These jobs cannot be provided by economic activity that substitutes capital for labor, consumes large amounts of materials and energy, and creates large volumes of pollution and waste, particularly with the current geometric growth in population. Paul Hawken points out that with a sextupling of population and increasing economic output over a hundred-fold, there will arise the reverse of the situation at the start of the industrial revolution, which was an abundance of natural resources and the ability of the biosphere to assimilate wastes: "Our thinking is backwards: we shouldn't use more of what we have less of [natural capital] to use less of what we have more of [people]."[4]

There is increasing social and political instability worldwide despite the end of the Cold War and despite increased economic globalization (which many argue contributes to the instability). According to Worldwatch Institute there is abundant evidence of global instability.[5] Some indicators are:

- There are 27 million environmental refugees;
- There is unprecedented migration of people from East to West and South to North; and,
- There are 68 regional military conflicts.

Contributing to the instability are the facts that the United Nations has seen its influence erode and there is increased isolationism on the part of major powers such as the United States.[5]

As the astronauts said in *Apollo 13*, "Houston, we have a problem!" There is a societal problem caused by the "design" of an economic and social system that lives off its support system in a degrading, unhealthy and unsustainable manner. Paradigm shifts in the relationship of humans to the environment as well as the relationship of humans with each other are needed. These shifts must result in a societal framework in which humans live in harmony with both natural systems and each other. However, these results cannot be achieved with current thinking. Being the visionary that he was, Thomas Camp recognized this in 1963 when he said in his book, *Water and Its Impurities*:[6]

> "Neither water treatment nor waste treatment can be a satisfactory remedy for pollution of our watercourses by pesticide sprays or by salt used for melting snow and ice on our highways. These materials must be controlled at their point of use, because they are damaging to land, plants and animals, as well as to water. Similarly, excess soil erosion cannot be abated by water or waste water treatment. Better land use is needed. In water quality problems, the whole environment must be examined."

As Albert Einstein has observed, "problems cannot be solved at the same level of awareness that created them." In the next twenty to forty years, society must adopt new strategies that allow the needs of an expanding population to be met in an environmentally sustainable and equitable manner. But current response to the situation has been irresponsible and dangerously inadequate. The prevailing ideology of growth has captured Western society's imagination to the degree that much of Western society continues to believe that more of the same resource-intensive and pollution-creating economic growth remains the best way to serve the common good.

A healthy environment is essential to human existence, health and well-being. Humans can live for about four minutes without air, four days without water, and four weeks without food. Plants, animals and the habitats they occupy provide the food that sustains human life. The earth and all its living organisms supply all of the raw materials needed for human activity.

All economic and social systems derive resources from, and are a part of, the biophysical system called the biosphere. There is no inherent conflict between protecting the environment and a strong human economy since the environment is the support system for all human activity. As Peter Dunne said in a *New York Times* editorial, "The environment is not a competing interest; it is the playing field on which all other interests intersect."[7]

How We Got Here — Western Human Beliefs

Prevailing Western beliefs about humanity and our relationship to our environment include:

- Humans are separate from nature, and are the highest and most dominant species on evolutionary scale;
- A denial of the existence of any threats to humanity or the environment on a global scale;
- Resources are free and inexhaustible;
- Technology fixes most problems;
- Nature has an infinite assimilation and remediation capacity; and,
- Material acquisition and accumulation are the most important determinants of success.

As a result, the general public has little awareness that a healthy natural environment is essential to our very existence. We see ourselves as separate from the natural world and are unaware that it provides all the resources that make life possible while absorbing our wastes and enriching our lives with its incredible diversity of plants and animals. Much of the population has little idea about where goods come from and where they go. There is also too little common knowledge about the destructive impact of pollution on human health. We believe that natural and physical resources are free and inexhaustible and that the environment can assimilate all our pollution and waste. The general public has little idea that it is not just industrial enterprise, but the aggregate of all human activities — all of the individual and the collective daily decisions — that are irreversibly changing the earth.

Vision for a Just & Sustainable Future

How do we create a life that allows all present and future humans to be healthy, have their basic needs met, have fair and equitable access to the earth's resources, have a decent quality of life and preserve the biologically diverse ecosystems on which everyone depends? Future scientists, engineers and business people must design technologies and economic activities that sustain rather than degrade the natural environment, and enhance human health and well-being. Human "systems" must mirror natural systems by having us live within the limits of these natural systems. We must dramatically reduce the resource and energy throughput of our economies and minimize our ecological footprint to maintain the life support system that will make a sustainable future possible. This impetus calls for a New Industrial Revolution that builds on the information and biotechnology revolutions of the past half century.

The vision of a sustainable future is one in which:

- *The world population is stabilized* at a level that is within the short- and long-term carrying capacity of the earth's finite resources. What this level should be is the subject of much debate. Most agree that this level is between eight and nine billion people — a level we will reach in the next twenty-five to forty years.
- *Resources are used efficiently.* Leading organizations (such as the Wuppertal Institute and the Factor 10 Club) and a growing number of individuals (such as Ernst von Weizsacker, Paul Hawken and Amory Lovins) have been calling for a huge increase in resource productivity — by a factor of 4 to 10 in order to increase wealth for 80 percent of the world's population and to decrease environmental impact. This increase is critical because the world's heavily industrialized economy is incredibly wasteful in its use of resources while the planet has a finite amount of resources and a finite ability to absorb and process wastes. For example,

only 3 percent of the total energy produced by a nuclear or coal-fired power plant ends up lighting an incandescent bulb. In their recently released book, *Factor Four: Doubling Wealth, Halving Resource Use,* Ernst von Weizsacker and Amory and Hunter Lovins call for a revolution in energy and resource productivity and provide over 50 demonstrated examples of factor 4 increases in energy, material and transportation productivity from a variety of institutions around the world.[8] With a few exceptions, the examples cost less than conventional means of doing business and they resulted in increased social and economic as well as environmental sustainability. From 1973 to 1986, the U.S. economy grew by 40 percent, yet energy consumption did not increase. Higher prices in oil led to industrial conservation and government efficiency standards for automobiles, refrigerators and electric motors. The economy saved $160 billion a year. However, there is still room for improvement. Germany and Japan obtain twice as much economic output per unit of energy consumed as the United States and ten to twelve times as much as China. Since 1986, the price of oil has fallen to a historical low due to the success of conservation. As a result, in the United States, the size (witness the growth in gas-guzzling sport/utility vehicles that now make up 45 percent of new car sales) and number of automobiles and the number of miles driven has continued to grow, driving energy consumption up steadily each year. The United States now imports more oil just for gasoline than the total amount of oil imported during the 1973 oil crisis.[9]

- *We mirror, learn from and live within natural systems.* Humans are the only species on earth that produce waste that cannot be used as a raw material or a nutrient for another species. Also, we are the only species to produce wastes that can be broadly toxic and that are toxic for long periods of time. A sustainable society would eliminate the concept of waste. Waste is not simply an unwanted and sometimes harmful byproduct of life; it is a raw material out of place. Waste and pollution demonstrate gross inefficiency in the economic system since they represent resources that are no longer available for use and/or create harm in humans and other species. A sustainable economy would mirror nature's "circular" method of using matter and employ the concepts of design through which all waste would be the "food" *(waste = food)* for another activity. This idea is illustrated in the concept of *industrial ecology.* Metal extraction and conversion would be replaced by strategies to continuously cycle existing metals through the economy. For example, recycling aluminum rather than using virgin bauxite ore cuts energy use by 95 percent and pollution by 99 percent.
- *We use renewable resources at a rate less than or equal to the natural environment's ability to regenerate the resource.* This practice means living off environmental income, not capital — for example, utilizing sustainable forestry, sustainable fishing and sustainable agriculture. Every ton of paper made from recycled fiber saves seventeen trees and cuts air and water pollution 30 to 50 percent. Organic farming and agricultural production that minimize the use of pesticides and fertilizers, while conserving soil and water, are safer and more sustainable.
- *We rely directly on solar energy to drive our economic system.* Over 85 percent of the world's energy comes from fossil fuels. This form of energy use causes major environmental and health problems such as black lung disease, air pollution, acid rain, oil spills and global climate change. The desire for a continuing "cheap" supply of fossil fuels historically in the last half-century has had enormous military and economic costs to keep oil and gas flowing around the world, especially from the Middle East. Moreover, this fossil fuel dependence is economically unsustainable for more than a few decades — it takes 10,000 days for nature to create the fossil fuels that we currently consume in one day.

- *We increase production of durable, repairable goods and eliminate persistent, toxic and bioaccumulative substances.* At the same time, we eliminate disposable goods as much as possible and detoxify the production process by minimizing the use and discharge of toxic substances. Products are designed for "disassembly" so that the materials can be utilized in making new products. For example, several automotive manufacturers are redesigning automobiles so that 90 percent or more of the materials can be recycled into new automobiles. In 1993, one of the world's leading manufacturers of shaving equipment had reduced its Toxic Release Inventory wastes (United States EPA definition) in this country by 97 percent from the company's 1987 level. According to *Factor Four,* between 1981 and 1993, a large chemical manufacturer developed a division-wide directive wherein 2,400 workers implemented 1,000 projects (costing under $200,000) to save energy or reduce waste.[8] For the 575 projects subsequently audited, the average annual return on investment was 204 percent and the annual savings was $110 million.
- *We focus on providing the ultimate ends of products or services not the products or services themselves.* German chemist Michael Braungart and Bill McDonough have invented the concept of *products of service.*[10] A key to resource efficiency is to understand products as a means to deliver a service to a customer. For example, people do not want energy, they want the service it provides such as heat or light. Similarly, people want access to people, places, things and experiences not necessarily increased transportation. One example of a company that has adopted this concept leases carpeting. The lessee gets the service of the product — warmth, softness, acoustic value and aesthetics for a fee. When the carpet is worn out, the company takes it back and recycles it into new carpet.
- *We create low-energy-consuming transportation systems.* We must accelerate the development of alternative fuel vehicles that minimize and eventually eliminate dependence on fossil fuels and accelerate the use of mass transportation.
- *All people understand their connection to the natural world and to other humans.* We understand our "ecological footprint" — *i.e.,* we know where products and services come from, where wastes go, and what they do to humans and other living species. We appreciate that driving a car in Ohio may cause flooding in Bangladesh through global warming, or that cutting down forests in Brazil may deprive someone in Hungary of a lifesaving drug. For all people (led by professionals such as engineers), minimizing our ecological footprint and "walking lightly" on the planet is second nature.
- *All current and future generations of humans are able to meet basic needs, pursue meaningful work and have the opportunity to realize full human potential personally and socially.* The average American receives 3,000 advertising messages per day oriented toward consumption. The American public is often portrayed as a group of consumers, not citizens. But increased consumption and material acquisition alone has not led to a happier, safer and more secure population in the United States, nor has it done so elsewhere. The prestigious Councils of the Royal Society of London and the United States National Academy of Sciences issued a statement calling for an urgent need for better understanding of human consumption and related behaviors and technologies, so that effective action may be taken to expedite the transition to a sustainable, desirable life for the world's people in the coming century.[11] In the statement the organizations said, "It has often been assumed that population growth is the dominant problem we face. But what matters is not only the present and future number of people in the world, but also how poor or affluent they are, how much natural resource they utilize, and how much pollution and waste they generate. We must tackle population and consumption together." Sufficiency of resource use and accumulation is as important as resource efficiency

and productivity. Beyond meeting basic needs, we must examine non-material ways to fulfill our needs for security, belonging, personal development and happiness that transcend materialism — a goal of most major spiritual and religious movements.

- *We institute timely economic, social and environmental signals that encourage environmentally and socially sustainable behavior.* The economic measures of success we use today, such as the gross national product (GNP) and consumer price index, discourage conservation and encourage waste, consumption and the substitution of capital for jobs. The price of goods and services reflects all the profits to the producers but does not include all of the social, environmental and health costs to society. In a sustainable society, we would have more development — *i.e.*, qualitative improvement in people and value added to resource use than quantitative growth in resource and energy intensive economies. Several national and international organizations and thousands of individuals have called for full cost (including social and environmental) accounting for economic activities, the development of macroeconomic indicators that truly reflect societal well-being (*e.g.*, Index for Sustainable Economic Welfare, Genuine Progress Indicator) and taxation policies that taxes the undesirables (energy and resource consumption) and not the desirable (employment and investment).
- *Nations act like a global family.* We must change the relationship between the developed and the developing countries. Industrial countries must reduce their consumption of the world's resources in the face of the desperate need of developing countries to improve health and to reduce poverty, social instability and population growth. A child born in the United States today will consume as much of the earth's resources and produce as much waste as more than 100 Bangladeshi children. We also need new approaches for transferring technology, for training and education, and for providing financial assistance to developing countries. These approaches must address population stabilization, improving the educational and social status of women, the international debt problem and the need for sustainable economic strategies.

The Role of Engineers

Engineers must lead this new industrial revolution. There is some excellent leadership by professional organizations such as the World Engineering Partnership for Sustainable Development, the World Federation of Engineering Organizations (WFEO) and the World Business Council for Sustainable Development (WBCSD) to make sustainable development a high priority in engineering and business — both in practice and in the education of future engineers. These organizations are promoting codes of practice, education, mentoring programs and policy changes that will encourage the engineering profession to lead this revolution.

A current fundamental problem is the underlying assumption (by many) that environmental protection should be left to environmental professionals such as environmental engineers. However, environmental specialists alone will not help us move toward a sustainable path. All humans consume resources, occupy ecosystems and produce waste. We need all professionals to carry out their lives and activities in a manner that is environmentally sound and sustainable. In addition, the current education and training of most environmental professionals who are and will be employed by government, industry, academia and environmental organizations is narrowly focused and incomplete. Most of these professionals are trained in dealing with a subset of environmental problems such as air pollution, water pollution or hazardous waste, but are not trained to deal with environmental issues in an integrated and comprehensive fashion. The focus of training is on controlling pollution and waste once created and in remediating environmental damage, rather than reducing or eliminating pollution and waste generation at the source.

Designing a sustainable future requires a paradigm shift toward a systemic perspective that encompasses the complex interdependence of individual, social, cultural, economic and political activities and the biosphere. The engineers of the future must be much more interdisciplinary — the lines between the traditional engineering disciplines must be much more fluid or removed completely. Engineers will have to join forces with biologists, chemists, meteorologists, economists, planners, political scientists, ethicists and community leaders in unprecedented ways to lead society on a sustainable path. Since it is likely that we will double the amount of housing and building construction in the twenty-first century (and buildings utilize a tremendous amount of materials and energy), it is imperative that civil engineers team up with architects, planners and other engineers to revolutionize construction.

There is a special role for civil/environmental engineers in the future. Rather than primarily designing technologies to control or remediate pollution, environmental engineers will be the inter-disciplinary systems specialists who will bring together, coordinate and manage all the specialists to solve complex environmental problems and promote sustainable development.

Moreover, all engineers must play a much stronger role in the public policy process to provide the right incentives for industry and others to move on a sustainable path so that engineers can be encouraged and supported to design sustainable technology. As Don Roberts advocates, engineers themselves must become better informed of the interdependence of environmental, economic, health and social issues, so that we can inform others and become leaders.[12] Otherwise, the agenda will be set by others who neither know the benefits nor the limits of technology in a sustainable modern society.

Educating Engineers for Sustainable Development

Such a shift in the thinking, values and actions of all individuals and institutions worldwide calls for a long-term societal effort to make environmental and sustainability concerns a central theme in all education, particularly for engineers, economists and business people. If we are to achieve a sustainable future, institutions of higher education must provide the awareness, knowledge, skills and values that equip individuals to pursue life goals in a manner that sustains human and non-human well-being. This "retooling" is critical since higher education prepares most of the professionals who develop, manage, teach in and influence society's institutions.

Several prominent engineering schools are making important strides, such as the Georgia Institute of Technology making sustainable technology a core mission and the Massachusetts Institute of Technology with its Program in Environmental Education and Research (PEER). Despite these efforts and those of a number of colleges and universities that have active environmental studies programs and train graduate professionals, education and research about the interdependence of, and a sustainable relationship between, humans and the rest of the environment is not a priority in higher education. As David Orr has said, "The crisis of humanity and the biosphere is a crisis of mind, perception and heart. It is not a problem in education; it is a problem *of* education."[13] To date, no engineering school in the United States (and quite possibly in the world) has made design for the environment, industrial ecology, pollution prevention or the relationship of technological development to sustainability the cornerstone of engineering education.

Future Engineering Education

The content of learning must embrace an interdisciplinary, systemic approach to address environmentally sustainable development on local, regional and global scales over short, medium and inter-generational time periods.

The context of learning must change to make the human/environment interdependence an integral part of normal teaching in all engineering disciplines rather than isolated as a special course or module in a program for environmental specialists only. Because the environment provides the basis for life and is a major determinant of the quality of life, it must be a fully integrated and prominent part of *all* education. Students must understand that we are all an integral part of nature and that we are coevolving with all the other species in the biosphere. All engineers must learn a number of concepts and skills such as:

- Systems thinking;
- How the natural world (including humans) evolved and works;
- The interdependence of humans and the environment including the relationship of population, consumption, culture, social equity, health and the environment;
- How to assess and minimize the ecological footprint of human economic activity;
- Technical, design, scientific and institutional strategies and techniques that foster sustainable development, promote energy and natural resource efficiency and conservation, mirror natural system resource use and cycling, remediate environmental problems, and preserve biological diversity;
- Social, cultural, legal, market and governmental frameworks for guiding sustainable development; and,
- Strategies to motivate environmentally just and sustainable behavior by individuals and institutions.

It is important that the educational process include an experiential education component to provide students with the opportunity to practice these skills on the campus and in the larger community, including in industry and government.

Recognizing the need to assist higher education in making this transition, a small group led by Senator John Kerry established Second Nature, a non-profit organization located in Boston. Its sole purpose is to increase the capacity of higher education to make justice and sustainability "second nature" in its learning, research, operations and community outreach. In its four years of existence, it has provided technical assistance, educational materials and helped train over 700 faculty and staff and between 25,000 to 30,000 students in 25 universities across the United States. Its sister organization, the Consortium for Environmental Education in Medicine (CEEM), is providing similar services to medical schools in Massachusetts, Rhode Island and Texas. Both Second Nature and CEEM and four other organizations — Management Institute for Environment and Business, Center for Respect of Life and Environment, National Wildlife Campus Ecology Program and Association of University Leaders for a Sustainable Future — have formed an Alliance for Sustainability through Higher Education to expand each member organization's scope and effectiveness to promote education for sustainability. These efforts are important but represent a tiny fraction of the effort that is needed to move higher education and society on a just and sustainable path.

Conclusions

As a society, we have two choices. First, continue business as usual — promote population and rapid economic growth that maximizes throughput of materials and energy and then head for the new horn of plenty, with no time for recycling, efficiency or restoration as the cure for all our social, health, political and environmental problems. Let nature set the limits that will come through environmental collapse, poverty, malnutrition, social instability and war. (One definition of insanity is doing the same thing over and over again and expecting a different result each time.)

A second choice is for humans (as the most self-aware species that can also learn very quickly) to take deliberate individual and collective steps to find civilized and cooperative ways to live in harmony with each other and the rest of nature. Accepting this path means respecting, mirroring and living within nature's limits, using energy and resources as efficiently as possible, maintaining the integrity of the life-support system and helping all people meet their needs.

The Chinese character for "crisis" is made up of two characters, "danger" + "opportunity":

Crisis	=	Danger	+	Opportunity
危機		危		機

There is danger ahead but there is also great opportunity. It is hoped that we, as engineers, are up to the challenge to make the best of the opportunity to design the technology that will lead us to a sustainable future.

NOTES — *This article was adapted from the author's Thomas R. Camp Lecture presentation to the Boston Society of Civil Engineers, sponsored by the BSCES Environmental Technical Group and held on March 31, 1998. The three automotive manufacturers that are redesigning vehicles so that they can be recycled are Volkswagen, Volvo and BMW. The Gillette Company reduced its wastes by 97 percent in six years. The Dow Company's Louisiana Division undertook the thousand projects to save energy or reduce waste. Interface adopted the "Evergreen Lease" program to lease and recycle carpeting.*

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REFERENCES

1. Schmidheiny, S., *Changing Course: A Global Business Perspective on Development and the Environment*, MIT Press, Cambridge, Mass., 1992.

2. *Agenda 21*, United Nations Conference on Environment and Development (UNCED), Rio de Janeiro, 1992, www.igc.apc.org/habitat/agenda 21.

3. Union of Concerned Scientists, *World Scientists' Warning to Humanity*, Cambridge, Mass., 1993.

4. Hawken, P., "Natural Capitalism," *Mother Jones*, March/April 1997.

5. Brown L.R., Flavin, C., & French, H., *State of the World: 1997; A Worldwatch Institute Report on Progress Toward a Sustainable Society*, W.W. Norton & Company, New York, 1997.

6. Camp, T.R., & Meserve, R.L., *Water and Its Impurities*, Hutchinson Ross, Stroudsburg, Penn., 1974.

7. Dunne, P., editorial in *The New York Times*, 1997.

8. von Weizsacker, E., Lovins, A., & Lovins, L.H., *Factor Four: Doubling Wealth, Halving Resource Use: The New Report to the Club of Rome*, Earthscan Publications, Ltd., London, UK, 1997.

9. *World Resources: A Guide to the Global Environment*, World Resources Institute & Oxford University Press, 1994.

10. McDonough, W., & Braungart, M., "The Next Industrial Revolution," *Atlantic Monthly*, Vol. 282, No. 4, October 1998.

11. Councils of the Royal Society of London and the United States National Academy of Sciences, "Towards Sustainable Consumption," 1997.

12. Roberts, D.V., "Sustainable Development: A Challenger for the Engineering Profession," *The Institute of Professional Engineers New Zealand*, Vol. 18, No. 1, 1991.

13. Orr, D.W., *Earth in Mind: On Education, Environment, and the Human Prospect*, Island Press, Washington, D.C, 1994.

Deep Foundations Integrity Testing: Techniques & Case Histories

Integrity testing can identify defects and serve as a means to evaluate and modify foundation design and construction.

LES R. CHERNAUSKAS &
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Deep foundations integrity testing is employed to assess the soundness of in-place constructed elements. The increased use of these members in the New England area over the past 20 years has resulted in an increased demand for quality control testing. Integrity testing is the process by which the soundness of the inspected object can be determined. Integrity testing of deep foundations has become common due to the combination of construction requirements and technological advances. Growth in the use of in-place constructed foundations (*e.g.*, drilled shafts), along with higher design loads and a more litigious legal climate, have spurred the need for integrity testing. Advances in the areas of instrumentation, data acquisition and signal processing accompanied the increased power of personal computers. These advances enhanced the capabilities and reduced the cost of developing methods for the integrity evaluation of foundations.

Deep foundations integrity testing mostly applies to foundations constructed from concrete/grout — such as drilled shafts, drilled mini-piles, pressure-injected footings and precast concrete piles. Testing is required for quality control during construction to detect flaws in the pile (*e.g.*, necking, cracking, voids, poor quality material, etc.). Such defects are applicable to cast-in-place (or injected in-place) concrete piles and, to a lesser extent, to precast concrete piles. In some cases, the foundation length must be determined. Integrity testing can be performed on any deep foundation type (including timber and steel piles) with some methods capable of determining foundation length even when the foundation is not directly accessible (*e.g.*, structure/cap coverage of the pile's top).[1]

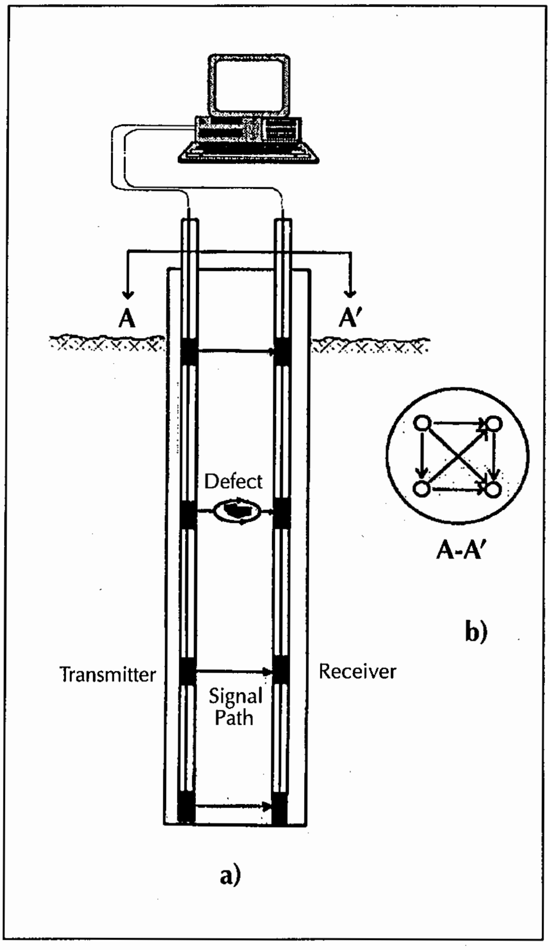


FIGURE 1. A typical crosshole sonic logging (CSL) test set-up showing a) the transmitter and receiver placed at different depths and b) a plan view of the CSL tubes noting possible test configurations.

Determining the integrity of a material can be accomplished by either intrusive or non-intrusive methods. Intrusive methods are more conventional and include drilling, coring or penetration via preinstalled conduits. These methods can include destructive testing (*e.g.*, on core samples), which provides direct information about the condition of the structure under consideration. However, the use of intrusive methods may compromise structural integrity once testing is completed. Non-intrusive testing can provide information about the condition of the structure without altering its structural integrity. Integrity testing by non-intrusive methods is often more cost effective, but it requires sophisticated equipment and specialty training to yield meaningful results. A number of sources provide more extensive information and analyses of non-destructive testing (NDT) methods.[2-5]

Background

Two techniques broadly categorize pile testing: small-strain and high-strain testing. Small-strain testing is aimed at investigating the pile integrity alone and is based on the measurement of sound/stress waves by either direct transmission or reflection. Common direct transmission techniques include:

- Crosshole sonic logging (CSL);
- Single-hole sonic logging (SSL); and,
- Parallel seismic logging.

In these methods a sonic pulse is produced by one transducer (transmitter) and the signal is picked up by another transducer (receiver). The transducers typically consist of a geophone or accelerometer. The methods differ in the location of the transducers and the pulse generation method. Common surface reflection techniques include:

- Pulse echo (or, sonic echo);
- Transient dynamic response (or, impulse response); and,
- Conventional high-strain dynamic testing.

In these methods, the reflections of waves generated at the top of the pile are measured. Since both generated and reflected signals are measured at the same location, more sophisticated instrumentation (typically, accelerometers and strain gages), data acquisition and signal processing procedures must be employed. The major difference among these techniques is whether the generated impact pulse propagates under high-strain or low-strain conditions.

Other common reflection techniques include the use of high-frequency, electromagnetic pulses (such as x-rays or microwaves). These methods are more commonly used for subsurface soil evaluation (*e.g.*, stratification, groundwater and bedrock) and/or concrete slab mapping (*e.g.*, rebar, voids, thickness and condition determination).

Direct Transmission Techniques

Crosshole Sonic Logging (CSL) Technique. The most common direct transmission integrity testing method is CSL (or, in Europe, sonic coring). The method is used to evaluate the condition of the concrete within cast-in-place piles (caissons or drilled shafts) as well as slurry or diaphragm walls. A piezoelectric transducer is used to generate a signal that propagates as a sound (compression) wave within the concrete and another transducer is used to detect the signal. Each transducer is placed into a vertical PVC or steel tube that has been attached to the reinforcement cage and filled with water prior to concrete placement. The water acts as a coupling medium between the transducer and the tube. A typical tube arrangement and testing principles are presented in Figure 1.

The source and receiver transducers are lowered to the bottom of their respective tubes and placed so that they lie in the same horizontal plane. The emitter transducer generates a sonic pulse (on the order of 10 pulses per second), which is detected by the receiver in the adjacent tube. The two transducers are simultaneously raised at a rate of around 1 foot per second until they reach the top of the drilled shaft. Typically, this process is repeated for each possible tube pair combination (perimeter and diagonals). Figure 1b shows the six tube combinations that can be tested (logged) using a configuration of four tubes within a drilled shaft. Increased shaft diameter calls for a larger number of tubes, which increases the number of combinations and, thereby, the resolution of the testing zone.

In homogeneous, good-quality concrete, the stress/sound wave speed, C, is typically around 12,000 to 13,000 feet per second and is related to the modulus, E, and unit weight, γ, and the gravitational acceleration, g, as follows:

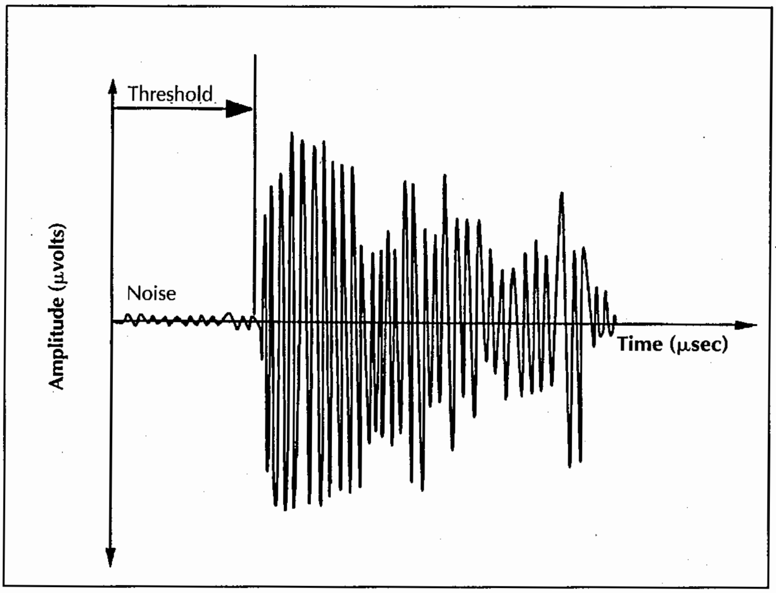


FIGURE 2. CSL typical testing signal.

$$C = \sqrt{E \bullet g / \gamma}$$

If for any reason the condition of the concrete is compromised, the wave speed will be reduced relative to the value of the wave speed in sound concrete. Figure 2 presents a typical sonic signal for which the propagation time between the transducers is measured. The vertical axis is the signal amplitude (in microvolts) and the horizontal axis is the time (in microseconds). The point where the amplitude begins to rapidly fluctuate indicates the arrival time of the signal to the receiver (or, the threshold time). Since the distance between the two tubes is known, the wave speed of the concrete between the tubes can be evaluated. The signal arrival times can then be plotted by depth to generate a log for the particular tube combination (see Figure 3). In addition to the threshold times, the energy of each signal may also be plotted by depth. This information can be used to compare signals of one zone to another where lower energy and/or longer arrival times correspond to compromised concrete quality and/or a defect.

Advantages to this method include the direct assessment of pile integrity and the ability to position the transducers in different elevations to create more signals, allowing the development of a tomographic presentation of the

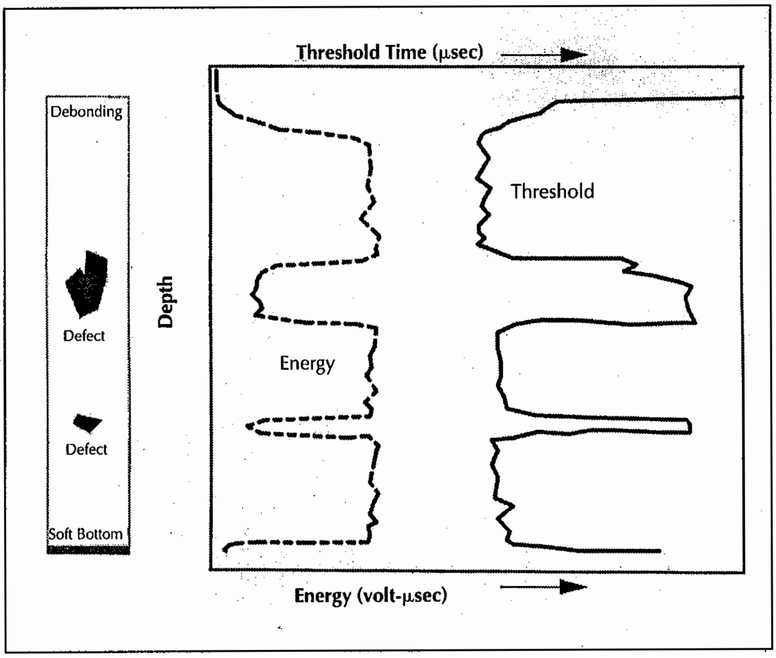


FIGURE 3. CSL results in the form of threshold time and energy versus depth.

investigated zone. The limitations of the method include detecting defects only when they exist between the tubes. Testing can be performed only on drilled shafts for which access tubes have been installed. Also, the method can only be used for drilled shafts, since other deep foundations are usually too small or are constructed using methods that do not lend themselves to accommodate the access tubes. Debonding between the tubes and concrete is common if testing occurs long after concrete placement. Testing in fresh concrete is also difficult since certain zones may cure at a slower rate, creating difficulties in the interpretation of the threshold time and energy. These zones may be interpreted, therefore, as poor-quality concrete.

CSL Case History. CSL testing was required for over 30 drilled shafts installed for the support of a state highway bridge in New Hampshire. The shafts were constructed using steel casing to the top of the rock. The soil was removed along with the casing and a 6-foot rock socket was advanced below the surface of the rock. The CSL tubes were attached to the reinforcement and placed within the shaft prior to placing the concrete. A plot of threshold time and energy against depth for a typical pair of tubes without defects is shown in Figure 4. The threshold time and calculated energy do not vary with depth, indicating uniform concrete with a wave speed of around 12,900 feet per second (tube spacing of 2 feet divided by average threshold time of 155 μsec). Approximately zero energy and no signal in the upper 6 feet are a result of the tubes sticking up above the top of the shaft.

Figure 5 presents the CSL test results for a pair of tubes indicating a soft bottom condition. The increased threshold time and decreased energy over the lowermost few feet suggest the influence of a slurry cake or a slurry/soil mixed with the concrete at the bottom of the rock socket. The soft bottom conditions were also encountered in several other shafts. Since all shafts had 6-foot rock sockets, their load-carrying ability did not rely on end bearing and the soft bottom conditions were deemed not to affect their performance.

Figure 6 presents the CSL test results for a shaft in which a defective zone was identified in the upper 14 feet. During the placement of the concrete and the pullout of the casing some of the surrounding soil along the upper 26 feet collapsed. As a result, the concrete level dropped 12 feet and a contaminated concrete zone was suspected. The extent of the contamination was not known at the time, and the CSL test log for other tube pair combinations (in addition to the data presented in Figure 6) confirmed that the upper 14 feet consisted of a zone of compromised concrete. This zone was chipped out, removed and replaced with new concrete.

Debonding between the tube and the concrete can create similar signal patterns to those that were detected for the compromised concrete. It is extremely important, therefore, to obtain both the installation log and nearest soil-boring log for each shaft to aid in CSL test inter-

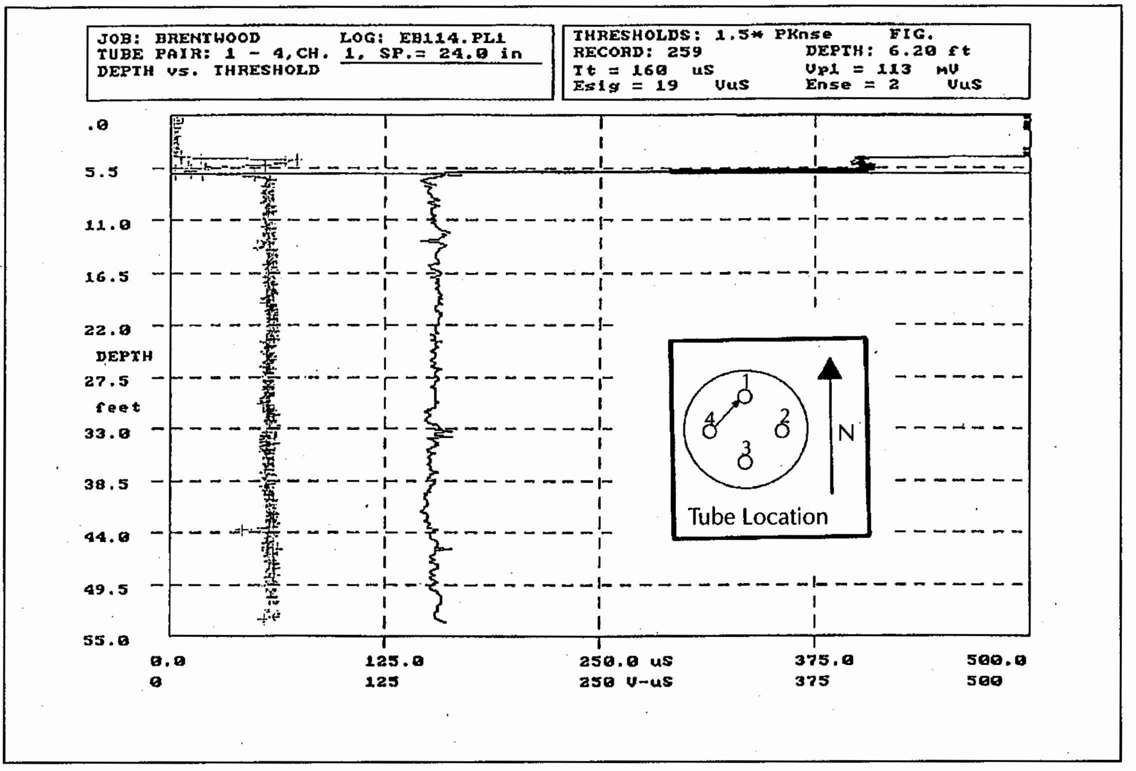


FIGURE 4. CSL threshold time and energy versus depth (no defects).

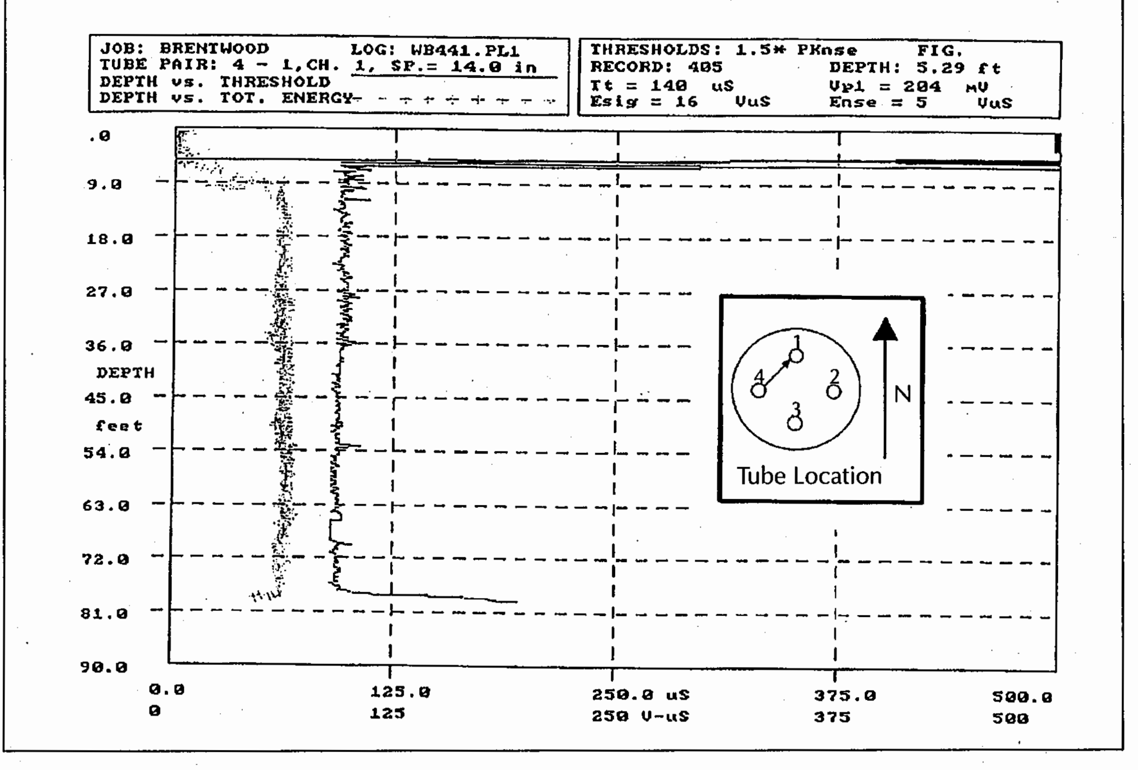


FIGURE 5. CSL threshold time and energy versus depth (soft bottom condition).

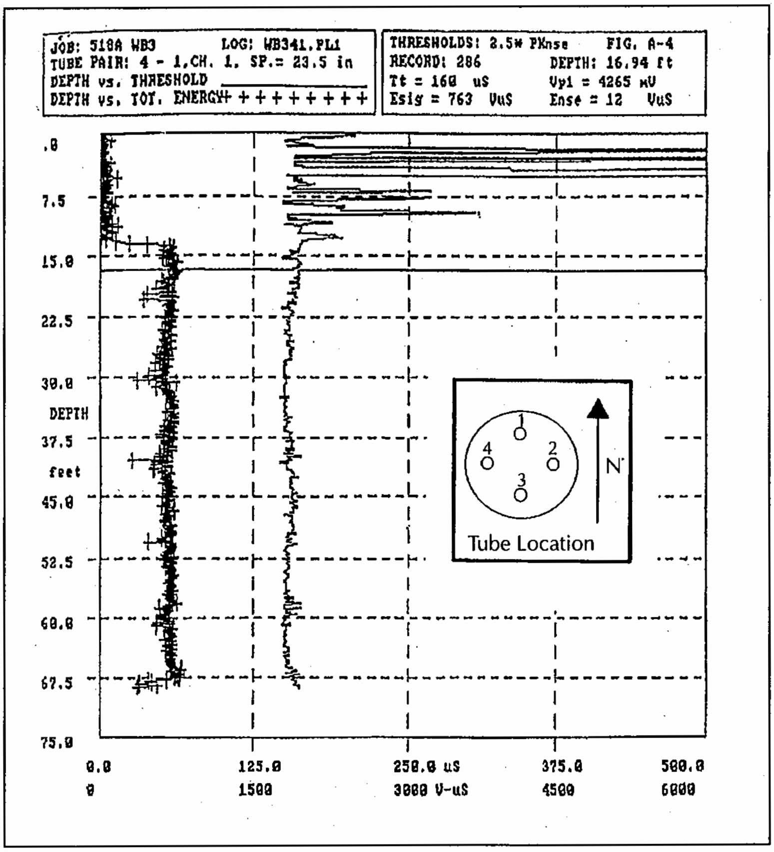


FIGURE 6. CSL threshold time and energy versus depth (defective zone in upper 14 feet).

pretation. For example, similar signals that were recorded in the upper few feet of other shafts in the same project were attributed to debonding. The major reason was that those CSL tests were performed almost two months after the concrete placement, thereby allowing sufficient time for the tubes to separate from the surrounding concrete in the upper shaft zone.

Recent Advances in CSL Testing. Following recent technological advances, a new concept in NDT equipment has emerged.[6,7] The use of laptop/portable PC-based systems and modular equipment components seem to be taking the place of the current dedicated systems. Naturally, the new concept allows small size, lighter, independent equipment with broader NDT applications. Such equipment has the advantage of employing common operating systems conforming to other requirements (*i.e.,* graphics presentations, spreadsheet, database and word processing). In addition, such systems can easily utilize updated algorithms, for example, for real-time on-screen tomographic presentation.

The first use in the United States of a portable personal computer-based CSL test system was applied for the analysis of some drilled shafts for highway construction near Worcester, Massachusetts. Figure 7 presents the layout of the test system's screen for shaft identification. User-friendly drag-and-drop features allow for a simplified and efficient use. Real-time updated data of the screen are presented in Figure 8. This dual presentation allows observing (as well as scaling, filtering and cutting among other features) the arrival time and energy signal (see Figure 3) simultaneously. The detection of a possible defective zone allows the acquisition of data in different sections by tracking the depth of both transmitter and receiver and its use in tomographic analysis, outlining the defective zone. The test system will probably result in a new generation of NDT equipment that is better suited for versatile testing demands, advanced analyses and field applications.

Additional Direct Transmission Techniques

Single-hole Sonic Logging (SSL). SSL is a variation of the direct transmission CSL method in which the source and receiver are placed in the same tube and the signal travels in a vertical direction (see Figure 9). The method is limited to defects adjacent to the tube and is usually used only when a drilled shaft requires integrity assessment after construction. Due to high coring costs, a single hole typically is advanced (often down the middle) to the bottom of the shaft or slightly below the depth where a defect is anticipated. It may also be desirable to perform SSL tests during CSL testing to isolate the location of a defect at a certain depth (*i.e.*, determining whether the defect identified by using CSL is adjacent to the tube or in between the tubes). Brettman and Frank describe a comparison between CSL and SSL tests.[8]

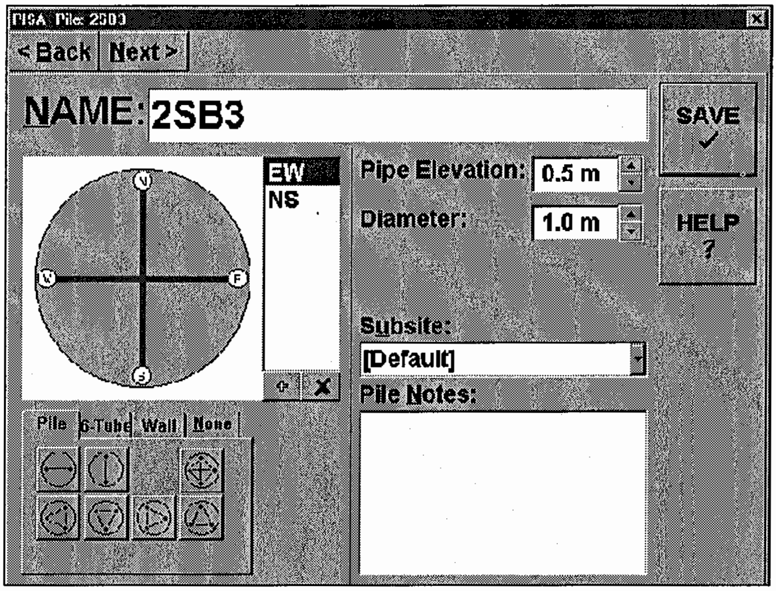


FIGURE 7. Layout of field screen for shaft identification.

Parallel Seismic Logging. Parallel seismic logging is another direct transmission integrity testing variation of the CSL test. The method is performed primarily for the assessment of the depth of older foundations. Although large voids or bulges can be identified along the deep foundation edge, it is not typically used for identifying defects. Figure 10 presents the procedure in which a boring is drilled in the ground adjacent to the existing deep foundation (usually within 2 to 3 feet of the deep foundation edge). The drilled hole is advanced well beyond the estimated tip elevation to ensure that the entire deep foundation profile can be logged. A capped PVC tube is placed within the drilled hole and surrounded with bentonite slurry/grout that bonds the tube to the edge of the boring.

A receiver transducer is placed at the bottom of the water-filled tube and pulled upwards at intervals of approximately 1 or 2 feet. At each depth interval, the foundation top is struck with an instrumented hammer that sends a pulse down the pile and the soil. This pulse is to be detected by the receiver. A typical profile of the signal arrival time with depth can be logged as shown in Figure 10b. A change in the rate of signal arrival time signifies either a large defect or the end of the pile.

The most attractive feature of this technique is that any deep foundation type can be tested as long as the drilled hole is close to the foundation. (Due to the higher cost associated with drilling, this technique is used to identify foundation depth only when other methods fail.)

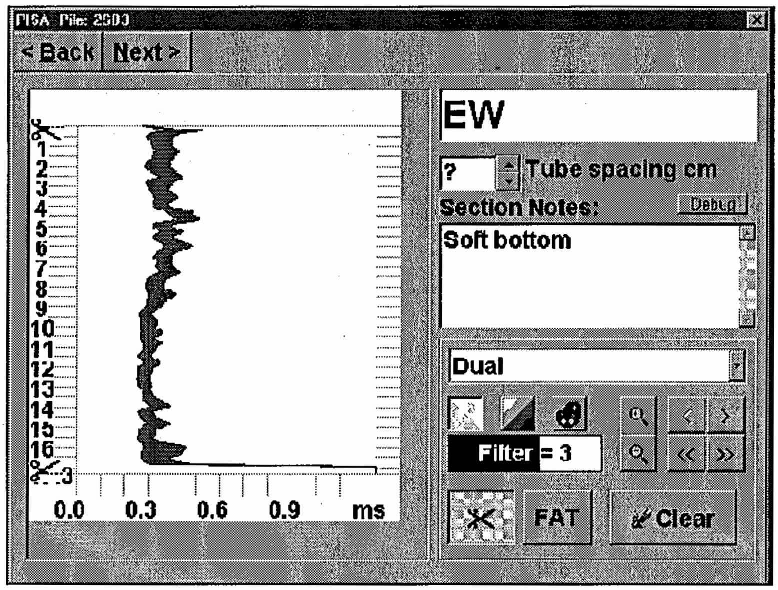


FIGURE 8. Real-time screen layout presenting arrival time and the energy signal simultaneously.

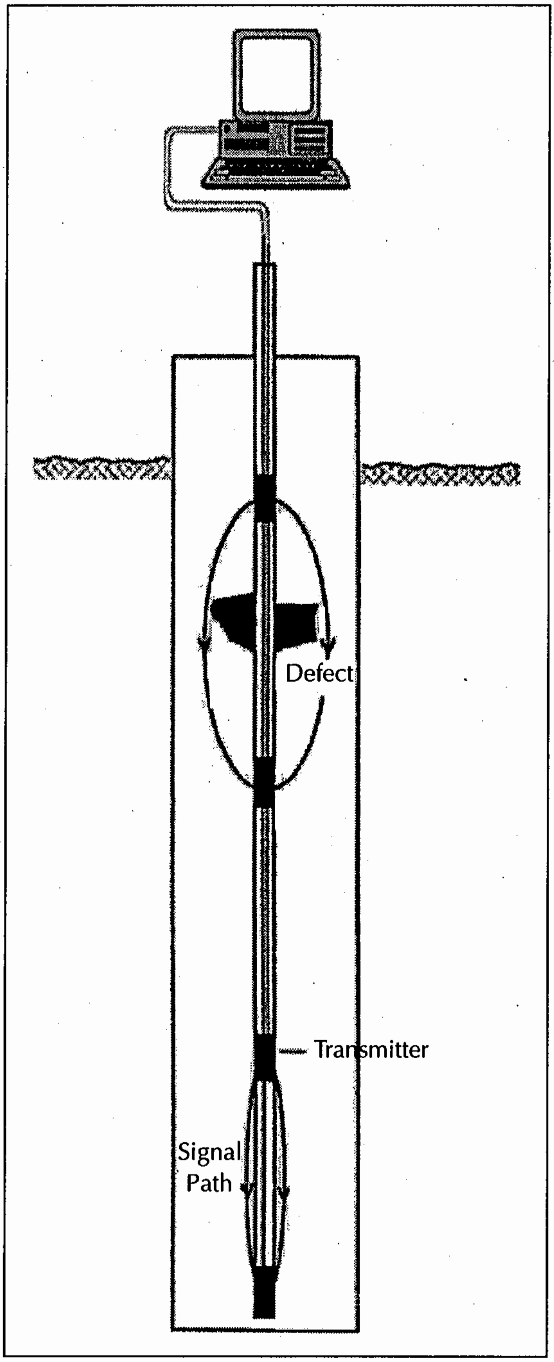


FIGURE 9. A typical SSL test set-up showing the transmitter and receiver placed at different depths.

Surface Reflection Techinques

Pulse Echo Method (PEM). PEM (also known as the sonic echo method) is a surface reflection integrity testing technique. A high-frequency accelerometer is attached to the pile top using a mild bonding agent such as petro wax or petroleum jelly. A light-weight hand-held hammer (1 to 3 pounds) is used to strike the pile top and generate a small-strain stress wave. The strains associated with the propagating stress wave are in the order of 1 $\mu\varepsilon$. Figure 11 presents a typical PEM integrity test set-up. The hammer is usually constructed from plastic to minimize the extraneous high frequencies generated by the steel. The accelerometer attached to the pile top measures the acceleration at impact and the reflections arriving at the surface from within the pile. This analog acceleration signal is recorded, digitized and integrated (using a computer) to create a velocity record.

The velocity record indicates the speed at which the pile material (at the point of measurement) moves due to the impact and reflected stress waves created by the hammer. Typical velocity and force records are shown in Figure 12. This record can be further processed using algorithms that enhance the signal through filtering, shifting, pivoting and magnification. This manipulation allows enhancement of the velocity signal for weak toe reflections, reducing the effect of unwanted noise and drifts, thereby aiding in the interpretation of the pile response.

Changes in the pile cross-section, concrete density and/or soil resistance affect the impedance in the direction of the traveling wave and create reflections of the stress wave that propagate back towards the pile top. These reflected stress waves can return in compression or tension, depending on the type of impedance change. The pile properties that define impedance, Z, are expressed as:

$$Z = (E \bullet A)/C$$

where:

C is the speed at which the stress wave propagates;
E is the elastic modulus; and,
A is the cross-sectional area.

Figure 13 illustrates the relationship between the variations in the pile impedance, the traveling wave and the reflections recorded at the surface. A reflected tension wave indicates a decrease in impedance. Conversely, a reflected compression wave indicates an increase in impedance. Combinations of these impedance changes can create complex reflections at the pile top. By inspecting the velocity record for these changes, the approximate location of the impedance change can be determined. At a time of $2L/C$ (where L is the pile length), the pile toe response can be identified by observing a reflected tension wave due to softer soil at the tip (the signal is in the opposite direction of the impact pulse — analogous to free-end conditions) or a reflected compression wave due to denser soil at the pile tip (the signal is in the same direction as the impact pulse — analogous to a fixed-end condition).

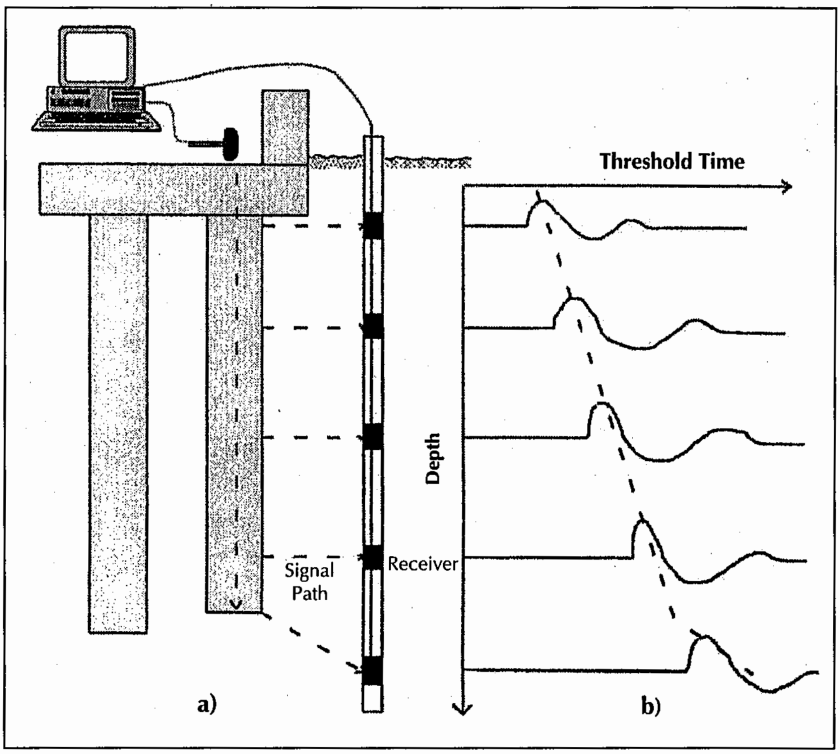


FIGURE 10. A typical parallel seismic testing arrangement showing a) instrumented hammer and receiver at several depths, and b) threshold time versus depth.

One of the most difficult tasks in the interpretation of the velocity record is distinguishing between the velocity reflections due to pile defects (*e.g.*, crack, neck, void or poor quality concrete) and velocity reflections due to soil resistance. Detailed quantification of defects is difficult (if not impossible) since the interpretation is based on reflected waves and also relies on an assumed wave speed. The most reliable way to use the method is by comparing the response from a large number of piles at the same site. Piles that indicate a response that is different from the majority should be further investigated.

PEM testing is simple and quick and, hence, can often be performed on all the piles at a site. PEM testing can be carried out on various deep foundation types and materials. Under certain conditions, PEM tests can be performed on piles that have been covered by a cap or grade beam structure. The small-strain PEM technique is generally effective to a depth of 20 to 30 pile diameters, depending on the magnitude and distribution of the frictional soil resistance.

Transient Dynamic Response (TDR) Method. The TDR method (also known as the impulse response method) is based on the PEM technique except that an instrumented hammer is used to generate the impact pulse. An accelerometer mounted in the hammer, or a force transducer built into an impulse hammer, permitting the determination of the impact force (using the hammer's mass) in addition to the velocity records obtained by the PEM test (see Figure 12a). Since a force transducer is not attached to the pile, only the impact force is recorded. The force and velocity records can be converted from the time domain to the frequency domain using a Fast Fourier Transform (FFT). The ratio of the velocity spectrum, V, over the force spectrum, F, yields the mobility spectrum (V/F in the frequency domain, presented in Figure 14), providing an indication of the pile's velocity response due to the induced excitation force.

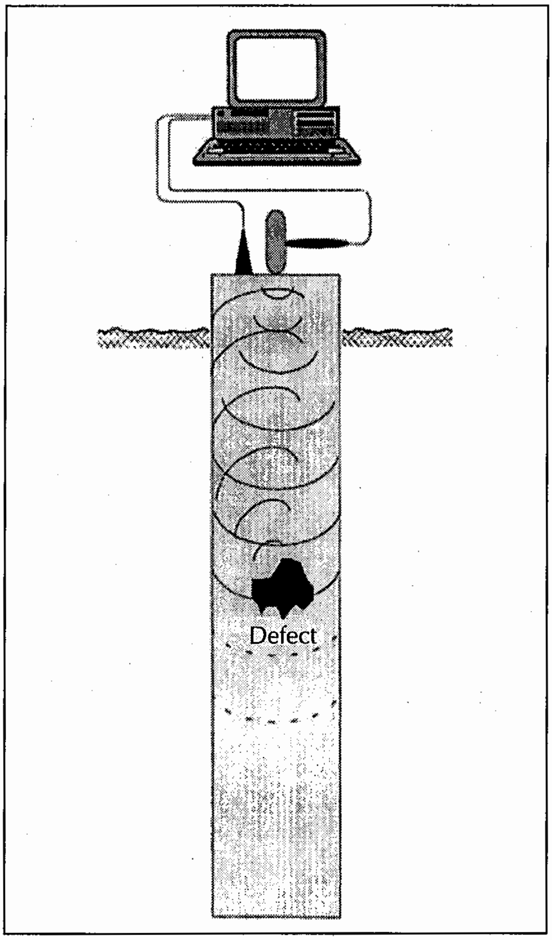


FIGURE 11. A typical PEM integrity test set-up.

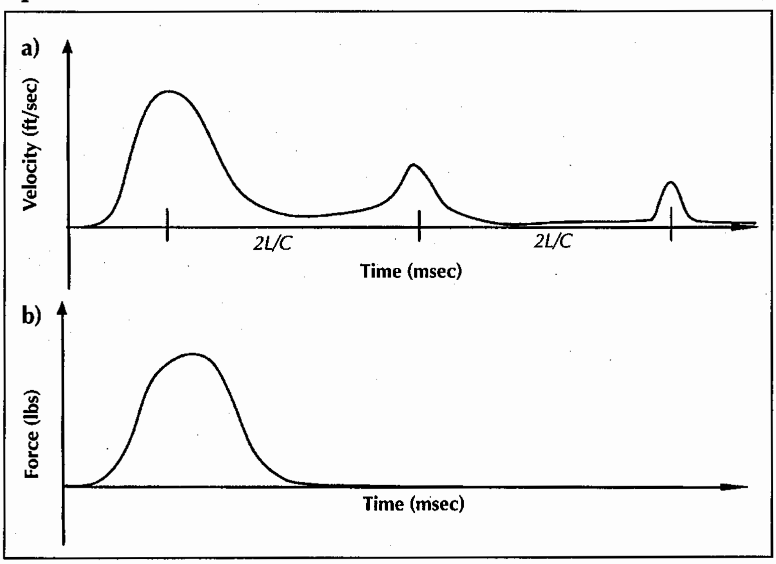


FIGURE 12. Typical PEM a) velocity and b) force records.

The TDR method allows additional insight compared to the PEM interpretation technique. Certain dominant frequencies can be identified and correlated to pile length and distance to variations either in the pile impedance or in the soil. In addition, the low-frequency components (less than 100 Hz) can provide an indication of the dynamic stiffness of the pile. Although low-strain methods permit obtaining an estimate of static pile behavior, they cannot accurately determine the pile bearing capacity. In contrast to dynamic measurements during driving or static load test to failure, these methods do not fully mobilize the pile's resistance.

PEM/TDR Case History: Pressure-Injected Footings. Approximately 600 pressure-injected footings (PIFs) were installed as part of the foundation system for a large entertainment complex in Worcester, Massachusetts. Two PIFs were visually observed to contain poor-quality, low-strength concrete reduced to a putty-like consistency near the pile tops. The upper few feet of these PIFs were cut off to remove the material and assess the extent of the defective zone.

Ten PIFs, including the visually observed defective piles, were selected for PEM/TDR integrity testing in order to assess the concrete quality in the shafts. The shafts consisted of corrugated metal shells filled with cast-in-place concrete. Reinforcement steel was installed within the upper 5.5 feet to allow for connection to the pile caps. The subsurface profile in the vicinity of the test area included 5 to 20 feet of granular fill over dense sand and gravel. The PIF bulbs were formed in this denser stratum.

Figure 15a presents the velocity record with pile length for a sound PIF. The signal indicates a decrease in the velocity around 24 feet, signifying a compression wave reflection due to the transformation from the shaft to the bulb, corresponding to an increase in the impedance. The velocity

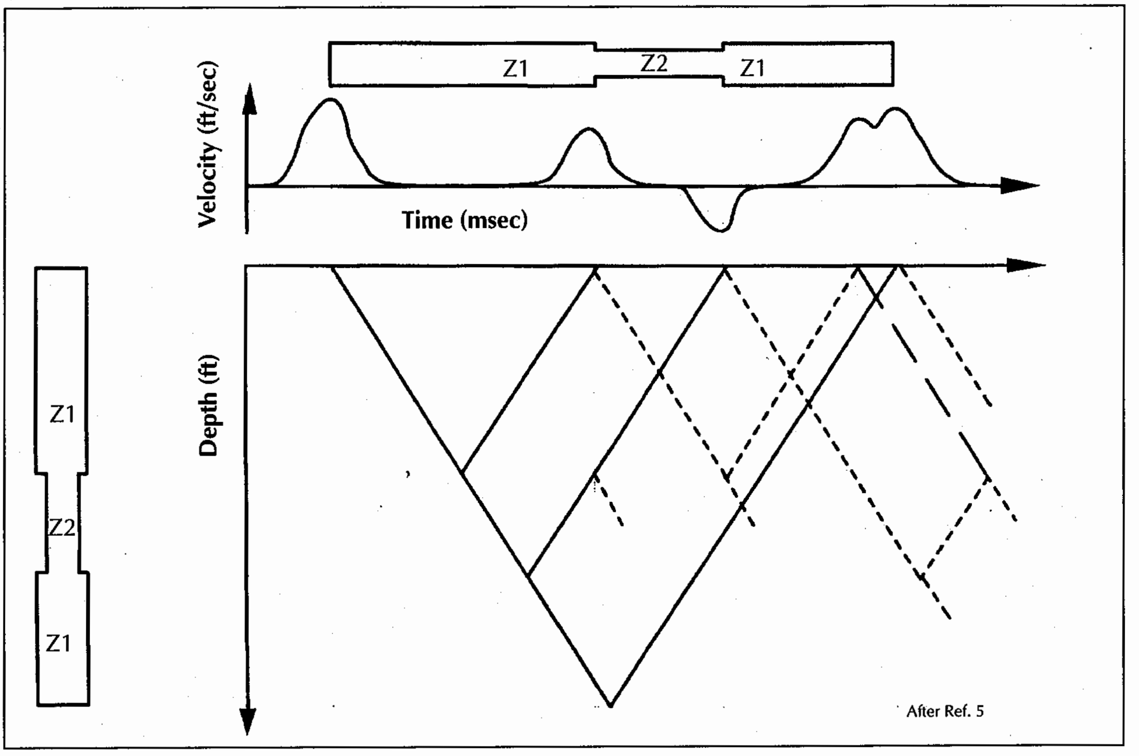


FIGURE 13. Wave propagation and reflections versus time and depth.

increases sharply at around 26 feet, due to a tension reflection from the bottom of the bulb (where the impedance decreases when transforming from the concrete bulb to the surrounding sand). The mobility spectrum for this PIF is presented in Figure 16a where peaks about 256 Hz apart appear between approximately 400 and 1600 Hz. This change in frequency, Δf, corresponds to a length of around 25 feet, based on the following relationship between time (t) and frequency (f):

$$t = 1/\Delta f$$

The relationship between time and distance (considering reflection) is also applied:

$$L = C \bullet t/2$$

The PIF shaft length was reported to be 23.7 feet, which closely agrees (considering the accuracy of the construction method and the testing procedure) with the above-determined length.

Figure 15b presents the velocity record with pile length for a PIF that was found to have a major defect. The velocity increases sharply at around 7 feet due to a discontinuity associated

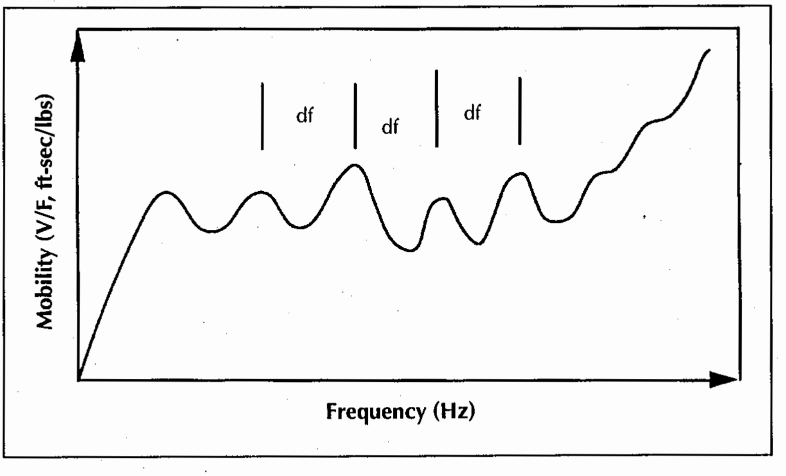


FIGURE 14. A mobility spectrum (V/F versus frequency) using records obtained by the TDR method.

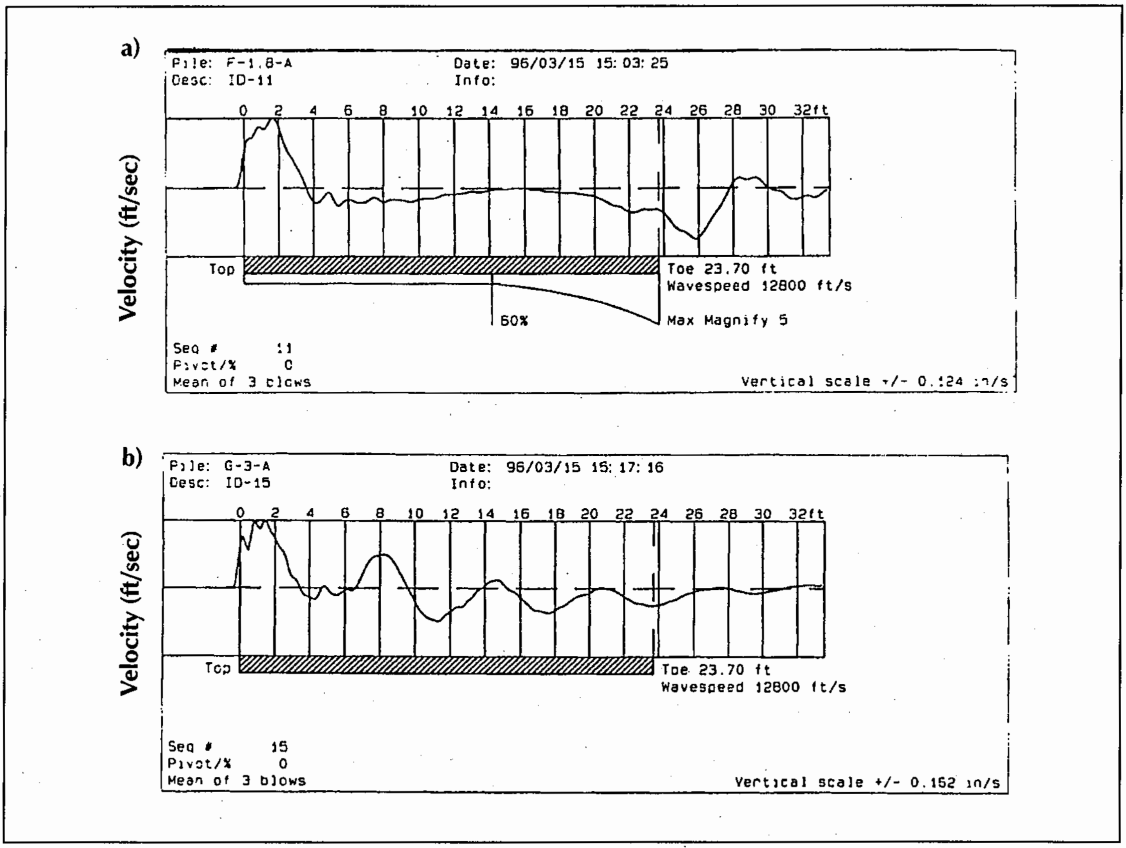


FIGURE 15. PEM velocity records versus time for a) a sound pile and b) a defective pile (for PIFs).

with a large reduction in the impedance. In fact, the low-magnitude stress wave could not pass through this defect and the reflections are repeated every 7 feet with the signal dampened with time. Even though the PIF shaft was reported to be 23.7 feet long, the length indicated by the test was around 7 feet since the defect occupied almost the entire cross-section. The mobility spectrum in Figure 16b looks significantly different from that of a sound pile presented in Figure 16a. In this case, the change in frequency is around 928 Hz, which corresponds to a length of 7 feet.

The soil around the "compromised" PIF was excavated to a depth of 10 feet. The corrugated shell was torched off the shaft around 8 feet below the top of the pile. When the shell was removed, the PIF fell over, due to a complete break in cross-section around 7.5 feet. Another PIF evaluated by PEM/TDR testing revealed a defect at around 5 feet. This PIF was also excavated. After its corrugated shell was removed, a large volume of water and putty-like concrete fell out of the shell. An approximate 20 percent reduction in cross-section was observed at a depth of 4 to 5 feet below the top of the PIF. As a result of the integrity testing and subsequent verification in the field, a reduced cross-sectional area was used to reassess the load-carrying ability of the foundations.

PEM Case History: Precast Concrete-Driven Piles. Damage in driven piles can be detected while monitoring the pile capacity using high-strain dynamic measurements. These tests are traditionally carried out on a small number of piles even though typical concrete pile breakage during installation is about 5 to 7 percent of the piles installed. Damage during driving or site work following the installation can result in piles with questionable integrity.

Figure 17 presents PEM test results on 14-inch-square concrete piles about 90 feet long that were driven for the support of multi-story buildings in Cambridge, Massachusetts. A re-

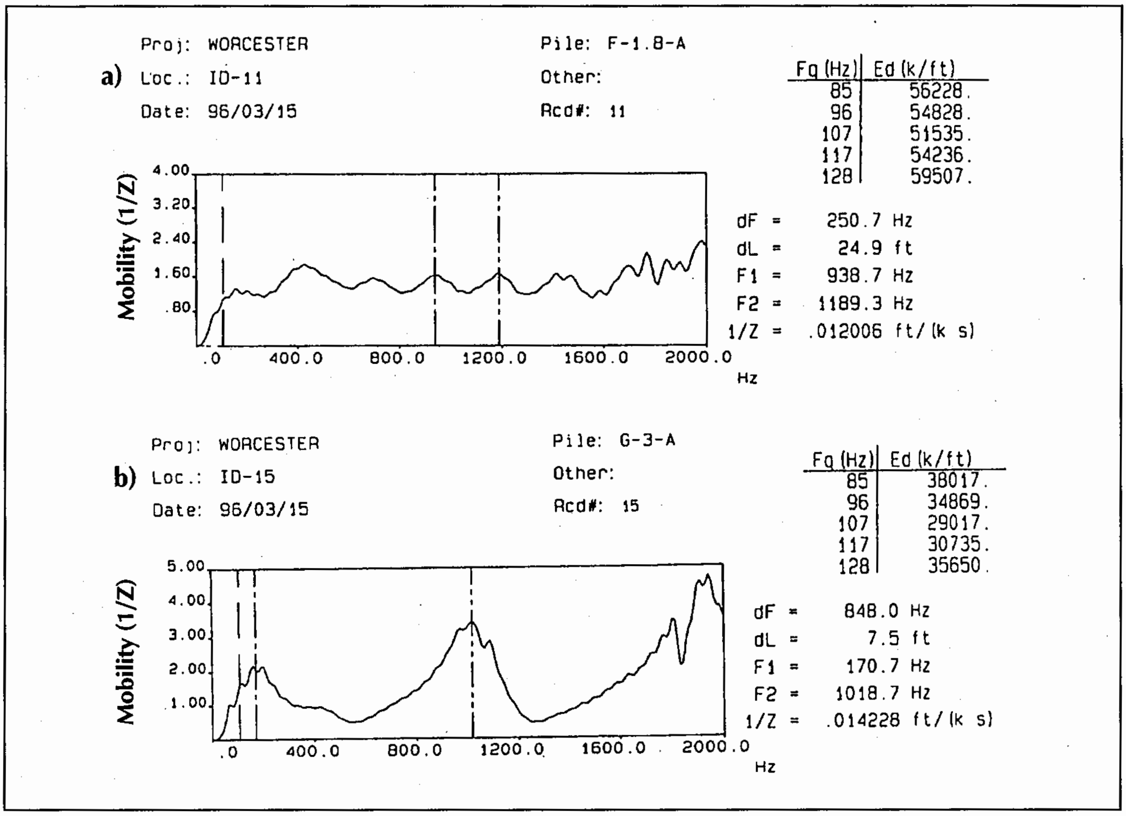


FIGURE 16. TDR mobility versus frequency responses for a) a sound pile and b) a defective pile (for PIFs).

petitive increased velocity reflection (at times corresponding to a distance of about 20 feet) is presented in Figure 17a. The repetitive reflection indicates damage extensive enough to prevent the signal from propagating any deeper than the indicated depth. However, no evidence is provided by the test regarding the compression load-bearing capability of the pile. Figure 17b presents the results obtained from a nearby sound pile for which the propagating signal responded to the variation in the soil type (sand layer at about 25 to 30 feet and a till layer at about 60 to 70 feet). The tip response was magnified due to the small energy used in the PEM testing. As a result, the technique's effectiveness at such depths is questionable.

The usefulness of the method with regard to time and cost savings was certainly a big advantage, allowing the identification of a large number of defective piles in a short period of time. However, the limitations regarding the nature of the damage and the structural ramifications need to be recognized as well.

High-Strain Integrity Testing During Pile Driving

Dynamic pile testing is commonly employed for evaluating the drivability and capacity of driven piles. The same method is also used to assess the capacity of cast-in-place shafts. When a ram strikes the pile head, it initiates a large strain wave that propagates down the pile as illustrated in Figure 18. External soil resistance or changes in the pile's impedance (due to variations in the pile's material or geometry) cause reflection waves that are recorded at the surface in a manner similar to that done for PEM/TDR low-strain methods. Typical dynamic pile testing instrumentation consists of two accelerometers and two strain transducers attached on opposite sides close to the top of the pile. Knowing the material properties and pile geometry at the point of meas-

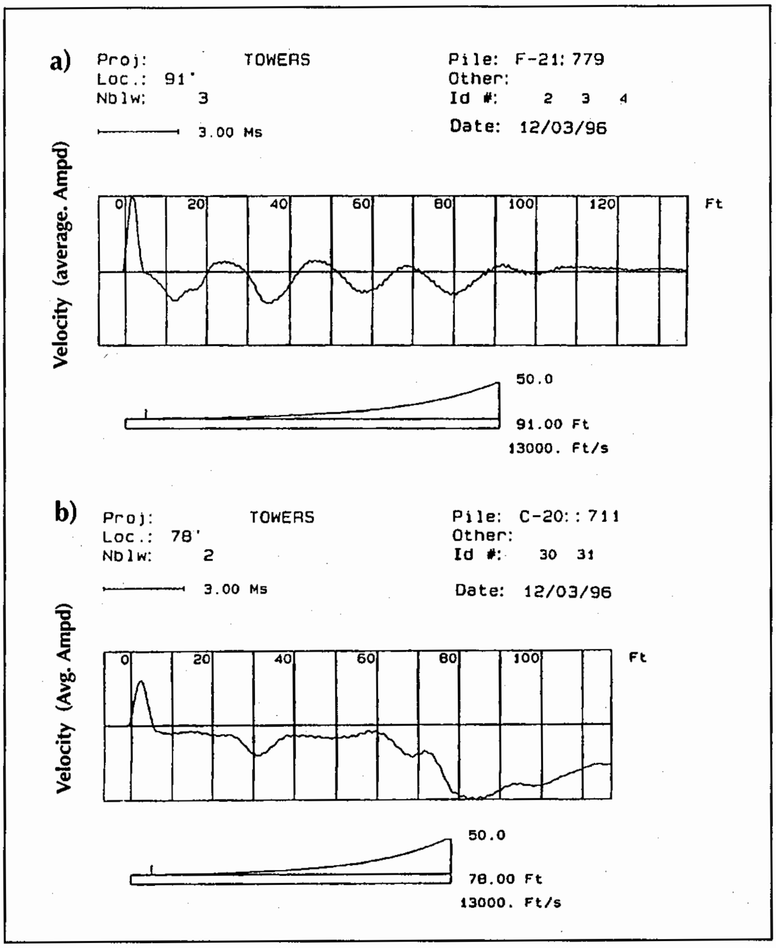


FIGURE 17. PEM velocity records versus time for a) a defective pile and b) a sound pile (precast concrete driven piles).

urement, the strain is converted to force, while the acceleration is integrated with time to produce a velocity record. These force and velocity records can be used to evaluate the pile's integrity. As long as there is no change in the pile impedance or as long as external forces (friction) are not activated, the force and velocity remain proportional. Reflections from the tip can be reviewed in light of two classical boundary conditions (see, for example, Timoshenko and Goodyear[9]): free-end and fixed-end conditions. Free-end conditions (analogous to easy driving through soft clay) call for zero stress and no velocity restrictions at the tip, resulting in a compression wave returning as a tension wave and velocity increase (theoretically doubling). Figure 19 presents reflections from a 48-inch-diameter pipe pile driven offshore with an initial penetration of about 3 feet. The downward velocity and compression stress returned from the tip as a tension wave and as increased downward velocity. Fixed-end conditions (analogous to hard driving against bedrock) call for zero velocity and no stress restrictions at the tip, resulting in a compression wave being reflected with a greater magnitude than the incident wave and a tip velocity of approximately zero.

If a pile contains a defect or is damaged during driving, the wave reflecting from the zone of decreased impedance is comparable to free-end conditions. These reflections would arrive at the measuring transducers before the reflections associated with the pile's tip since the damaged zone is located at a point along the pile between the top and the tip. The detection of damage during driving is routine and usually is associated with tension cracking of concrete piles. Other structural damage (*e.g.*, splice breakage) can also be identified. The advantage of high-stress wave propagation testing over small-strain integrity testing is its ability to quantify the structural significance of the discontinuity. While a small-strain wave would indicate a complete discontinuity for any size crack across the pile, the high-strain stress wave would pass through these discontinuities enabling the transformation of compression forces, therefore indicating the adequacy of the structural member.

Case History. Several hundred H-piles were installed for the support of an elevated walkway in the Boston area. Dynamic pile testing was specified for capacity monitoring and the driving operation progressed routinely. One of the inspected piles exhibited a clear damage profile during driving. Figure 20 presents the force and velocity records obtained during the driving of that pile. The force and velocity (multiplied by the pile's impedance) signals at the pile top shortly before and after damage detection are depicted in Figures 20a and 20b, respectively. Since the early damage identification was dismissed, driving continued and the dynamic records for the subsequent blows are presented in Figures 20c, 20d and 20e. A clear velocity increase accompanied by a force decrease attests to the development of the damage. The record shown as Figure 20e suggests that the pile essentially "ends" at mid-point, indicating a complete detachment between the upper and lower pile sections. The identified damage was associated with a full penetration weld splice that apparently disintegrated during driving. When the pile was pulled out of the ground only the upper section above the weld was extracted with severe deformations at the weld connection.

Discussion

A variety of non-destructive, intrusive and non-intrusive deep foundation integrity test-

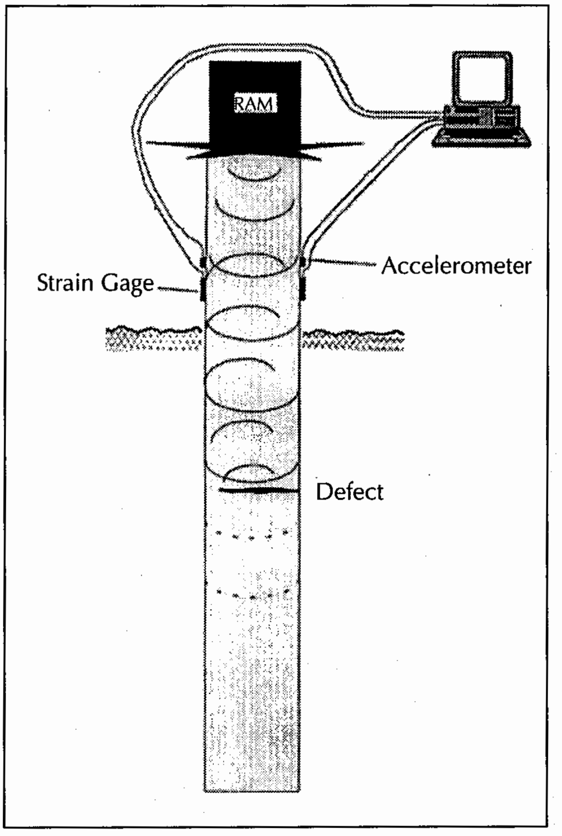
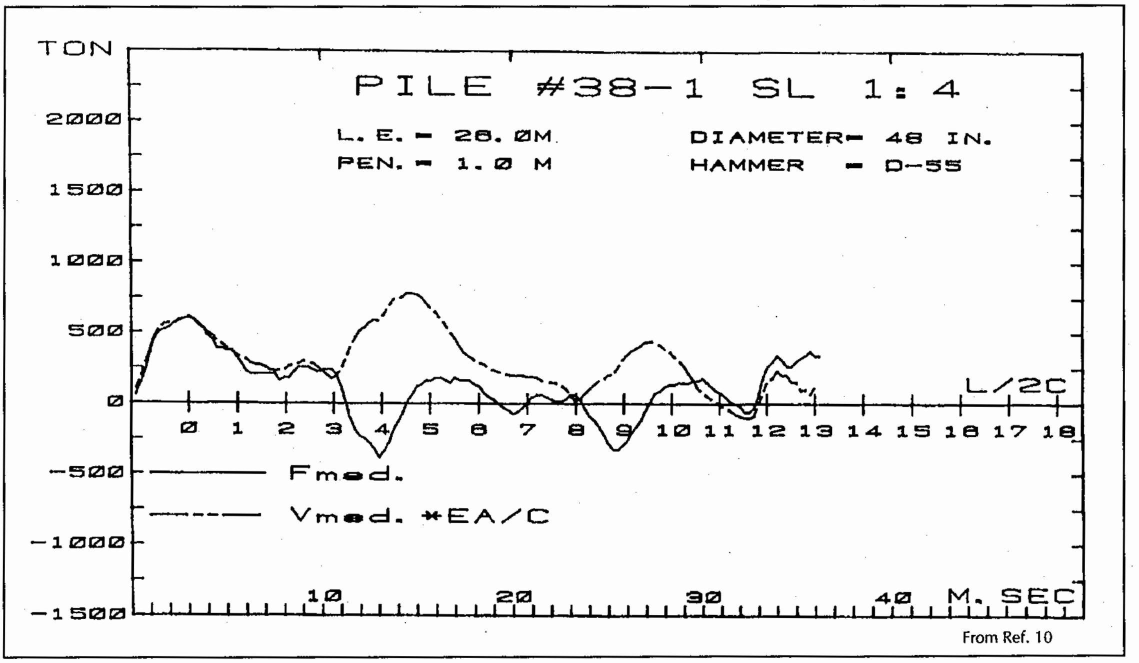


FIGURE 18. A typical dynamic test set-up.



From Ref. 10

FIGURE 19. Measured force and velocity (times the pile impedance) at the pile top versus time during initial penetration.

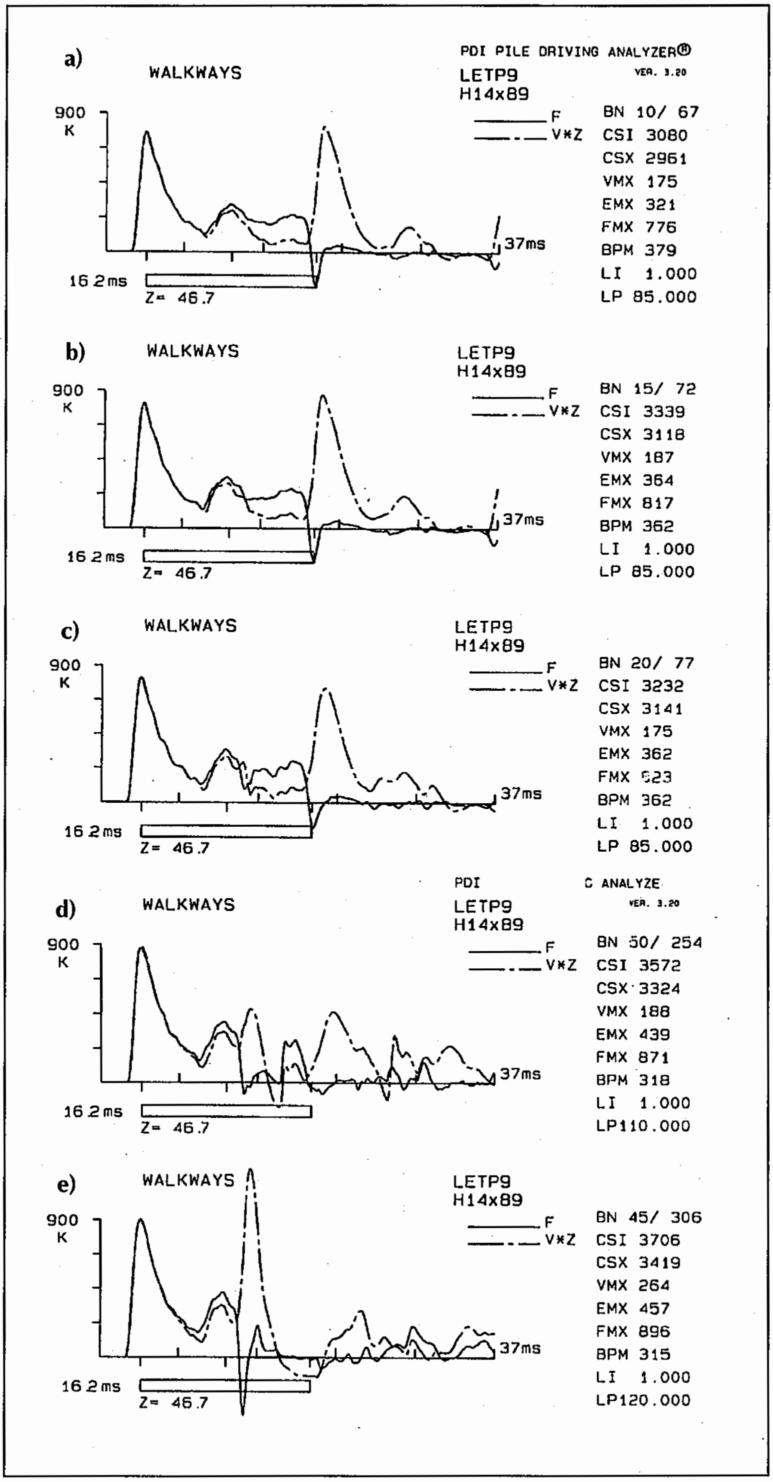


FIGURE 20. Force and velocity records obtained during the driving of a steel H-pile a) shortly before detecting damage, b) showing initial damage, c) as the damage develops, d) as the damage progressed and e) upon complete discontinuity.

ing methods provide different benefits and drawbacks. The methods' strengths and limitations are related to their effectiveness, time (in terms of preparation, testing and interpretation) and associated cost. In general, the direct transmission methods necessitate considerable preparation and can provide higher accuracy in the zone bounded by the penetrating sleeves. Surface reflection techniques require only minimal preparation but are limited in their zone of meaningful operation and accuracy. The selected testing method needs to reflect the anticipated result and the associated course of remedial action. When selecting a method, it is best to review the comparative studies of known embedded defects.[2,11]

The ability of a method to detect a certain defect should be examined in light of the defect's influence on foundation serviceability. This course of action leads to the selection of an integrity testing method based on the expected outcome. For example, the possible detailed data provided by the direct transmission methods should not result in rejecting using a caisson just because certain zones suggest a lower quality of concrete. Such decisions need to be associated with the design loads and the load-bearing assessment of the tested caisson. The surface reflection methods, on the other hand, allow extensive testing with the expectation that detailed investigations should be carried out on the suspected caissons only. Choices, therefore, should be made regarding the quantity and quality of the testing program. For example, many piles can be tested with the ability to detect major defects (where possibly undetected defects are not expected to compromise the pile's load-carrying ability), or detailed studies of a smaller number of piles can be performed, or a combination of the two methods can be implemented.

Conclusions

The reviewed methods and the presented case histories demonstrate that deep foundations integrity testing is useful and has significant importance. PEM/TDR and CSL techniques are routinely used to assess the quality and condition of cast-in-place and driven piles. Conventional dynamic testing is effective in evaluating pile integrity during driving or whenever a driving system is available. In some cases, the results of the integrity testing were used to reject the piles; in other cases, they were used to re-evaluate or redesign the piles. Frequently, integrity testing is used to confirm anticipated defects in the piles. When using an adequate testing method, along with engineering judgment, integrity testing of deep foundations can be employed as an important tool with sound economical justification.

Integrity tests are a useful and important tool — especially true when a match exists between the implemented technique, foundation type, user expertise and the owners' expectations. Solid engineering judgment, analysis and decision-making enhances the ability to utilize the test results and, hence, their usefulness and importance.

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REFERENCES

1. Finno, R., Prommer, P., & Gassman, S., "Non-Destructive Evaluation of Existing Deep Founda-

tions," *Proceedings of US/Taiwan Geotechnical Engineering Collaboration Workshop,* Taipei, Taiwan, January 1995.

2. Baker, C.N., Drumright, E.E., Briaud, J., Mensah-Dwumah, F., & Parikh, G., "Drilled Shafts for Bridge Foundations," *Final Report Under Contract No. DTFH61-88-Z-00040,* Federal Highway Administration, February 1992.

3. Holeyman, A.E., "Technology of Pile Dynamic Testing," *Proceedings of the 4th International Conference on the Application of Stress Wave Theory to Piles,* Balkema, Rotterdam, The Netherlands, September 1992.

4. Rausche, F., Likins, G., & Ren King, S., "Pile Integrity Testing and Analysis," *Proceedings of the 4th International Conference on the Application of Stress Wave Theory to Piles,* Balkema, Rotterdam, The Netherlands, September 1992.

5. Vyncke, J., & VanNieuwenburg, D., "A Mathematical Treatise of Pile Integrity Testing," *Proceedings of the Conference on Pile Dynamic Testing: Integrity and Bearing Capacity,* International Society of Soil Mechanics, Foundation Engineering, Brussels, Belgium, 1987.

6. Amir, E.I., & Amir, J.M., "Testing Piles with Virtual Instruments," *Proceedings of the DFI Conference,* Vienna, Austria, 1998.

7. Amir, E.I., & Amir, J.M., "Recent Advances in Ultrasonic Pile Testing," *Proceedings of the Third International Geotechnical Seminar on Bored and Augured Piles,* Ghent, Belgium, 1998.

8. Brettman, T., & Frank, M., "Comparison of Crosshole and Single Hole Sonic Integrity Logging Methods," *Proceedings of the 5th International Conference on the Application of Stress Wave Theory to Piles,* Orlando, Florida, September 1996.

9. Timoshenko, S.P., & Goodyear, J.N., *Theory of Elasticity,* McGraw Hill, 1934.

10.Paikowsky, S.G., "Use of Dynamic Measurements to Predict Pile Capacity Under Local Conditions," Master's Thesis, Dept. of Civil Engineering, Technion-Israel Institute of Technology, July 1982.

11. Smits, M.Th.J.H., "Pile Integrity Tests," *Proceedings of the 4th International Conference on the Application of Stress-Wave Theory to Piles,* The Hague, Netherlands, September 21-24, 1992, chapter 3 of the test results volume, A.A. Balkema/RotterDam/Brookfield, 1996.

Sustainable Development Indicators of Some European & Asian River Basins

Compilations of comparative data for a bioregional set of river basins might have value in assembling similar information for river basins around the world to aid in sustainable river basin management.

SUSAN E. MURCOTT

A group of 24 river basin specialists, representing a range of disciplines, gathered in Moscow from October 21 to 24, 1997, for the "NATO Advanced Research Workshop on Sustainable Management of Transboundary Watercourses: Theory and Practice." International environmental lawyers, scientists, engineers, economists and policy specialists were represented. The workshop provided a unique opportunity to review the theory and practice of integrated and sustainable river basin management and to discuss and compare transboundary river basin issues for the following major river basins in West, Central, and Eastern Europe and Western Asia:

- Rhine,
- Danube,
- Odra,
- Douro,
- Dneiper,
- Dneistr,
- Amu-Darya, and,
- Sry-Darya.

Presentations during the first day provided the conceptual framework. Integrated and sustainable river basin management was approached from the general perspectives of the New European Directive and the World Bank. Water law principles, ecosystem orientation and climate change impacts on water resources were also among the key themes.

Presentations given on the next day addressed transboundary watershed issues in each of the individual river basins. The workshop was organized so that at least one, and possibly several, specialists from the Rhine, Danube, Odra, Douro, Dneiper, Dneistr, Amu-Darya and Sry-Darya river basins gave presentations.

The last day involved discussions of three working groups: scientific, policy/management and legal, and a closing plenary session in which a summary and conclusions were offered.

Participants in the scientific working group recognized that, together, they represented a wealth of information and knowledge of major river basins in West, Central and Eastern Europe and Western Asia. They agreed that it would be useful to summarize this information and knowledge in the simple format of fact/sustainability indicator sheets for each river basin. A sample fact/sustainability indicator sheet for the Rhine basin is provided in Table 1 to show the general format for these sheets.

Historical Developments in the Study of River Systems

The scientific working group was aware of the historical development in the study of river systems, beginning in the early 1900s, when most scientific studies were conducted on small river segments or reaches. By the late 1950s, there was a shift to more holistic views of flowing water, and in the 1960s and 1970s emphasis was placed on watersheds as the logical basic unit for river studies as well as on land-water interactions. Next, a major shift occurred in the 1980s, with the recognition that many aspects of river dynamics could only be understood through an integrated spatial and temporal perspective.[1] In the 1990s, with attention being directed at human impacts on the global environment (such as global climate change), there has been an ever-increasing impetus towards extending the scale of focus from micro-scale (river reach), to meso-scale (river basin) to macro-scale (bio-regional). The NATO Advanced Research Workshop provided the opportunity to address river basin issues at the meso- and macro-scales.

Sustainable Development & Sustainability Indicators

Since the concept of *sustainable development* was first articulated in the 1970s, made widely known by the 1986 Brundtland Report, *Our Common Future,* and internationally embraced at the United Nations Conference on Environment and Development (the so-called Rio Earth Summit) in the document "Agenda 21," scores of people in fields ranging from architecture to industry to zoology have been discussing sustainable development. Principles for sustainably managing water resources were first articulated by people from more than 100 countries during the 1992 International Conference on Water and Environment. These "Dublin Principles" (see Table 2) were subsequently endorsed by major international conferences, including the 1992 "Rio Earth Summit."

An extensive review of sustainable development definitions, principles, criteria, indicators, conceptual frameworks and information systems was presented at the 1997 American Association for the Advancement of Science (AAAS) annual conference as part of an International Institute for Applied Systems Analysis seminar.[2] That presentation included a compilation of 29 sets of sustainability indicators, dating from 1972 through 1997. The web site, www.sustainableliving.org, covers portions of the AAAS presentation, including:

- Over 50 definitions of sustainable development;
- 17 sets of sustainable development principles;
- 12 sets of sustainable development criteria;
- The 29 sets of sustainability indicators (noted above); and,
- 17 sustainable development conceptual frameworks.

This information was compiled from materials written by many of the major leaders in the sustainable development movement (for example, the United Nations [UN], non-governmental organizations [NGOs], the World Bank, the Organization for Economic Cooperation and Development [OECD], etc.). The "raw materials" included on this web site are intended to aid visitors in understanding the complex notion of sustainable development.

The practical application of sustainable development concepts must be based on an

TABLE 1.
Fact/Sustainability Indicator Sheet for the Rhine Basin

River Length (km)	1,320
Basin Area (km^2)	188,000
Population (millions)	50
6 Riparian Countries	Switzerland, France, Germany, Austria, Liechtenstein, The Netherlands
6 + 2 Basin Countries	Switzerland,* France,* Germany,* Austria, Liechtenstein, The Netherlands* + Luxembourg,* Belgium
Principal Uses	Discharge of water sediment & ice; ecological backbone; potable, industrial & agricultural water supply; navigation; power generation; cooling water; recreation, tourism, swimming; fisheries; nature; landscape; receiving water for treated wastewater; source of building materials
Existing System of Data Collection	There is an international monitoring network. As far as possible, ISO standards are applied. In other cases, harmonized measurement & analysis methods are applied.
Existing System of Data Exchange	Water levels. For emergency situations: discharges of instantaneous water quality parameters are required immediately after becoming available; otherwise, these data are made available on an annual basis.
Major Transboundary Conflicts	Major conflicts do not exist at the moment
Major Watershed Problems	Non-point source pollution, especially nutrients, heavy metals & organic micro-pollutants; flood protection in the long run.
Average Flow at Transboundary (million m^3/yr)	Basel: 1,000 m^3/s (Switzerland, Germany, France) Lobith: 2,200 m^3/s (Germany, Netherlands)
Peak Flow at Transboundary (million m^3/yr)	Basel: 4,000 m^3/s Lobith: 12,800 m^3/s
Minimum Flow at Transboundary (million m^3/yr)	Basel: 350 m^3/s Lobith: 600 m^3/s
Number of Dams/Weirs	450
Live Storage Capacity (million m^3/yr)	Above Basel: 1.8 billion Below Basel: 0.7 billion
Water Quality (% Clean)	90% Clean
Water Quality	at Lobith (Germany, Netherlands)
TSS	50 mg/l
TSS (annual load to ocean)	0.7** × 10^6 tons/yr
TDS (mg/l)	600**
TDS (annual load to ocean)	44.7** × 10^6 tons/yr
Dissolved Oxygen	10 mg/l
BOD5	2.8 mg/l
Total Phosphorus	0.25 mg/l
Nitrate	4 mg/l
Toxins	0.03 mg/l (extractable organic halogens = sum parameter)
Percent Wastewater Treatment	90-95% biological treatment (implementation of phosphorus & nitrogen removal)
Annual Precipitation (mm/yr)	1,100
Annual Evapo-transpiration (mm/yr)	580 mm/l
Irrigated Area (ha)	Unknown (depends on precipitation & evapotranspiration)
Commerical Fish Catch	
Legal (million tons/yr)	70 (Netherlands Guilders)
Illegal (million tons/yr)	
Number of Endangered Species From Red Book	Objective is to return disappearing species such as salmon, etc.
River Flow Diversion to Other Catchments (km^3/yr)	Small amount
Length of Diking (km)	approximately 2,500
Water Consumption	
Drinking (l/day)	130 (Netherlands); 400 (Switzerland)
Industrial (million m^3/yr)	1,000
Irrigation (million m^3/yr)	5,000
Cooling (million m^3/yr)	12,000

Notes: * Contracting parties to the Agreement of Berne in 1963, covering 98 percent of the river basin.
**Global Environmental Monitoring System (GEMS): www.cciw.ca/gems/atlas-gwq/gems1.html.

TABLE 2.
The "Dublin Principles"

Principle No. 1: Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment.

Since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems. Effective management links land and water uses across the whole of a catchment area or groundwater aquifer.

Principle No. 2: Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels.

The participatory approach involves raising awareness of the importance of water among policy-makers and the general public. It means that decisions are taken at the lowest appropriate level, with full public consultation and involvement of users in the planning and implementation of water projects.

Principle No. 3: Women play a central part in the provision, management and safeguarding of water.

This pivotal role of women as providers and users of water and guardians of the living environment has seldom been reflected in institutional arrangements for the development and management of water resources. Acceptance and implementation of this principle requires positive policies to address women's specific needs and to equip and empower women to participate at all levels in water resources programs, including decision-making and implementation, in ways defined by them.

Principle No. 4: Water has an economic value in all its competing uses and should be recognized as an economic good.

Within this principle, it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failure to recognize the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources.

agreed upon set of sustainability indicators. Generally speaking, indicators simplify and briefly represent (qualitatively and quantitatively) essential, complex and dynamic information — for example, weather forecasts, economic indicators such as inflation rate and gross national product (GNP), population statistics, such as birth, death and life-expectancy rates, and so forth. The overall purpose of any indicator is to present complex information in a simple way. The identification of an agreed upon set of river basin and water-related sustainability indicators is merely one element of an integrated and sustainable approach to river basin management. Just as the identification, for example, of low life-expectancy rates is not to be confused with public health programs to increase life expectancy, so, too, river basin and water-related indicators are not intended to substitute for actions necessary to maintain or restore water quality or river basin functions. They are simply a first step in providing basic information.

Since the idea of sustainable development indicators first gained attention, a number of river basin and water-related indicators have been put forward. Table 3 provides a compilation of river basin and water-related sustainability indicators, grouped under three headings: water use, water quality, and ecosystems and natural resources.

Sustainability Indicators

Cognizant of river basin and water-related sustainability indicators such as those listed in Table 3, the scientific working group proposed fact/sustainability indicator sheets for each of the river basins under discussion. Individual river basin fact/sustainability indicator sheets were generated by a designated participant and reviewed by collaborators. These sheets are intended to briefly present basic scientific information concerning each particular river basin. (A sample fact/sustainability indicator sheet for the Rhine basin has been provided in Table 1.) Common parameters are used to allow comparisons across river basins. The parameters selected represent data from the various different disciplines.

Numerous efforts to collect and present data on a regional or global set of river basins have been made in the past.[3-7] One such effort was the Global Environmental Monitoring System (GEMS). The GEMS program was established in the mid-1970s by the United Nations Environment Program (UNEP) as a follow-up to the 1972 UN Stockholm Conference on the Environment. As a collective effort to monitor the world environment in order to protect human health and preserve essential natural resources, it involves the participation of numerous UN agencies and the collaboration of several organizations around the world. One program component of GEMS, called "Water," focused on monitoring and assessment of freshwater quality in all regions of the world. Since December 1977, as the lead agency for the implementation of this program, the World Health Organization (WHO) has coordinated a wide group of activities in collaboration with water-related units of UNEP — the World Meteorological Organization (WMO) and UNESCO. The main objectives pursued under GEMS/Water are:

- Determination of the status and trends in quality of freshwater in various parts of the world; and,
- Improvement of water quality monitoring and assessment capabilities in all countries in support of sustainable environmental management practices in their respective water resources sector.

However, participants at the Moscow workshop did not believe that fact/sustainability indicator sheets showing comparative data for a bioregional set of river basins had been previously assembled. They became convinced that the kind of information presented in these sheets not only provides useful overviews of the river basins covered at the October 1997 NATO Advanced Research Workshop, but also might be relevant to similar reviews of sustainability factors affecting other major river basins around the world.

TABLE 3.
River Basin & Water-Related Sustainability Indicators

Water Use
- Qualitative description of uses of water resources
- Percent of population served by treated water supply
- Percent of population served by sanitary services
- Daily household water use per capita
- Rates of water withdrawal & consumption by key economic sectors (agriculture, industry, commercial, domestic)
- Rates of water recirculation by key industrial sectors
- Total water withdrawal compared to growth in GNP
- Degree of utilization of freshwaters
- Groundwater reserves where withdrawal exceeds recharge
- Occurrence of contaminated groundwater

Water Quality
- River quality — entering a country, leaving a country
- Concentrations of dissolved oxygen, phosphorus & nitrogen in freshwater
- Pesticide concentration in freshwater
- Concentration of fecal coliform in freshwater
- Number of people with unacceptable domestic water quality
- Percent of municipal wastewater treatment
- Municipal discharges of BOD, TSS & phosphorus to freshwater
- Pulp & paper mill discharges of BOD & TSS to freshwater

Ecosystems & Natural Resources
- Wetlands of international importance that are highly protected/little disturbed
- Index of watershed naturalness
- Percent of streams one can drink from safely
- Groundwater reserves
- Number of threatened & endangered species
- Fish harvest in relation to sustained yield

Note: This compilation draws on indicator sets from the International Union for the Conservation of Nature and Natural Resources (IUCN), 1980; the Organization for Economic Cooperation and Development (OECD), 1991; CSIRO, Australia, 1992; the World Bank, 1995; and www.sustainableliving.org.

NOTE — *Aided by a grant from BSCE's John R. Freeman Fund, the author spent five days in Moscow in late October 1997 attending the NATO Advanced Scientific Workshop, where she presented a paper entitled, "The Danube River Basin: A Model of Integrated and Sustainable Watershed Management?" She was also the invited leader of the Scientific Working Group, summarizing its work for the benefit of the overall meeting. This article provides an overview of the entire event. Copies of Murcott's Danube paper and the fact/sustainability indicator sheets on the other river basins are available upon request from the author (Susan Murcott, Ecosystems Engineering, 58 Orne St., Marblehead, MA 01945). All of these materials — Danube paper and the sustainability sheets — are planned for publication in 1999 by Kluwer Academic Press in The Netherlands (Wouters, P., & Vinogradov, S., eds., "Sustainable Management of Transboundary Watercourses: Theory and Practice," NATO Advanced Research Workshop).*

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REFERENCES

1. Cushing, C.E., Cummins, K.W., & Minshall, G.W., eds., *Ecosystems of the World: River and Stream Ecosystems*, Vol. 22, Elsevier, Amsterdam, 1995.

2. Murcott, S., "Sustainable Development: Definitions, Principles, Criteria, Indicators, Conceptual Frameworks and Information Systems," paper presented at the annual conference of the American Association for the Advancement of Science, Seattle, February 1997.

3. Gleick, P., ed., *Water in Crisis*, New York, Oxford University Press, 1994.

4. UNESCO, "Discharge of Selected Rivers of the World," in *Studies Reports Hydrology, Vols. I, II, III*, Paris, 1969, 1971.

5. World Watch, *State of the World 1984-1997*, Washington, DC.

6. World Commission on Environment and Development, *Our Common Future*, Oxford University Press, New York, 1987.

7. World Resources Institute, "Freshwater," in *World Resources 1990-1991*, Oxford University Press, New York, 1991.

Applying Continuous-Flow Stirred Tank Reactor Methodology to Mussel Biomonitoring & Effluent Discharge Data

If water quality criteria are adopted, the use of continuous-flow stirred tank reactor methodology provides a straightforward way to estimate total maximum daily loads.

WINDSOR SUNG

Boston Harbor has been the subject of great public interest over the last two decades. It has been called the dirtiest harbor in the United States. This designation was based primarily on the evidence of polycyclic aromatic hydrocarbon (PAH) sediment concentrations studies that had been conducted in the early 1970s. The agency in charge of the Boston-area wastewater infrastructure since the mid-1950s was the Metropolitan District Commission (MDC). The MDC applied for a waiver from the secondary treatment requirement mandated by the Federal Water Pollution Control Act of 1972. However, that request was denied and the Massachusetts Water Resources Authority (MWRA) was created by the Massachusetts legislature in 1984 to oversee the required massive design and construction activities associated with compliance (the Boston Harbor Project). Two major components of the compliance activities included:

- A secondary treatment plant on Deer Island; and,
- A nine-mile long outfall that extends from Deer Island to Massachusetts Bay.

The current timetable calls for the outfall to be operational by 1999, with secondary treatment to be phased in from 1998 to 2000.

Caged mussels are used routinely to assess the potential for the bioaccumulation of contaminants from wastewater discharges into

TABLE 1.
Selected Recent Studies on the Mixing Characteristics of Boston Harbor

Investigator	Year	Ref.	Application	Volume (10^8 m^3)	Q (10^8 m^3/day)	t (days)
Sung	1991	1	Copper & Zinc	7.9	2.6	3.0
Adams *et al.*	1992	2	Nitrogen	6.0	1.2	5.0
Signell & Butman	1992	3		6.2 to 7.2	0.8 to 2.5	2.5 to 9.0

shellfish areas. Results from these studies can also be used to infer time-averaged water column contaminant concentrations in receiving waters. The Deer Island Wastewater Treatment Plant (DIWTP) is the major point source load for various contaminants into Boston Harbor. Many studies have been performed for the Boston Harbor Project from the late 1970s to the present, each with its own set of objectives. What is needed is an integration of the several different studies and monitoring programs into a relatively simple mixing model for Boston Harbor so that first-order approximations to assess water quality can be easily carried out.

An early study observed that metals such as copper and zinc behaved conservatively as the wastewater effluent from the Deer Island Wastewater Treatment Plant (DIWTP) is mixed in Boston Harbor.[1] An empirical relationship was developed between the harbor-wide concentration of copper and zinc as measured in the 1980s and the wastewater mass discharge rate (gallons/day) into Boston Harbor. This approach is analogous to treating Boston Harbor as a continuous-flow stirred tank reactor (CFSTR). The important parameters for a CFSTR are:

- The volume, V, in cubic meters; and,
- The volume flow rate, Q, in volume per time (for example, cubic meters per day).

The ratio of V and Q is t, the hydraulic detention (or residence time). Also, the mass discharge rate, M (in mass per time), is needed. For a conservative substance (no reactive terms), the steady state concentration, C_{ss}, is equal to M divided by Q.

Adams *et al.* developed a similar approach for nutrients in Boston Harbor (in particular, nitrogen) and recommended values for V, Q and t.[2] Signell and Butman modeled tidal exchange and dispersion in Boston Harbor and reported on similar parameters.[3] These estimates are summarized in Table 1. The studies listed in Table 1 represent a small sample of the many hydrologic studies that have been performed on Boston Harbor, which have ranged from dye studies to computer modeling exercises. However, Table 1 lists just the most current studies. Stolzenbach *et al.* provides a more complete listing of the various studies performed on Boston Harbor, including studies from the 1950s.[4]

Methodology

The MWRA deployed blue mussels (*Mytilus edulis*) in caged arrays near the current outfall and other sites from 1987 to 1996 to assess the potential for the "bioaccumulation" of contaminants from its wastewater discharge into shellfish. MWRA also monitored the Deer Island wastewater effluent using techniques with low detection limits — below parts per billion (ppb) — since the summer of 1993 so that fairly reliable estimates of the mass discharge rates are available for the time period (June to August) that the mussels are deployed. The mussels are typically harvested from Gloucester or Sandwich and are deployed for 60 days moored in three locations:

- A "dirty" control (the Discovery site in the inner harbor close to the New England Aquarium);
- The Deer Island site (where the current discharge occurs); and,
- A "clean" control (at the approximate location of the future outfall site).

Figure 1 shows the location of these sites and various physical features of the harbor system.

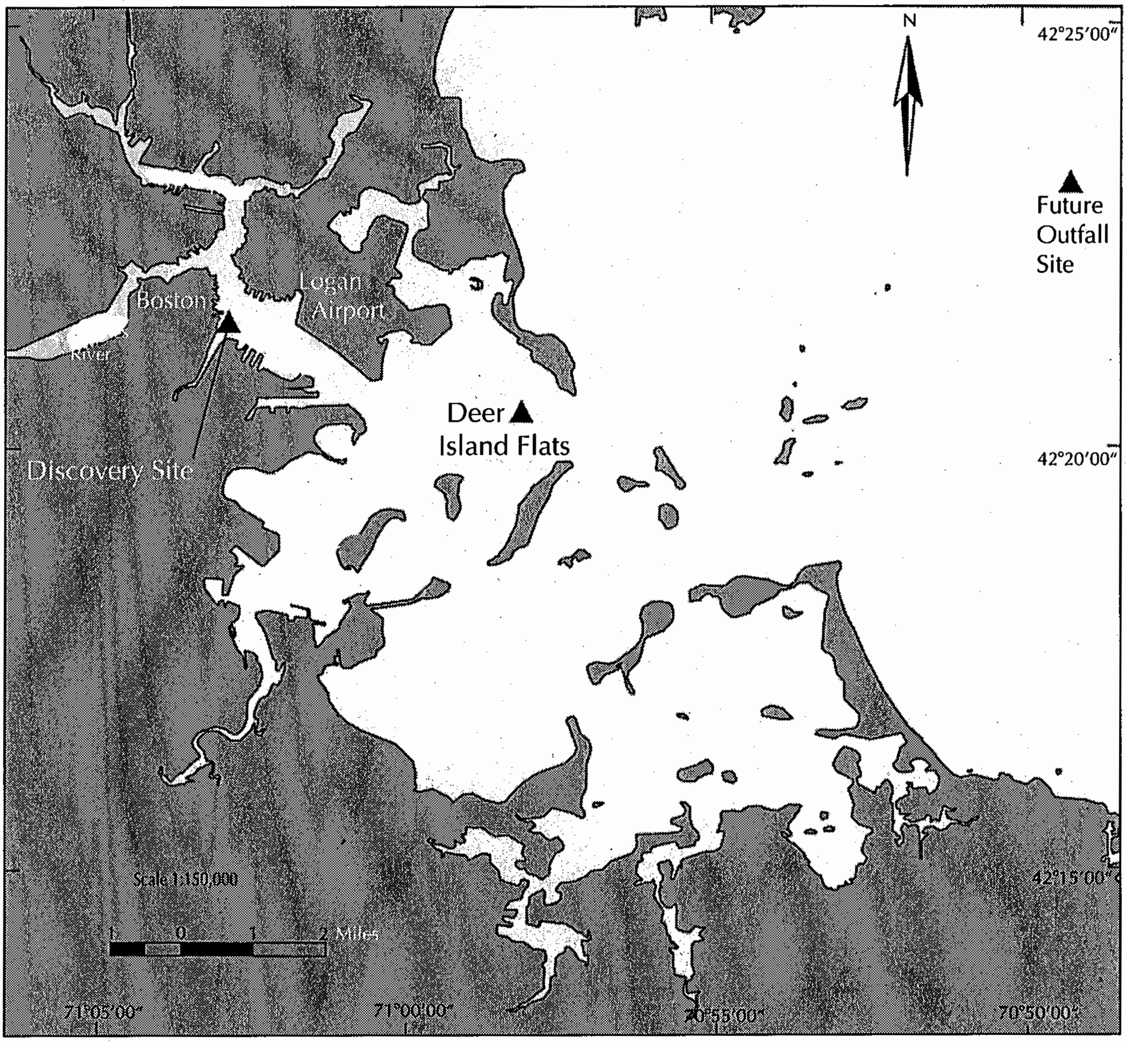

FIGURE 1. The location of mussel deployment sites in Boston Harbor.

For a detailed methodology on biomonitoring and actual mussel data, see the series of reports by Downey,[5] Downey *et al.*,[6-8] Hillman and Peven,[9] Mitchell *et al.*,[10,11] and MWRA.[12] (The various annual fish and shellfish reports are referred to as bioaccumulation studies.) For a detailed methodology and results on Deer Island effluent characterization, see Hunt *et al.*[13] and Butler *et al.*[14]

The partition coefficient, K_d, is often used to describe the relation between dissolved and total metals.[15] While the partition coefficient has often been used as a constant, it is now well understood that it is a function of pH, temperature, total dissolved solids or salinity (both effects from chloro-complexation and from ionic strength effects), as well as particulate composition (for example, percent of iron):[16]

$$K_d = C_s/C_w$$

where:

C_s is the surface bound contaminant expressed usually in μg/g (ppm) or ng/g (ppb); and,

C_w is the aqueous contaminant concentration expressed in μg/l or ng/l.

If the partition coefficient is treated as a constant, the dissolved fraction of the total metal can be shown to be equal to:

$(1 + K_d \times TSS \times 10^{-6})^{-1}$

where:

TSS is the total suspended solids concentration in mg/l;
The 10^{-6} is a conversion factor; and,
K_d has units l/kg in this treatment.

The partition coefficient is assumed to be constant partly due to relatively constant environmental conditions (marine pH and salinity are relatively constant), and mostly due to the lack of actual data.

An analogous relation can be derived for the mussel body concentration and water concentration known as the bioconcentration factor (BCF):[15]

$$BCF = C_m/C_w'$$

where:

C_m is the contaminant mussel body burden expressed as ppm or µg/g; and,
C_w' is the aqueous contaminant concentration expressed now as ppm or ppb rather than mass per volume.

Reported mussel tissue concentrations are typically based on five replicate composite samples pooled from fifty mussels. The BCF as defined has units mass/mass (for example, g/g). BCF must be distinguished from the bioaccumulation factor (BAF), which takes into consideration ingestion pathways and exposure scenarios. The use of a constant BCF is probably overly simplistic, but the proper development of BAFs is beyond the scope of this study. It is assumed that the usual 60 days of deployment is sufficient for the mussel to acclimatize from its location of harvest to the deployed site and to integrate over daily variations so that a "pseudo-equilibrium" is reached. The 1987 MWRA bioaccumulation study monitored both the concentration of various contaminants in the receiving waters weekly during the deployment period and the mussel body contaminant concentrations.[12] This data set allowed BCFs to be developed, particularly for lead.

The calculated BCF for lead from the 1987 study is used to calculate aqueous lead concentrations in receiving waters from 1993 to 1996.[12] It is assumed that the major source of lead into Boston Harbor is from DIWTP discharge. Volume flow rates, Q, are calculated so that the aqueous lead concentrations multiplied by Q are equal to the mass discharge rates from DIWTP for the same time period. The calculated flow rates from lead are applied to the mass discharge rates of other contaminants (mercury, copper, zinc and pyrene) to calculate the concentrations in water and the corresponding BCFs.

Spatial differences of mussel body burdens are attributed to differences in receiving water concentrations. Pyrene in mussels from the Discovery site provided estimates for river pyrene concentrations. Calculated BCFs and aqueous contaminant concentrations are compared with values from previous studies whenever available. The result is a consistent empirical framework for placing various studies into context.

Results & Calculations

Table 2 summarizes mussel tissue body burdens for lead, mercury and pyrene at the Deer Island site. Comparing shellfish body burdens and effluent loading revealed an apparent correlation between the mussel body burden of metals with the mass discharge rate (see Figures 2 and 3 for lead and mercury, respectively). The regression lines from Figures 2 and 3 are forced through the origin to be consistent with the adopted assumptions. The aqueous concentrations of lead and mercury would become zero if the mass discharge rates were zero, and the corresponding mussel body concentration would also need to be zero. The slopes of these regression lines contain information about the contaminant's BCF and Q. In particular, the ratio of the mercury slope to the lead slope is 0.0013 divided by 0.00079, or 1.6. This kind of relation is not observed for organic contaminants, such as total PAH (see Figure 4), which is a family of compounds with different physico-chemical properties. It is possible that other PAH sources are affecting mussel concentrations since it is known that rivers can be a major source of high molecular weight PAH compounds such as pyrene.[17]

The 1987 Bioaccumulation Study.[12] The 1987 MWRA bioaccumulation study monitored both the concentration of various contami-

TABLE 2.
Selected Contaminant Concentration in Mussels From Deer Island, Massachusetts

Year	Lead in Mussels (ppm dry weight)	Mercury in Mussels (ppm dry weight)	Pyrene in Mussels (ppb dry weight)
1987	7.2±2.0	0.12±0.10	356±96
1991	6.1±1.2		200±50
1992			347±93
1993	5.9±3.1	0.18±0.03	90±30
1994	9.1±2.3	0.21±0.07	110±21
1995	8.0±1.8	0.06±0.04	83±8
1996	6.3±1.3	0.15±0.04	174±61

nants in the receiving waters weekly during the deployment period and the mussel body contaminant concentrations. This data set allowed BCFs to be developed. For certain contaminants such as mercury, measurements in the receiving waters were below detection method limits so they could not be used directly. Copper and zinc have not been measured in mussels after 1991. Different organic compounds have been measured in different years (for example, different sets of PAH compounds are measured from 1987 to 1992 and 1993 on).

Lead. The laboratory-derived BCF for lead concentrations in blue mussels was reported by Schulz-Baldes to range from 800 to 2,500 (for wet weight and total lead).[18,19] The 1987 MWRA bioaccumulation study monitored lead concentration in the receiving waters weekly during the mussel deployment period and reported a dissolved lead concentration of 84.9±24.1 ng/l and a particulate lead concentration of 341.9±137 ng/kg.[12] The ratio of soluble to total lead is 0.2, and is typical of Deer Island wastewater (based on available discharge monitoring NPDES reports[20]). Morel *et al.* showed that, at equilibrium, lead should desorb from particulates due to their strong tendency to form chloro-complexes.[21]

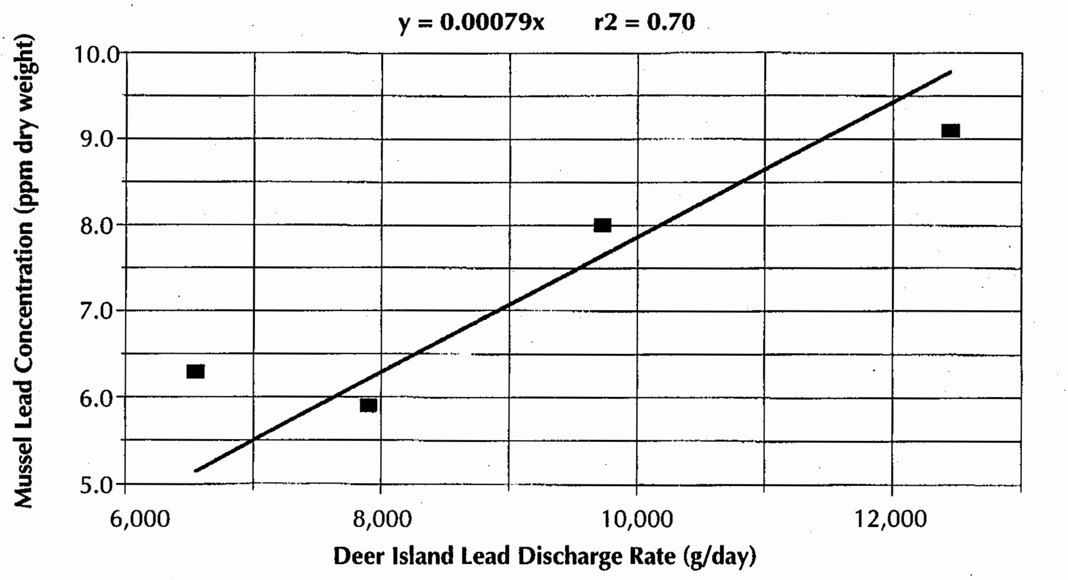

FIGURE 2. Mussel lead and mass discharge rate.

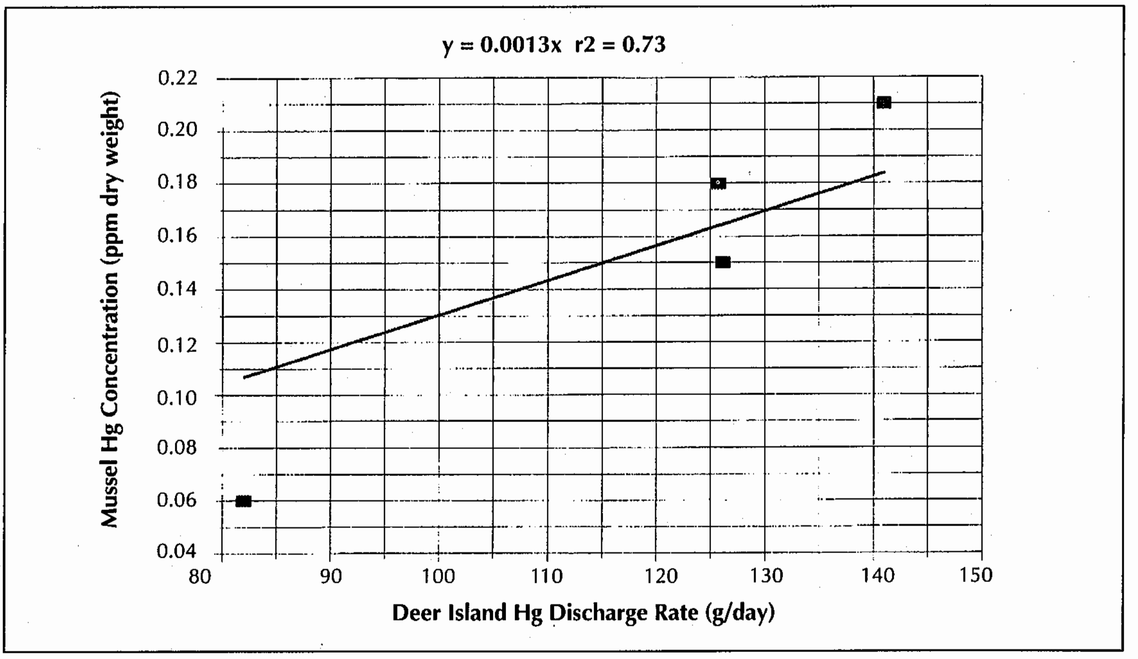

FIGURE 3. Mussel mercury and mass discharge rate.

Using the observed mussel body concentration of lead (7.2 ppm dry weight) and the soluble lead concentration (84.9 ng/l, or 84.9×10^{-12} — with seawater density close to 1 kg/l), the BCF for lead on a dry weight basis was calculated by dividing 7.2×10^{-6} by 84.9×10^{-12}. The result is 84,806, or 8.5×10^{4} (dimensionless). The BCF range (based on the reported standard deviations of the aqueous and mussel body concentrations) is quite large and varied from

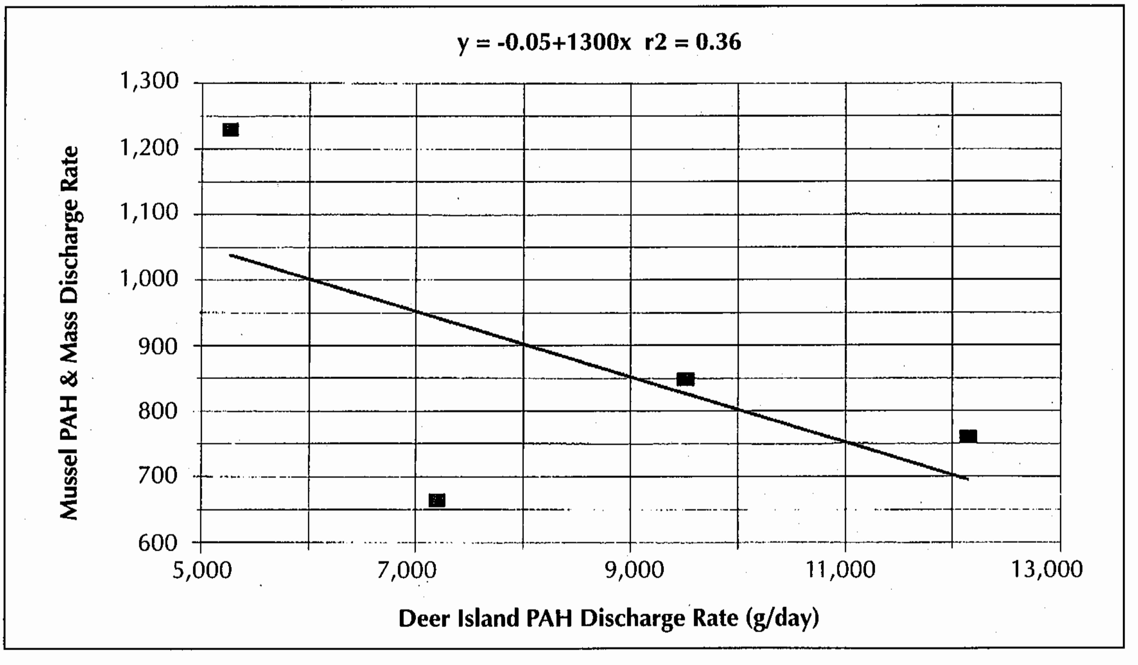

FIGURE 4. Mussel PAH and mass discharge rate.

TABLE 3.
Calculated Q From Measured Mussel Concentration & Effluent Discharge at Deer Island

Year	Observed Lead in Mussels (ppm dry weight)	Calculated Aqueous Lead Concentration (10^{-9} g/l)	Measured DIWTP Effluent Lead Load (g/day)	Calculated Q (10^8 m^3/day)
1987	7.2	85		
1991	6.1	72		
1993	5.9	70	7,900	1.1
1994	9.1	110	12,000	1.2
1995	8.0	94	9,700	1.0
1996	6.3	74	6,500	0.88

4.8×10^4 to 1.5×10^5. In comparing these results against the published results, the BCF must take into account dry versus wet weight, and take into account the dissolved to total metals ratio (which is 0.2). Mussels are typically 80 percent water. Therefore, the wet weight concentration is typically only 0.2 of the dry weight, plus the additional 0.2 ratio of dissolved to total lead. Therefore, the 8.5×10^4 BCF should be modified by multiplying it by the wet to dry weight ratio (0.2) and also multiplied by the dissolved to total lead ratio (0.2). The result is 3,400, which is close to the values reported in the literature (800 to 2,500).

The calculated BCF of 8.5×10^4 is used to calculate lead concentration in receiving waters, as shown in Table 3. It is then assumed that the major source of lead into Boston Harbor is from the DIWTP discharge. Volume flow rates, Q, are calculated so that the aqueous lead concentration multiplied by Q would equal the mass discharge rate from DIWTP (shown in the last column of Table 3). The calculated flow rates are well within the range observed for the exchange of Boston Harbor and Massachusetts Bay waters as shown in Table 1.

Spatial Variation of Lead. The spatial variation of lead in mussel tissue can be illustrated by a 1995 bioaccumulation study (other studies show similar results).[16] Table 4 shows the lead concentration in mussels collected from Gloucester prior to deployment, and from the Discovery and Deer Island sites after deployment. The calculated aqueous lead concentration using the BCF is also shown. The difference in mussel body concentration is attributed to differences in surrounding water conditions, with the lowest aqueous lead concentration at Gloucester, followed by Deer Island, and the highest aqueous lead concentration at the Discovery site. Higher aqueous heavy metal concentrations (copper and zinc) in the Inner Harbor have been observed previously and may reflect additional sources (such as rivers) and mixing conditions.[22,23]

Mercury. The measurement of mercury in wastewater and seawater at low concentrations is problematic, but theory predicts that the ratio of dissolved to total mercury in wastewater should be even lower than that for lead. The 1987 bioaccumulation study reported that soluble and particulate mercury in receiving waters were less than 7.1 ng/l and 7.3 ng/kg, respectively.[12] However, Morel *et al.* showed that, at equilibrium, both lead and mercury should desorb from particulates due to their strong tendency to form chloro-complexes.[21]

The calculated flow rates from lead are now used with the mass discharge rates of mercury from 1993 to 1996 to calculate mercury concentrations in water, and the corresponding BCFs (see Table 5). The geometric mean of the BCF for mercury is 1.2×10^5, and this BCF is used to calculate the mercury concentration in 1987 for comparison to the measured value. The calculated dissolved mercury concentration is 0.9 ng/l, which is consistent with the reported value of less than 7 ng/l. Using a K_d of 10^6 l/kg (from Ref. 24) and a total suspended solids (TSS) concentration of about 9 mg/l (from Ref. 12), it can be calculated that the ratio of dissolved to total mercury is about 0.1:

TABLE 4.
Measured Mussel Body Lead Concentration & Calculated Aqueous Lead Concentration From Gloucester, Deer Island & Discovery

Gloucester Mussel Lead Concentration (ppm dry weight)	Deer Island Mussel Lead Concentration (ppm dry weight)	Discovery Mussel Lead Concentration (ppm dry weight)	Calculated Aqueous Lead Concentration at Gloucester (10^{-9} g/l)	Calculated Aqueous Lead Concentration at Deer Island (10^{-9} g/l)	Calculated Aqueous Lead Concentration at Discovery (10^{-9} g/l)
6.1 ± 0.7	8.0 ± 1.8	8.5 ± 1.2	71 (range 36 to 141)	92 (range 41 to 204)	100 (range 49 to 202)

$1/(1 + 10^6\ (l/kg) \times 9\ (mg/l)\ x\ (10^{-6}))$

Therefore, the total mercury is about 9 ng/l, which is within the detection limits reported by the study.[12]

The BCF for mercury in oysters was reported by Kopfler to be 4×10^4 based on wet weight.[25] When converted to dry weight, the BCF is about 2×10^5. This result is fairly close to the geometric mean. It should be noted that the variation in BCF would be less if the 1995 mercury value of 0.06 ppm is considered to be suspect (one of the five composite samples reported a non-detect and a value of zero was adopted for the calculation of the average for that sample).

The ratio of the calculated BCF for mercury and lead is 1.4 (1.2×10^5 divided by 8.5×10^4), which is very close to the ratio of the regression line slopes for mercury and lead of 1.6 as shown in Figures 2 and 3.

Copper & Zinc. The 1987 bioaccumulation study also reported on copper and zinc.[12] However, copper and zinc were measured again in mussels in 1991 only. Unfortunately, the zinc data are difficult to interpret due to the presence of a zinc anode adjacent to the cage for corrosion control. Mass loading rates of copper and zinc from Deer Island in 1991 are available from the DIWTP NPDES reports.[20] Tables 6 and 7 show the calculations for copper and zinc, respectively.

The calculated flows from copper and zinc for 1991 are on the low side and differ from each other by almost a factor of 2. If the actual flow is closer to that calculated from copper, then the calculated zinc concentration should be closer to 971 ng/l (66,000 divided by 0.68×10^{11}) rather than 1,817 ng/l. This result is more in line with the values measured by Sunda and Huntsman,[22,23] with reported harbor-wide concentrations of zinc of 930 ng/l in 1988 and 700 ng/l in 1989. It is also possible that the NPDES loads of copper and zinc are incorrect due to the use of methods with relatively high detection limits (and assuming the concentrations to be at half the detection limit when it is non-detect).

TABLE 5.
Calculated BCF for Mercury

Year	Mercury in Mussel (ppm dry weight)	Calculated Aqueous Mercury Concentration (10^{-9} g/l)	Calculated BCF
1987	0.12	0.98	1.2E+05
1993	0.18	1.1	1.6E+05
1994	0.21	1.2	1.7E+05
1995	0.06	0.79	7.5E+04
1996	0.15	1.4	1.0E+05

TABLE 6.
Calculated BCF & Q for 1991 From Copper Data at Deer Island

Year	Copper in Mussels (ppm dry weight)	Measured Copper (10^{-9} g/l)	BCF Copper	Calculated Copper (10^{-9} g/l)	Copper Loading (g/day)	Calculated Q (10^8 m^3/day)
1987	9.6	943	10,180			
1991	9.7		10,180 (assumed)	953	65,000	0.68

Pyrene. The pyrene data are of interest because they show obvious spatial differences. Mussel concentrations from the Discovery site (Inner Harbor) are higher than that of the Deer Island site. This difference is attributed to high pyrene loads from the rivers that flow into the harbor (for example, from the Charles and Mystic rivers). The aqueous pyrene concentration at Deer Island is calculated with the flow rates obtained with the lead data and the measured pyrene loads and shown in Table 8. The calculated BCF is applied to the Discovery site mussels to calculate the pyrene concentration in surrounding waters.

Mixing of Charles River & the Inner Harbor. Hilton *et al.* reported on field tracer studies and numerical model experiments on the residence time of freshwater in Boston's Inner Harbor.[26] They showed a functional relation between inner harbor dilution, S, and the freshwater flow rate, Q_f (in m^3/sec), as S equal to 780 divided by Q_f plus 11.1. Average freshwater flow rates of the Charles River (daily flow rates averaged from June to August) were obtained from the U.S. Geographic Survey gage at Waltham and multiplied by a factor of 1.21 to reflect the conditions closer to the confluence of the Charles and Mystic rivers. Values for S are calculated from the function and equated to:

$$(C - C_h)/(C_r - C_h)$$

where:
- C is the contaminant concentration after mixing between river water and harbor water (the sixth column in Table 8);
- C_h is the contaminant concentration in the harbor (the third column in Table 8); and,
- C_r is the river contaminant concentration (calculated from S and shown in Table 9).

Note that the observed pyrene concentration from the Massachusetts Bay Program in 1992 ranged from 47 to 422 ng/l for the Charles and Mystic rivers.[17] The calculated river pyrene concentrations are within the observed ranges.

A similar calculation using naphthalene would have produced a negative river concentration. This result is not unexpected because naphthalene is a relatively volatile compound and is not appropriate to be modeled as a conservative contaminant. In this case, a first-order rate constant, k, should be attached to the CFSTR model so that the new steady-state concentration in the harbor, C_{ss}, is equal to:

$$(M/Q)(1 + kt)^{-1}$$

TABLE 7.
Calculated BCF & Q From Zinc Data at Deer Island

Year	Zinc in Mussels (ppm dry weight)	Measured Zinc (10^{-9} g/l)	BCF Zinc	Calculated Zinc (10^{-9} g/l)	Zinc Loading (g/day)	Calculated Q (10^8 m^3/day)
1987	170.5	2,143	78,000			
1991	145.0		78,000 (assumed)	1,817	66,000	0.36

TABLE 8.
Calculated BCF of Pyrene & Aqueous Concentrations

Year	Pyrene in Deer Island Mussel (ng/g)	Calculated Aqueous Pyrene (ng/l)	Calculated BCF	Pyrene in Discovery Mussel (ng/g)	Calculated Aqueous Pyrene Around Discovery (ng/l)
1993	90	1.1	82,000	245	3.0
1994	110	1.6	69,000	480	7.0
1995	83	1.5	55,000	228	4.1
1996	174	1.5	120,000	474	4.1

Note: Geometric mean is equal to 78,000.

Applications

The utility of treating Boston Harbor as a CFSTR is that it allows relatively easy and straightforward evaluation of water quality in and around the harbor — for example, the assessment of total maximum daily loads (TMDL) using published water quality criteria (WQC). For example, if the marine WQC for copper is 2.9 μg/L, then the TMDL for copper is on the order of 348 kg/day (1.2×10^{11} 1/day multiplied by 2.9×10^{-6} g/l). To put this value into perspective, the MWRA discharge load for copper in 1996 was about 58 kg/day. Additional refinements can be made (for example, inclusion of reactive terms such as sorption and settling, other sources such as sediment fluxes, etc.). Safety factors also can be incorporated. A similar application to lead indicate a TMDL of about 1,020 kg/day (using a WQC of 8.5 μg/l). The MWRA discharge load for lead in 1996 was about 17 kg/day. These estimates could provide a first-order approximation of acceptable total contaminant loads. Further work is required to estimate non-point source loads such as atmospheric deposition and riverine loads.

Limitations

It is becoming increasingly clear that the exchange between Boston Harbor and Massachusetts Bay is complex and dependent on the thermocline/pynocline depth in the bay, tidal heights, freshwater flow and meteorological conditions.[27] Boston Harbor may receive Massachusetts Bay intrusions from mid-depth at the level of the pynocline from June to August, posing some uncertainty to the applicability of using a simplistic CFSTR model. Measurements by Wallace *et al.* have shown that trace metal concentrations in "pure" bay waters are typically an order of magnitude less than that of harbor waters, so the contribution from bay water is not entirely negligible.[12] If it is possible to link the harbor and bay as two CFSTRs, then conditions in the harbor would be modified by feedback from the bay. This refinement requires information about the flow from the bay into the harbor, concentrations in the bay, outflow from the bay to the Gulf of Maine, and other loads into the bay. This information is not always available for the time periods of interest (from June to August). The simple CFSTR

TABLE 9.
Observed Freshwater Flow, Calculated *S* & Calculated River Pyrene Concentration

Year	Q_f (m³/sec)	Calculated *S*	Calculated River Pyrene Concentration (ng/l)
1993	2.3	58	111
1994	4.0	52	282
1995	2.3	58	152
1996	6.7	44	116

model that allows for a first-order approximation for water quality assessments is perhaps acceptable over a more refined formulation, as long as its assumptions and limitations are recognized.

Conclusion

The application of measured BCFs, measured mass discharge rates and CFSTR methodology produced a consistent empirical framework for placing various biomonitoring and discharge studies into context. The use of BCFs permits linking the mussel body concentrations of metals (in particular, lead) to receiving water concentrations, which in turn permits calculating mass loading rates or water exchange rates. Different sources and other submodels (for example, for the Inner Harbor) can account for spatial differences in mussel data.

The BCF values calculated from this survey follow this descending order (with approximate values):

- Mercury (1.2×10^5);
- Lead (8.5×10^4);
- Zinc (?);
- Pyrene (7.8×10^4); and,
- Copper (1.0×10^4).

The BCFs can be used along with mussel body concentrations (if they have been "deployed" for similar time periods) to obtain a first-order approximation of surrounding water concentrations, and are probably correct within a factor of 3 (based on the observed variation in mussel body burden for lead and measured lead concentration in the 1987 bioaccumulation study[12]).

The application of a CFSTR provides for a straightforward way to estimate TMDL if WQC are adopted for the harbor. Partition coefficients can be used to relate dissolved to total metals. And BFC can be combined with WQC to compare calculated shellfish body burdens against U.S. Food & Drug Administration limits adopted for the protection of human health.

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WINDSOR SUNG, *P.E., D.E.E., was an independent consultant working with ENSR on MWRA-related projects when this article was conceived and written. He is now working as a Project Manager at MWRA in the Waterworks Division.*

REFERENCES

1. Sung, W., "Observations on the Temporal Variations of Dissolved Copper and Zinc in Boston Harbor," *Civil Engineering Practice*, Vol. 6, No. 1, Spring 1991.

2. Adams, E.E., Hansen, J.W., Lago, R.L., Clayton, P., & Zhang, X., "A Simple Box Model of the Nitrogen Cycle in Boston Harbor and the Massachusetts Bays," *Civil Engineering Practice*, Vol. 7, No. 2, Fall 1992.

3. Signell, R.P., & Butman, B., "Modeling Tidal Exchange and Dispersion in Boston Harbor," *Journal of Geophysical Research*, Vol. 97, 1992.

4. Stolzenbach, K.D., Adams, E.E., Ladd, C.C., Madsen, O.S., & Wallace, G., "Transport of Contaminated Sediments in Boston Harbor," *MWRA Environmental Quality Department Technical Report No. 93-12*, Massachusetts Water Resources Authority, Boston, 1993.

5. Downey, P.C., "Bioaccumulation of Selected Organic Compounds and Metals in Mussels Deployed Near Deer Island Discharge and in Massachusetts Bay, 1993," *MWRA Environmental Quality Department Technical Report No. 94-8*, Massachusetts Water Resources Authority, Boston, 1994.

6. Downey, P.C., & Young, K., "Bioaccumulation of Selected Organic Compounds and Metals in Mussels Deployed Near Deer Island Discharge and in Massachusetts Bay, 1991," *MWRA Environmental Quality Department Technical Report No. 92-10*, Massachusetts Water Resources Authority, Boston, 1992.

7. Downey, P.C., Comeau, J.K., Binkerd, R.C., & Williams, J.W., "Bioaccumulation of Selected Organic Compounds and Metals in Mussels Deployed Near Deer Island Discharge and in Massachusetts Bay, 1992," *MWRA Environmental Quality Department Technical Report No. 93-8*, Massachusetts Water Resources Authority, Boston, 1993.

8. Downey, P.C., Moffet, B.D., & Lescarbean, G.R., "Bioaccumulation of Selected Organic Compounds and Metals in Mussels Deployed Near Deer Island Discharge and in Massachusetts Bay, 1994," *MWRA Environmental Quality Department Technical Report*

No. 95-9, Massachusetts Water Resources Authority, Boston, 1995.

9. Hillman, R.E., & Peven, C.S., "1994 Annual Fish and Shellfish Report," *MWRA Environmental Quality Department Technical Report No. 95-5*, Massachusetts Water Resources Authority, Boston, 1995.

10. Mitchell, D.F., Mounce, T., Morton, J., Sullivan, K., Moore, M., & Downey, P., "1995 Annual Fish and Shellfish Report," *MWRA Environmental Quality Department Technical Report No. 96-3*, Massachusetts Water Resources Authority, Boston, 1996.

11. Mitchell, D.F., Mounce, T., Morton, J., Sullivan, K., Moore, M., & Downey, P., "1996 Annual Fish and Shellfish Report," *MWRA Environmental Quality Department Technical Report No. 97-10*, Massachusetts Water Resources Authority, Boston, 1997.

12. MWRA, *Secondary Treatment Facilities Plan: Vol. V Effluent, Appendix X, Bioaccumulation*, Massachusetts Water Resources Authority, Boston, 1988.

13. Hunt, C., West, D.E., & Peven, C.S., "Deer Island Effluent Characterization and Pilot Treatment Plant Studies: June 1993-November 1994," *MWRA Environmental Quality Department Technical Report Series No. 95-7*, Massachusetts Water Resources Authority, Boston, 1995.

14. Butler, E., Higgins, M., Chiapella, J., & Sung, W., "Deer Island Effluent Characterization Studies: January-December 1995," *MWRA Environmental Quality Department Technical Report Series No. 97-3*, Massachusetts Water Resources Authority, Boston, 1997.

15. Hemond, H.F., & Fechner, E.J., *Chemical Fate and Transport in the Environment*, Academic Press, New York City, 1994.

16. Sung, W., "Some Observations on Surface Partitioning of Cd, Cu and Zn in Estuaries," *Environmental Science Technology*, Vol. 29, 1995.

17. Menzie-Cura & Associates, Inc., "Measurements and Loadings of Polycyclic Aromatic Hydrocarbons in Storm Water, Combined Sewer Overflows, Rivers, and Publicly Owned Treatment Works Discharging to Massachusetts Bays," *Massachusetts Bays Program MBP-95-06*, Boston, 1995.

18. Schulz-Baldes, M., "Toxicity and Accumulation of Lead in the Common Mussel *Mytilus edulis* in Laboratory Experiment," *Marine Biology*, Vol. 16, 1972.

19. Schulz-Baldes, M., "Lead Uptake From Seawater and Food, and Lead Loss in the Common Mussel *Mytilus edulis*," *Marine Biology*, Vol. 25, 1974.

20. MWRA, "NPDES Compliance Summary Report, Fiscal Year 1992," *MWRA Environmental Quality Department Technical Report Series No. 93-14*, Massachusetts Water Resources Authority, Boston, 1993.

21. Morel, F.M.M., Dzombak, D.A., & Price, N.M., "Heterogeneous Reactions in Coastal Waters," in *Ocean Margin Processes in Global Change*, edited by R.F.C. Mantoura, J.M. Martin & R. Wollast, Wiley Interscience, New York City, 1991.

22. Sunda, W.G., & Huntsman, S.A., "Concentrations and Chemical Speciation of Trace Metal Contaminants in Coastal Waters of the Northeastern United States," *National Marine Fisheries Service Beaufort Laboratory Summary Progress Report for FY88 to the National Ocean Service*, February 1989.

23. Sunda, W.G., & Huntsman, S.A., "Concentrations, Chemical Speciation and Toxicity of Trace Metal Contaminants in Coastal Waters of the Northeastern United States," *National Marine Fisheries Service Beaufort Laboratory Summary Progress Report for FY89 to the National Ocean Service*, March 1989.

24. Mason, R.P., Fitzgerald, W.F., Hurley, J., Hanson, A.K., Donaghay, P.L., & Sieburth, J.M., "Mercury Biogeochemical Cycling in a Stratified Estuary," *Limnol. Oceanogr.*, Vol. 38, No. 6, 1993.

25. Kopfler, F., "The Accumulation of Organic and Inorganic Mercury Compounds by the Eastern Oyster *Crassostrea virginica*," *Bull. Environ. Contam. Toxicol.*, Vol. 11, 1974.

26. Hilton, A.B.C., McGillivary, D.L., & Adams, E.E., "The Residence Time of Freshwater in Boston's Inner Harbor," submitted to *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE*, Vol. 124, No. 2, March/April 1998.

27. Kelly, J.R., Albro, C.S., & Geyer, W.R., "High-Resolution Mapping Studies of Water Quality in Boston Harbor and Massachusetts Bay During 1994," *MWRA Environmental Quality Department Technical Report Series No. 96-1*, Massachusetts Water Resources Authority, Boston, 1996.

The Use of Back Analysis to Reduce Slope Failure Risk

Back analysis can be used to develop highly reliable computational models of slopes to determine failure risk and provide a means to develop reliable designs.

JAMES MICHAEL DUNCAN

According to the *Random House Dictionary*, *back analysis* is a form of analysis that "starts from a known result and works backward to prove a proposition."[1] Back analysis is frequently used in landslide repair. In that case, the known result is the fact that the landslide has occurred. The proposition to be proved involves the conditions at the time of failure.

In the best use of back analysis, the conditions at the time of failure — including slope geometry, external loads from water or other sources, soil weights, soil strengths, distribution of soils within the slope and piezometric levels within the slope — are estimated using all the information that can be assembled. For the conditions so established, the factor of safety with respect to stability of the slope is computed. If the computed value of the factor of safety, *F*, is equal to 1.0, the estimated conditions have been proven to be consistent with the fact that the slope failed. If the computed value of the factor of safety is not 1.0, the conditions are adjusted, still maintaining consistency with the available information. Through repeated trials a set of conditions is established that results in a factor of safety equal to 1.0 and is consistent with the known facts.

Back analysis is sometimes described as a process of calculating shear strength from a failure. In fact, it is both more and less than a calculation of shear strength. Back analysis is *more* than a simple calculation of shear strength because, in the end, a complete computational model has been developed that is consistent with the conditions at the time of the slope failure. The model includes geometry, loads, soil weights, soil strengths, piezometric levels and the method used to compute the factor of safety. While estimates and assumptions are always necessary to fill in gaps in knowledge, adjusting the model so that the factor of safety is equal to 1.0 for the failure condition produces a complete and reliable computational model.

Back analysis is *less* than a simple calculation of shear strength because, to compute the shear

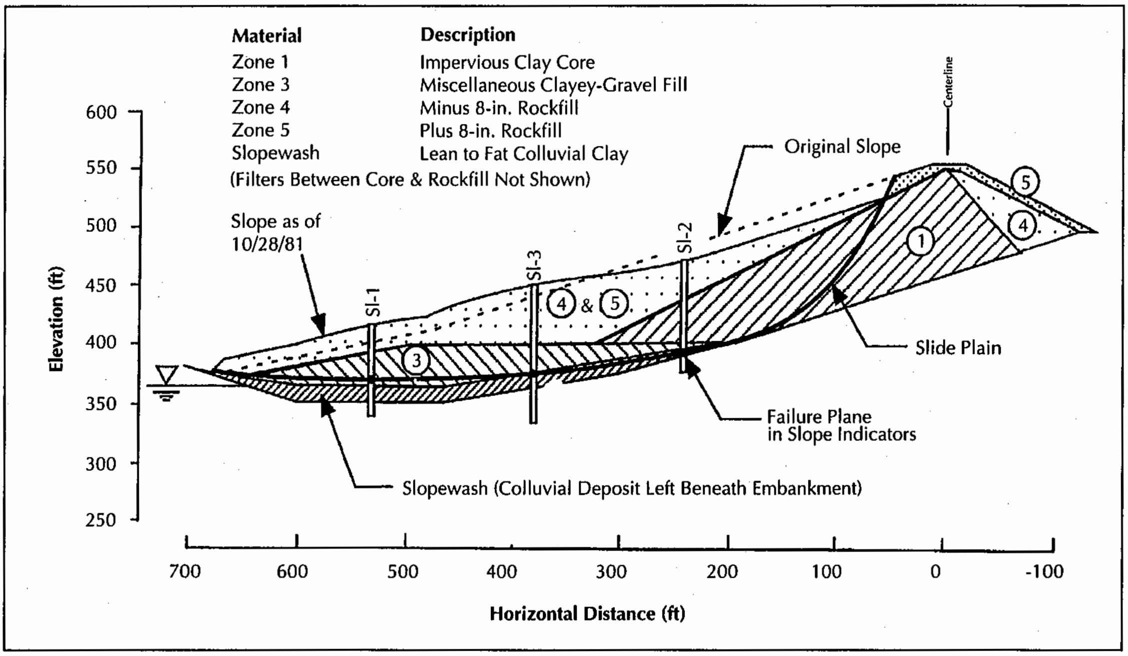

FIGURE 1. Slide in the upstream slope of the San Luis Dam.

strength of a particular soil zone within the slope, values of all of the other quantities must be estimated. If the estimates were changed, the "calculated" shear strength would also change to maintain the the end result of a factor of safety equal to 1.0.

Even fairly wide variations in some of the assumptions have little effect on the results of forward analyses used to design slope stabilization measures, provided that the back analysis results are used consistently in the forward analysis. In addition, all of the elements of the computational model should be reasonable and consistent with all known facts about the conditions at the time of failure.

Practical use of back analysis is best illustrated by showing how it has been applied. Case histories on three projects — San Luis Dam repair, Olmstead landslide stabilization and La Esperanza abutment drainage — provide an excellent means of describing how back analysis can be properly used.

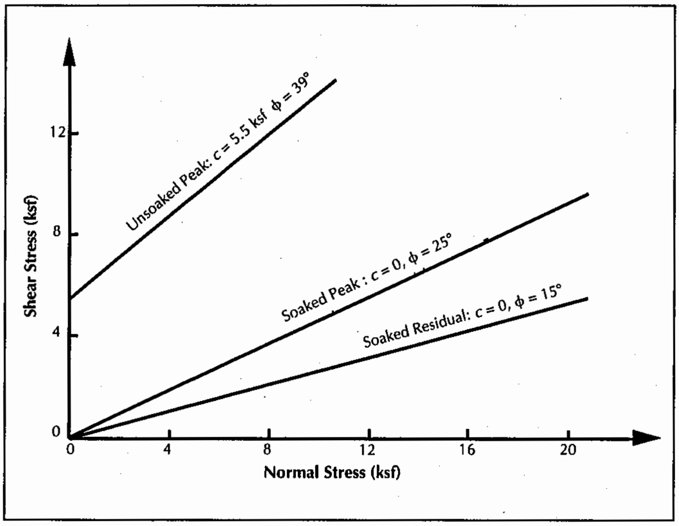

FIGURE 2. The strength of highly plastic clay slopewash from the foundation of the San Luis Dam.

San Luis Dam Repair

San Luis Dam impounds a pump-storage reservoir on the California Aqueduct System, about 90 miles southeast of San Francisco. In September 1981 a slide occurred in the upstream slope of the embankment as the reservoir was being drawn down.[2-4] A cross-section through the embankment where the slide occurred is shown in Figure 1.

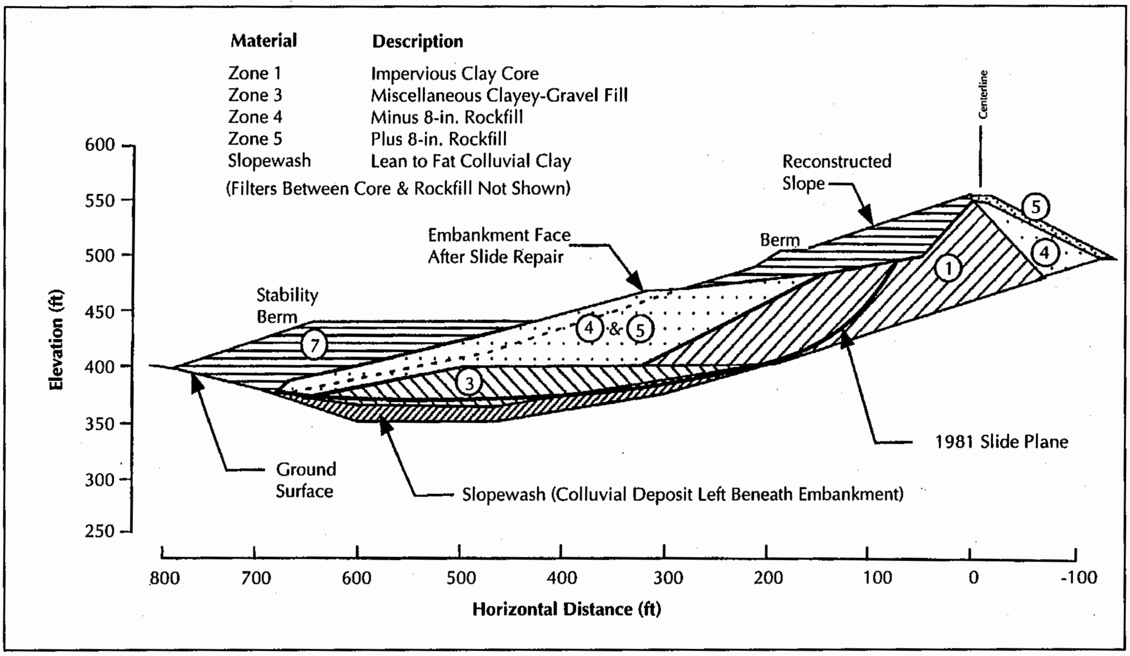

FIGURE 3. The San Luis Dam embankment after slide repair.

A key factor in the occurrence of the slide was the highly plastic clay *slopewash* (a naturally-occurring soil formed by weathering, erosion and down-slope movement) that blankets the hillside beneath the upstream slope of the dam. When the embankment was constructed, this material was dry and very strong. When it was wetted by filling the reservoir it softened dramatically and, since it was subjected to repeated cycles of shearing due to rise and fall of the reservoir, its strength was reduced to the residual value.[4] Shear strengths of the slopewash material, measured on specimens cut from undisturbed block samples obtained in a dry area downstream from the dam, are shown in Figure 2.

The slide was stabilized by constructing a berm against the upstream slope, as shown Figure 3. The factor of safety with the berm in place was evaluated in two steps:

1. Back analyses were performed to develop a computational model for the slope. A key element in this model was the strength of the highly plastic clay slopewash. The back analyses showed that the shear strength of the slopewash had been reduced to residual strength by wetting and shear displacement.

2. Forward analyses were performed to calculate the factor of safety with the berm in place. The forward analyses used the computational model developed through the back analyses, with the berm added to the cross-section as shown in Figure 3. The results of the analyses are summarized in Table 1.[4]

Olmsted Landslide Stabilization

To provide sufficient and reliable navigation capacity on the lower Ohio River, the U.S. Army Corps of Engineers is replacing Locks and Dams 52 and 53 with the proposed Olmsted Locks and Dam. This facility will include:

- Two locks, each 110 feet wide and 1,200 feet long, adjacent to the Illinois shore;
- A 2,200-foot wide navigable pass controlled by wicket gates; and,
- A 426-foot wide gated spillway.

Evidence of instability on the Illinois shore at the Olmsted site was first discovered in 1987 during the foundation investigation for the proposed locks and dam. On the basis of geomorphic features such as scarps, cracks, leaning trees and hummocky terrain, the approxi-

TABLE 1.
Computed Factors of Safety for the San Luis Dam Embankment

Stage	Phase & Condition of Slopewash	Slopewash Strength		
		c (ksf)	ϕ (degrees)	Computed F
Pre-failure	1. End of Construction (Slopewash Dry)	5.5	39	4.0
Pre-failure	2. Reservoir Full (Slopewash Soaked, Fully Softened)	0	25	2.0
Pre-failure	3. Drawdown (Slopewash Soaked, Fully Softened)	0	25	1.3
Failure	4. Drawdown (Slopewash Soaked, Residual)	0	15	1.0
Post-repair	5. Drawdown With Berm (Slopewash Soaked, Residual)	0	15	1.21

mate extent of unstable ground was mapped. The slide was found to be about 3,000 feet long.

In late May and early June 1988, a rapid drop in the river level from elevation 290 feet to elevation 283 feet took place over a 10-day period. In the lower portion of the river bank, near-vertical scarps up to 3 feet high developed 150 feet to 200 feet from the shoreline. Over the next month, the scarps and cracks propagated parallel to the river and eventually reached a total length of 3,100 feet. A cross-section through the landslide is shown in Figure 4.

Key factors in the occurrence of the slide were the low shear strength of the upper part of the McNairy I formation beneath the slope, and the artesian pressures in this formation. The McNairy I formation contains alternating layers of clay and fine sand varying from about an inch to about a foot in thickness. The position of the rupture surface (as shown in Figure 4) was established based on 12 inclinometers and 5 piezometer breaks. The rupture surface through the McNairy I was horizontal over a considerable distance. This orientation is consistent with shearing parallel to bedding, through clay layers. At the back of the slide, the rupture surface cut across bedding, passing through both clay layers and sand layers.

Different shear strengths were used for shear parallel to bedding in the McNairy I,

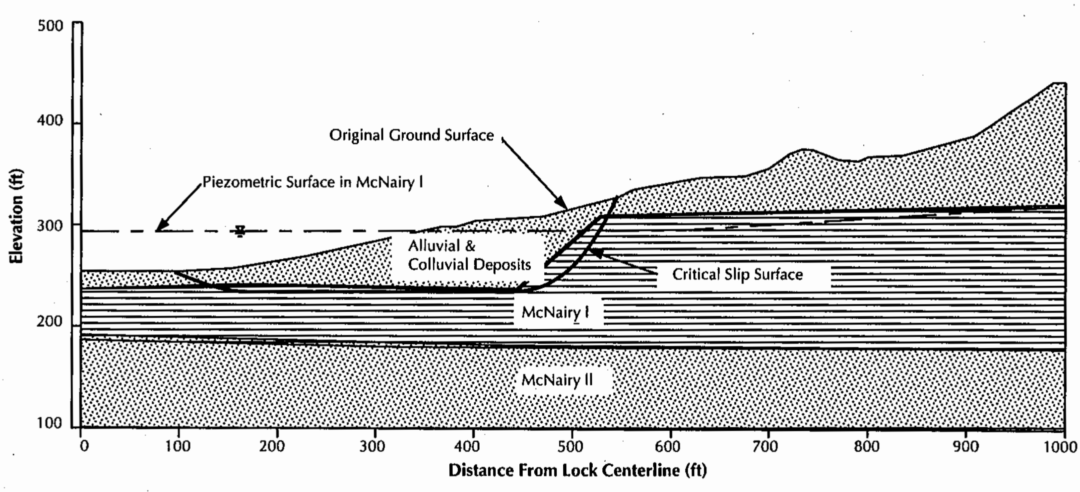

FIGURE 4. A cross-section through the landslide at Olmstead Locks and Dam on the Ohio River.

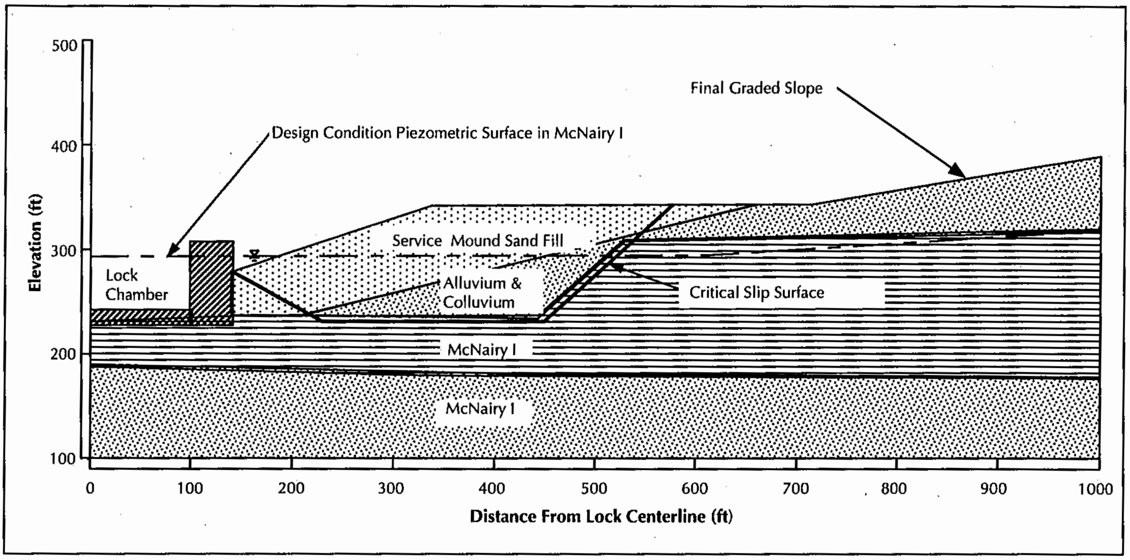

FIGURE 5. Long-term stability condition at Olmstead Locks and Dam on the Ohio River.

where the shear plane could pass entirely through clay and shear across bedding, and where shearing would necessarily involve both sand and clay. The McNairy I was assigned anisotropic shear strength values — with ϕ' equal to 10 degrees where the slip surface was within 5 degrees of horizontal and ϕ' equal to 25 degrees where the slip surface was inclined more than 5 degrees from horizontal. These values were thought to represent reasonable estimates of the residual strengths for bedding shear and cross-bedding shear.[5]

The piezometric levels in the McNairy I had been observed in a number of piezometers before the landslide occurred, and it was possible from these observations to estimate the piezometric level at the time of sliding.[5] Because the horizontal permeability of the McNairy I was much higher than the vertical permeability, the piezometric surface was nearly horizontal from the head of the landslide to the toe, and there were significant artesian pressures in the McNairy I beneath the lower part of the slope.

The slide was stabilized by constructing a service mound sand fill, which formed a buttress between the slope and the lock wall, as shown in Figure 5.[6] The factor of safety with the service mound fill in place was calculated in two steps:

1. Back analyses were performed to develop a computational model for the slope. Key elements in this model were the anisotropic shear strength of the McNairy I, and the piezometric levels in the slope. Using the same computational model, factors of safety varying from 0.95 to 1.00 were computed for four sections through the 3,100-foot-long slide.[5]

2. Forward analyses were performed to calculate the factor of safety during construction and at the end of construction of the berm. The analyses showed that it would not be feasible to construct the berm in stages, with each stage consisting of placing an inclined layer of fill against the slope. However, if the fill was placed in horizontal layers between the lock wall and the slope, the computed factor of safety increased steadily as the elevation of the berm was raised, reaching 2.1 at the end of construction, with the cross-section shown in Figure 5. The results of the analyses are shown in Table 2.[6]

La Esperanza Abutment Drainage

La Esperanza Dam impounds a water supply reservoir on the Carrizal River in northern Ecuador. The spillway of the dam is founded on potentially unstable shale in the right abutment.[7] The shale is essentially horizontally bedded, and contains numerous randomly oriented joints, with an average spacing of a few

TABLE 2.
Computed Factors of Safety for the Illinois Shore at Olmstead

Condition	Computed *F*
1. Pre-construction Landslide, After Drop in River Level	0.99
2. Post-construction, With Lock & Stabilizing Berm in Place	2.1

inches to about 2 feet. A cross-section through the abutment and spillway is shown in Figure 6.

Minor slides occurred during the excavation of the slope below the spillway, calling attention to a weak layer of breccia (brecciated shale) at the base of the slope. It seems likely that the brecciated layer was formed by valley wall rebound as the valley was eroded in the shale. The slides that occurred during construction were shallow, and did not threaten the spillway. However, larger slides through the shale and breccia, extending further up the slope, could damage the spillway, and it was seen as necessary to install drains in the right abutment to improve its stability.

The types and locations of drains needed to improve stability were determined in two steps:

1. Back analyses were performed to develop a computational model for the slope. Key elements in this model were the shear strength of the breccia, the shear strength of the shale and the piezometric surface within the abutment. These quantities were estimated based on laboratory tests and correlations to estimate the shear strength of the breccia, and observed water levels in exploratory borings for the piezometric surface. The shear strength estimated for the jointed shale was based on engineering judgment, with consideration of the fact that the shale would have higher strength than the breccia.

The objective of the back analysis was to determine what piezometric surface would correspond to a factor of safety equal to 1.0. The piezometric level so determined (which is shown in Figure 6) was higher than the water levels observed in exploratory borings. It was concluded that the shear strengths and piezometric surface were reasonable and probably conservative because the computational model was adjusted to give a factor of safety of 1.0, although no deep slide had occurred.

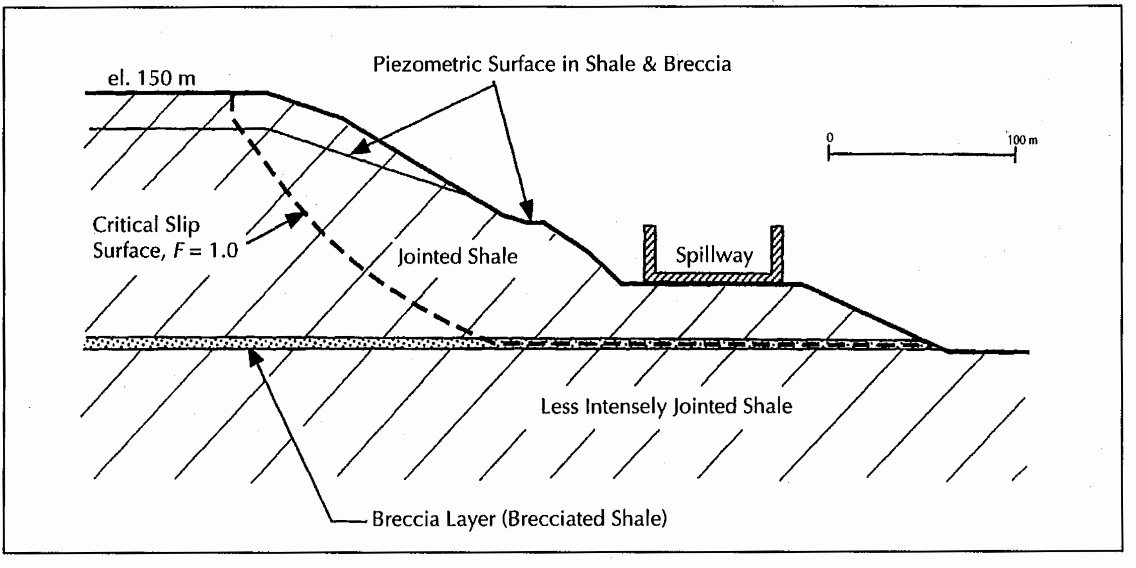

FIGURE 6. A cross-section through La Esperanza Dam's right abutment and spillway.

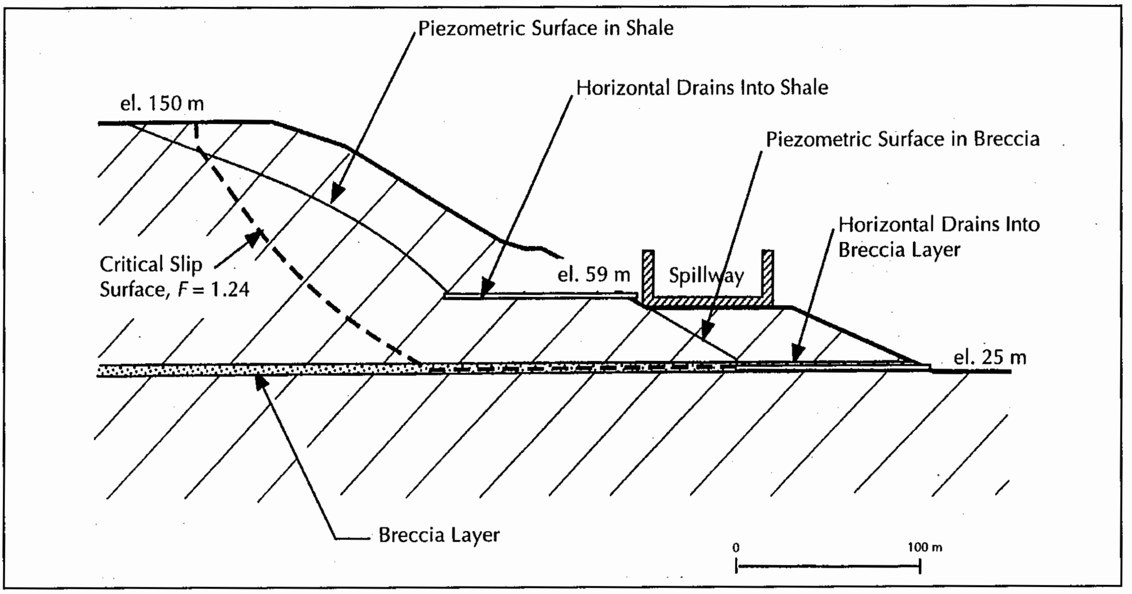

FIGURE 7. Drains in the right abutment of La Esperanza Dam.

2. Forward analyses were performed to determine the types and locations of drains needed to assure improved stability even if it should happen that impounding water in the reservoir, combined with exceptionally heavy rainfall, might cause the piezometric level to rise above the position shown in Figure 6.

As shown in Figure 7, it was assumed that the piezometric surface would rise to the ground surface in the upper part of the abutment, but would be lowered within the lower part of the abutment by installing two rows of horizontal drains at elevation 25 meters (in the breccia layer) and at elevation 59 meters (above the spillway). The computed factor of safety for the condition shown in Figure 7 is 1.24. The results of the analyses are shown in Table 3.

TABLE 3.
Computed Factors of Safety for the Right Abutment of La Esperanza Dam

Condition	Computed F
Initial Condition Shown in Figure 6 (Assumed to Be Marginally Stable)	1.0*
Drained Condition Shown in Figure 7, With Two Levels of Drains (90 m at el. 25 m & 120 m at el. 59 m)	1.24

* Achieved by adjusting shear strengths & piezometric surface.

The Effect of Assumptions in Back Analyses

As illustrated by these three examples, estimates and assumptions are always needed to fill gaps in knowledge when a computational model is developed by back analysis. However, adjusting the model so that the factor of safety is equal to 1.0 for the failure condition results in a reliable computational model in spite of the fact that it involves assumptions. If all of the elements of the model are consistent with the known facts, and if the computational model is used consistently in forward analysis, the assumptions will have little effect on the results of the forward analyses.

For example, the slope shown in Figure 8 was excavated by trimming back the original hill slope to a steeper configuration. (Please note that the slope shown in Figure 8 is hypothetical. Any resemblance to an actual failure is coincidental.) The shear strengths shown in the upper part of Table 4 were based on laboratory tests, and the piezometric level shown in

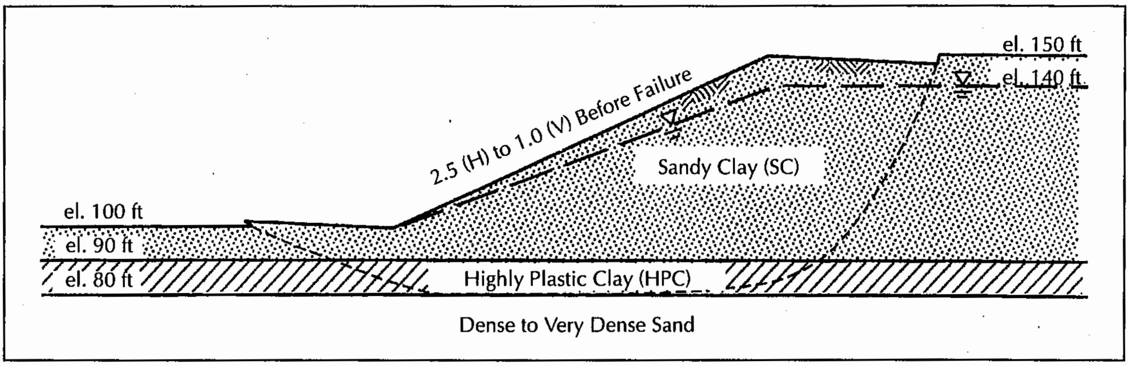

FIGURE 8. Failure in a hypothetical slope.

Figure 8 was based on water levels observed in exploratory borings.

For the conditions shown in Figure 8 and the strengths shown at the top row of Table 4, the computed factor of safety is 1.41, but the slope failed. Slope indicators installed after the failure showed that the rupture surface passed through the highly plastic clay. Piezometers installed after the failure showed that the piezometric surface in the highly plastic clay, and in the overlying layer of mixed sandy clays and clayey sands, was essentially as assumed in design.

It was proposed to stabilize the slope by installing vertical drain wells as shown in Figure 9, with horizontal drains drilled from the bottom of the slope to drain the water from these wells by gravity. It was estimated that these drains would draw down the average piezometric level along the line of drain wells to elevation 128 feet. This elevation is above the intersection of the drains with the wells, allowing for head losses associated with flow to the wells and through the drains. The factor of safety with the drains installed was calculated in two steps:

1. Back analyses were performed to develop a computational model for the slope. After reviewing the shear strengths for the layer of mixed sandy clays and clayey sands, it was concluded that the values used in the original analyses (shown in the top row in Table 4) were reasonable. Likewise, it was concluded that the piezometric levels used in the original analyses (shown in Figure 8) were reasonable. It seemed likely that the strength of the highly plastic clay might be lower than thought originally, and the friction angle for this layer was adjusted downward to achieve a factor of safety of 1.0 for the slope. It was found that, for a factor of safety of 1.0, a friction angle of 14 degrees

TABLE 4.
Original Design Analysis, Back Analysis & Redesign Analyses of a Hypothetical Slope

Analysis	SC Clay Strength	SC Unit Weight	HP Clay Strength	Piezometric Elevation	Computed F
Original Design Analysis	$c' = 300$ psf $\phi' = 35°$	$\gamma = 130$ pcf	$c' = 0$ $\phi' = 25°$	140 ft	1.41
Back Analysis	$c' = 300$ psf $\phi' = 35°$	$\gamma = 130$ pcf	$c' = 0$ $\phi' = 14°$	140 ft	0.99
Redesign Analysis	$c' = 300$ psf $\phi' = 35°$	$\gamma = 130$ pcf	$c' = 0$ $\phi' = 14°$	128 ft	1.16

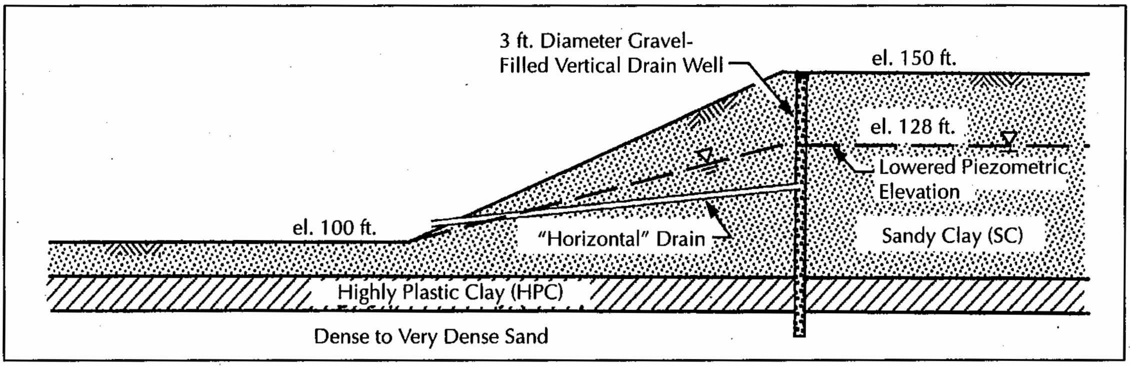

FIGURE 9. Drain wells to stabilize the hypothetical slope.

would be required in the highly plastic clay, as shown in the middle row of Table 4. This seemed reasonable because 14 degrees was approximately equal to the estimated residual friction angle of this material.

2. Forward analyses were performed for the conditions shown in Figure 9 in order to determine the factor of safety with the drains installed. The computed factor of safety, with the piezometric level at elevation 128 feet and ϕ' equal to 14 degrees in the highly plastic clay, was 1.16. The results of these analyses are summarized in the bottom row in Table 4.

In order to perform the back analyses, it was necessary to estimate (or assume) the strength of the sandy clay and the position of the piezometric surface. Because there are some uncertainties in these assumptions, it is reasonable to pose the following question: How would the computed factor of safety for the stabilized slope be affected, if different assumptions were used as the basis for the back analysis? To answer this question, the back analysis and forward analysis were repeated using different assumptions for the strength of the sandy clay.

First, the strength of the sandy clay was assumed to be much *higher* than assumed originally. When this assumption was made, the strength of the highly plastic clay required for a factor of safety equal to 1.0 in the back analysis was lower (as shown in the middle row in Table 5). However, the factor of safety calculated in the forward analysis was the same (*i.e.*, 1.16).

Next, the strength of the sandy clay was assumed to be much *lower* than assumed originally. When this assumption was made, the strength of the highly plastic clay required for a factor of safety equal to 1.0 in the back analysis was higher (as shown at the bottom row in Ta-

TABLE 5.
The Effect of Varying Sandy Clay Strength Used in the Back Analysis of a Hypothetical Slope

Analysis	Assumed SC Clay Strength	HP Clay Strength for F = 1.0 in Back Analysis	F With Piezometric Elevation at 128 Feet
Original	c' = 300 psf ϕ' = 35°	c' = 0 psf ϕ' = 14°	1.16
High SC Strength	c' = 600 psf ϕ' = 40°	c' = 0 psf ϕ' = 9.6°	1.16
Low SC Strength	c' = 100 psf ϕ' = 30°	c' = 0 psf ϕ' = 18.2°	1.16

ble 5). However, the factor of safety calculated in the forward analysis was again 1.16.

This exercise shows that the factor of safety calculated in the forward analysis is not strongly affected by the assumptions made as the basis for the back analysis. In this case, although the assumptions vary so widely as to stretch the bounds of credibility, the factor of safety calculated in the forward analysis remains the same because, in each case, the results of the back analysis are used consistently in the forward analysis.

Factor of Safety & Reliability

It stands to reason that, when back analysis can be used to reduce uncertainties in design, it would be justified to use smaller factors of safety than are used when shear strengths are based on laboratory tests or correlations. But, how much smaller factors of safety should be used? For example, should the value of 1.16 for the slope shown in Figure 9 be considered acceptable?

Answering this question in a vacuum is difficult. Different geotechnical engineers, drawing on different experiences, might well reach different conclusions. Furthermore, the consequences of another failure should be reckoned. If the consequences of failure are benign, a smaller factor of safety could be tolerated than if the consequences are severe financially, or if a failure would pose a threat to life.

Factors of safety used in geotechnical engineering are based on experience, and it appears that factors of safety that are conventionally used for slope stability are appropriate for conditions where shear strengths are based on laboratory tests, or are estimated based on correlations. When the computational model is based on back analysis, much uncertainty is eliminated, but the degree of uncertainty is not indicated by the value of factor of safety. Christian *et al.* showed that a high value for the factor of safety for a condition involving much uncertainty may involve greater risk than a low value for a condition involving little uncertainty.[8,9] To evaluate the importance of uncertainty and the level of risk that results from uncertainty, another measure of safety is needed. The probability of failure or, more precisely, the probability that the actual factor of safety is less than 1.0, is such a measure.

Probability of failure, as it is used in reliability theory, is the probability of an event occurring, sometimes called a "negative outcome." With regard to factor of safety calculations, the "event" is that the factor of safety is less than 1.0. In this context, then, what is called the probability of failure in reliability theory is the probability that the factor of safety could be less than 1.0, given the possible variations in the values of the quantities involved in its calculation.

Reliability as it is used in reliability theory is the probability of a "positive outcome." Reliability is the complement of the probability of failure. Thus, if there is a 0.5 percent probability that the factor of safety is less than 1.0, the reliability (the probability that the factor of safety is greater than 1.0) is 99.5 percent.

The probability that the factor of safety is less than 1.0 can be calculated using a simple method, with the same amount and quality of data as used in more traditional geotechnical engineering factor of safety calculations. The calculated value of this probability should be viewed as no more accurate than the results of most geotechnical analyses. Even so, it provides a useful measure of the combined effects of uncertainties in the values of the parameters involved in computing the safety factor.

Several sources have outlined simple and effective procedures for estimating the probability that the factor of safety is less than 1.0.[10-12] Using the methods they described, this probability can be calculated following these steps:

1. Estimate the *most likely values* (MLVs) of the parameters required for the analysis. These values can be estimated using the same types of data ordinarily used for deterministic analysis, and applying engineering judgment in the same way. However, a conservative bias should not be built into the parameter values. Most likely values are appropriate.

2. Estimate the standard deviations of the parameters. Where too few data are available to compute the standard deviation by formal statistical methods, reasonable values can be estimated using the *three-sigma rule* and engineering judgment.

3. Calculate the factor of safety using the most likely values of the parameters. This

value of the factor of safety is the most likely value of the factor of safety (or, F_{MLV}).

4. Calculate factors of safety with the value of each of the variables in turn *increased* by one standard deviation from its most likely value, and the other variables assigned their most likely values. These factors of safety are denoted as $(F^+)_i$, where i denotes the parameter whose value is increased. There are N values of $(F^+)_i$, where N is the number of parameters involved in the calculation of F.

Also calculate factors of safety with the value of each of the variables in turn *decreased* by one standard deviation from its most likely value, and the other variables assigned their most likely values. These factors of safety are denoted as $(F^-)_i$. There are N values of $(F^-)_i$, where N is the number of parameters involved in the calculation of F.

5. Use the Taylor series method to compute the standard deviation of the factor of safety by using Equation 1.

6. Determine the probability of the factor of safety being less than 1.0 using Table 6.

EQUATION 1.

$$\sigma_F = \sqrt{\left(\frac{\Delta F_1}{2}\right)^2 + \left(\frac{\Delta F_2}{2}\right)^2 + \ldots \left(\frac{\Delta F_N}{2}\right)^2}$$

where:

σ_F = standard deviation of factor of safety

$\Delta F_1 = \{(F^+)_1 - (F^-)_1\}$, $\Delta F_2 = \{(F^+)_2 - (F^-)_2\}$, etc.

Computing Probabilities That the Factor of Safety May Be Less Than 1.0

Table 6 is convenient because it shows values of the probability of a factor of safety of less than 1.0 related to F_{MLV} and σ_F. Its shortcoming is that only approximate values of the probability of a factor of safety of less than 1.0 can be determined for values of F_{MLV} and σ_F that are intermediate between the values listed in the table. It may sometimes be desirable to have a means of computing more precise values of the probability of a factor of safety of less than 1.0.

The key to computing more precise values of the probability of a factor of safety of less than 1.0 is to compute the value of the log normal reliability index, β_{LN}, using Equation 2.

When β_{LN} has been computed, the value of the probability of a factor of safety of less than 1.0 can be determined accurately in either of two ways:

1. Use tables of the standard cumulative normal distribution function, which can be found in many textbooks on probability and reliability. For example, the value of β_{LN} computed for the original design analysis of the hypothetical slope, corresponding to F_{MLV} equal to 1.41 and σ_F equal to 0.204, is 2.31. The standard cumulate normal distribution function (the reliability) corresponding to a β_{LN} equal to 2.31 is 0.9896.[13] The probability of a factor of safety of less than 1.0 is one minus the reliability (or equal to 1.0 minus 0.9896), which is 0.0104.

2. Use the built-in function NORMSDIST in Microsoft Excel. The argument of this function is the reliability index, β_{LN}. In this spreadsheet program, under "Insert Function," "Statistical," choose "NORMSDIST," and type the value of β_{LN}. For example, for β_{LN} equal to 2.31, the result is 0.989556, which corresponds to the probability of a factor of safety less than 1.0 of 0.0104. Table 6 was developed using this function.

These methods assume a log-normal distribution of factor of safety. The log-normal distribution was selected because the central limit

EQUATION 2.

$$\beta_{LN} = \frac{\ln\left(\dfrac{F_{MLV}}{\sqrt{1+(\sigma_F / F_{MLV})^2}}\right)}{\sqrt{\ln\left(1+(\sigma_F / F_{MLV})\right)^2}}$$

where:

β_{LN} = log normal reliability index,

σ_F = standard deviation of factor of safety (see Equation 1), and

F_{MLV} = most likely value of factor of safety.

TABLE 6.
Probabilities That a Factor of Safety Is Smaller Than 1.0

	Standard Deviation of Factor of Safety																
%	0.02	0.04	0.06	0.0675	0.08	0.1	0.12	0.14	0.16	0.2	0.2041	0.25	0.3	0.4	0.5	0.6	0.8
1.10	0.000	0.461	4.259	6.375	10.099	15.740	20.557	24.557	27.882	33.057	33.503	37.733	41.219	46.245	49.871	52.727	57.124
1.12	0.000	0.080	1.830	3.201	6.022	10.986	15.689	19.825	23.384	29.079	29.576	34.322	38.250	43.887	47.899	51.018	55.746
1.14	0.000	0.010	0.685	1.443	3.330	7.314	11.590	15.630	19.261	25.286	25.822	30.987	35.310	41.251	45.912	49.293	54.353
1.163	0.000	0.001	0.185	0.501	1.525	4.304	7.840	11.527	15.050	21.210	21.772	27.285	31.988	38.805	43.614	47.291	52.735
1.18	0.000	0.000	0.062	0.207	0.797	2.779	5.693	8.999	12.328	18.423	18.993	24.664	29.590	36.808	41.913	45.804	51.529
1.20	0.000	0.000	0.015	0.065	0.342	1.578	3.771	6.553	9.559	15.417	15.982	21.727	26.850	34.480	39.912	44.047	50.101
1.25	0.000	0.000	0.000	0.002	0.027	0.295	1.125	2.602	4.583	9.275	9.773	15.204	20.480	28.823	34.953	39.651	46.499
1.30	0.000	0.000	0.000	0.000	0.001	0.037	0.254	0.843	1.883	5.062	5.443	10.001	14.965	23.516	30.131	35.297	42.872
1.35	0.000	0.000	0.000	0.000	0.000	0.003	0.042	0.219	0.653	2.482	2.736	6.148	10.435	18.687	25.534	31.046	39.253
1.40	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.044	0.189	1.083	1.230	3.511	6.916	14.433	21.247	26.958	35.674
1.41	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.031	0.144	0.904	1.033	3.109	6.329	13.657	20.433	26.166	34.966
1.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.009	0.140	0.172	0.897	2.569	7.840	13.855	19.494	28.766
1.60	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.014	0.160	0.743	3.707	8.270	13.256	22.399
1.70	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.019	0.163	1.501	4.474	8.420	16.783
1.80	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.026	0.512	2.171	4.962	12.057
1.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.145	0.936	2.695	8.276
2.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.034	0.355	1.340	5.407
2.20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.034	0.248	1.964
2.40	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.030	0.563
2.60	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.124
2.80	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020
3.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002

F_{MLV}

theorem indicates that the normal distribution is the most likely form of distribution of a quantity resulting from the addition and subtraction of many randomly distributed values.[14] It follows that the log-normal distribution is the most likely form of distribution of a quantity that results from many multiplication and division operations, because multiplication and division are equivalent to adding and subtracting logarithms.

The Three-Sigma Rule

The three-sigma rule is very useful for estimating the value of the standard deviation of a parameter when too little data is available to calculate the standard deviation using formal statistical methods.[13] The three-sigma rule relies on the fact that, as shown in Figure 10, 99.73 percent of all of the values of a normally distributed variable lie within plus or minus three standard deviations ($\pm 3\sigma$) of the mean (or most likely value). For practical purposes this is 100 percent (or all values). This fact can be used to estimate the standard deviation, as follows:

1. Estimate the highest conceivable value (HCV) and the lowest conceivable value (LCV) of each variable, using all available data, correlations and engineering judgment. A conscious effort should be made to make the range wide because the objective is to encompass all conceivable values. Controlled experiments have shown that there is a tendency to estimate a range of values that is narrower than the actual range.[15]
2. Compute the value of standard deviation by subtracting the LCV from the HCV and dividing the result by 6.

The three-sigma rule makes it possible to overcome an often-encountered barrier to the use of reliability methods — insufficient data. Using it, engineers can estimate values of standard deviation on the basis of the same kinds of judgments required to select parameter values for deterministic analyses.

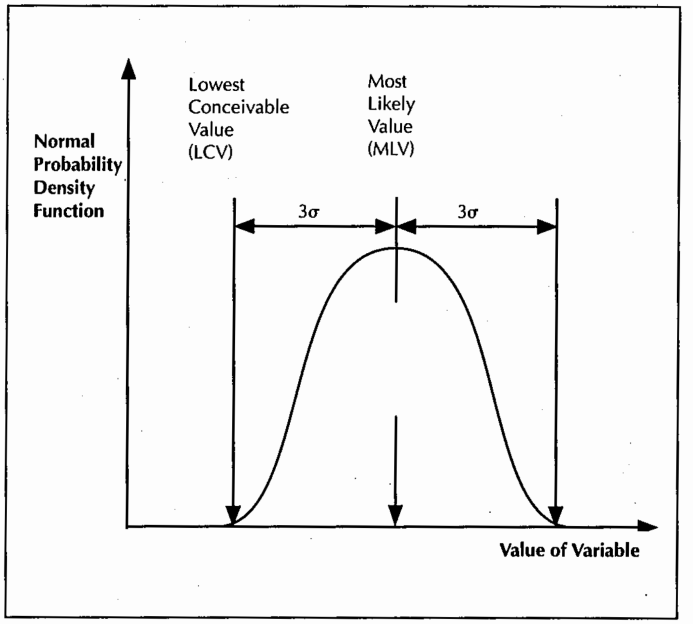

FIGURE 10. The basis for the three-sigma rule.

Probability of Factor of Safety Less Than 1.0 for the Hypothetical Slope

The method outlined by Wolff and the U.S. Army Corps of Engineers has been applied to the hypothetical slope shown in Figures 8 and 9 to evaluate the reliability of the original design, and to evaluate the reliability of the redesign based on back analysis.[10-12] The results are shown in Tables 7 and 8.

As noted previously, and shown in the top row of Table 7, the factor of safety calculated in the original design, using the most likely values of all of the parameters, was 1.41. There were four major sources of uncertainty in the original design — the strength of the sandy clay, the unit weight of the sandy clay, the strength of the highly plastic clay and the piezometric elevation. The highest and lowest conceivable values and corresponding standard deviations for each of these quantities are shown in Table 7, together with values of F^+ and F^- corresponding to varying their values by plus or minus one standard deviation from the most likely values. Also shown are the values of ΔF for each variable, the standard deviation of the factor of safety computed by subtracting the LCV from the HCV and dividing the result by 6, and the probability of failure from Table 6. The location in Table 6 corre-

TABLE 7.
Reliability Analysis of the Hypothetical Slope — Original Design

With all quantities assigned their most likely values: F_{MLV} = 1.41			
Variable Quantity	**Parameter Values**	**Factors of Safety**	
Sandy Clay Strength			
Most likely value	c' = 300 psf, ϕ' = 35°		
Highest conceivable value	c' = 1000 psf, ϕ' = 45°	F^+ = 1.55*	
Lowest conceivable value	c' = 0 psf, ϕ' = 25°	F^- = 1.31*	ΔF = 0.24**
Standard deviation	σ_c = 167 psf, σ_ϕ = 3.3°		
Sandy Clay Unit Weight			
Most likely value	γ = 130 pcf		
Highest conceivable value	γ = 145 pcf	F^+ = 1.46	
Lowest conceivable value	γ = 115 pcf	F^- = 1.38	ΔF = 0.08**
Standard deviation	σ_γ = 5 pcf		
Highly Plastic Clay Strength			
Most likely value	c' = 0, ϕ' = 25°		
Highest conceivable value	c' = 0, ϕ' = 35°	F^+ = 1.54	
Lowest conceivable value	c' = 0, ϕ' = 15°	F^- = 1.29	ΔF = 0.25**
Standard deviation	σ_c = 0, σ_ϕ = 3.3°		
Piezometric Elevation			
Most likely value	el. = 140 ft		
Highest conceivable value	el. = 150 ft	F^+ = 1.52	
Lowest conceivable value	el. = 120 ft	F^- = 1.32	ΔF = 0.20**
Standard deviation	σ_{el} = 5 ft		
Standard deviation of factor of safety (see Equation 1) = 0.2041			
Probability of factor of safety less than 1.0 (see Table 6) = 1.03%			

*F^+ is calculated with both c' and ϕ' increased by one standard deviation, and F^- is calculated with both c' and ϕ' decreased by one standard deviation.
**$\Delta F = F^+ - F^-$

sponding to the original design is highlighted. The probability of the factor of safety being less than 1.0 is 1.03 percent.

As noted previously, and as indicated in the top row of Table 8, the factor of safety calculated in the redesign, based on the results of the back analysis, was 1.16. All of the parameters except the piezometric level are determined reliably by the back analysis and are, therefore, not subject to significant uncertainty. This being the case, the standard deviation of the redesign factor of safety is much smaller than for the original design factor of safety. The probability of the factor of safety being less than 1.0 is 0.5 percent. The location in Table 6 corresponding to the redesign is highlighted.

Although the factor of safety for the redesign is lower than the factor of safety for the original design (a factor of safety equal to 1.16 as compared to 1.41) the probability of the redesign factor of safety being less than 1.0 is smaller (0.5 percent as compared to 1.0 percent). This difference is a direct result of the fact that the redesign was based on back analysis, which eliminates much uncertainty.

It is not the purpose of this example to indicate that the redesign condition analyzed above represents a sufficiently reliable long-term condition for the slope. In terms of the probability of a factor of safety less than 1.0, it is not much different from the original design, and it might be desirable to increase the factor of safety to a value greater than 1.16, and reduce the value of the probability of failure even more, by additional stabilizing measures. For example, if the spacing between

TABLE 8.
Reliability Analysis of the Hypothetical Slope Redesign

With all quantities assigned their most likely values: $F_{MLV} = 1.16$ (values are shown in Table 4)			
Variable Quantity	**Parameter Values**	**Factors of Safety**	
Piezometric Elevation			
Most likely value	el. = 128 ft		
Highest conceivable value	el. = 140 ft	$F^+ = 1.23$	
Lowest conceivable value	el. = 110 ft	$F^- = 1.10$	$\Delta F = 0.13$**
Standard deviation	$\sigma_{el} = 5$ ft		
Standard deviation of factor of safety (see Equation 1) = 0.0675			
Probability of factor of safety less than 1.0 (see Table 6) = 0.5%			

**$\Delta F = F^+ - F^-$

wells was reduced so that the average piezometric level was lowered by an additional 3.0 feet, the factor of safety would increase from 1.16 to 1.20, and the value of probability would decrease to 0.05 percent.

The consequences of failure and the cost of stabilization are important factors in determinating the acceptable level of risk. These factors are beyond the scope of this hypothetical exercise. It is clear, however, that being able to compute the probability that the factor of safety will be less than 1.0 (in addition to computing the most likely value of the factor of safety) provides a more complete basis for making this judgment.

Conclusions

The preceding examination of back analysis, factor of safety and reliability supports these conclusions:

- Back analysis can be used to develop highly reliable computational models of slopes. It can be used where slopes have failed, such as at the San Luis Dam and Olmsted Locks and Dam, and where slopes have not failed, such as at La Esperanza Dam.
- When the results of back analysis are used for the design of slope stabilization measures, they should be used consistently with the assumptions made in the back analysis. While assumptions are inevitably required to develop computational models, adjusting the elements of the model through back analysis results in a model that is not significantly affected by the assumptions, provided that they are reasonable and fit all the known facts.
- As the hypothetical example described above clearly indicates, it is justified to use lower-than-conventional factors of safety when the computational model can be based on back analysis, because back analysis reduces slope failure risk.
- Reliability theory is a very useful complement to conventional deterministic analyses. Using the Taylor series method, it is possible to compute the probability of the factor of safety being less than 1.0 through the application of simple formulas. Computing both the most likely value of the factor of safety and the probability that the factor of safety could be less than 1.0 affords a better basis for judging analytical results than does computing only the factor of safety.
- The effort involved in computing the probability of the factor of safety being less than 1.0 is not great. Each of the additional computations required only involves changing the value of one variable and repeating the calculations. As compared with conventional deterministic

analyses, using the Taylor series method to compute the probability of a factor of safety of less than 1.0 may add 5 percent to the effort, and 50 percent to the value of the analysis.

- The three-sigma rule provides a very useful technique for overcoming the frequently encountered problem of too few data to compute the standard deviation by formal statistical methods. Using the three-sigma rule, it is possible to estimate standard deviations by means of the same combination of data, correlations and engineering judgment that are involved in all geotechnical engineering analyses.

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REFERENCES

1. Flexner, S.B., & Hauck, L.C., editors, *The Random House Dictionary of the English Language*, 2nd Ed., Random House, New York, 1983.

2. Stark, T.D., & Duncan, J.M., "Mechanisms of Strength Loss in Stiff Clays," Report to U. S. Bureau of Reclamation, Geotechnical Engineering Report, Department of Civil Engineering, Virginia Polytechnic Institute and State University, July 1987.

3. Duncan, J.M., & Stark, T.D., "The Causes of the 1981 Slide in San Luis Dam," The Henry M. Shaw Lecture, North Carolina State University, Department of Civil Engineering, April 12, 1989.

4. Stark, T.D., & Duncan, J.M., "Mechanisms of Strength Loss in Stiff Clays," *Journal of the Geotechnical Engineering Division, ASCE*, Vol. 117, No. 1, January 1991.

5. Filz, G.M., Brandon, T.L., & Duncan, J.M., "Back Analysis of Olmsted Landslide Using Anisotropic Strengths," *Transportation Research Record No. 1343*, Rockfall Prediction and Control and Landslide Case Histories, 1992.

6. Duncan, J.M., Wissmann, K.J., & Brandon, T.L., "Stability and Settlement of Lower Bank and Service Mound Fills at Olmsted Locks and Dam," Report to Geotechnical Branch, Louisville District, U. S. Army Corps of Engineers, 1994.

7. Duncan, J.M., Bolinaga, F., & Morrison, C.S., "Analysis and Treatment of Landslides on the Abutments of La Esperanza Dam," *Proceedings of the First Pan-American Symposium on Landslides*, August 1-5, 1994, Guayaquil, Ecuador.

8. Christian, J.T., Ladd, C.C., & Baecher, G.B., "Stability and Performance of Slopes and Embankments - II," *Volume 2, Geotechnical Special Publication No. 31*, 1992.

9. Christian, J.T., Ladd, C.C., & Baecher, G.B., "Reliability Applied to Slope Stability Analysis," *Journal of Geotechnical Engineering Division, ASCE*, Vol. 20, December 1994.

10. Wolff, T.F.. "Evaluating the Reliability of Existing Levees," report of a research project, entitled *Reliability of Existing Levees*, prepared for U.S. Army Engineer Waterways Experiment Station Geotechnical Laboratory, September 1994.

11. U.S. Army Corps of Engineers, "Engineering and Design Introduction to Probability and Reliability Methods for Use in Geotechnical Engineering," *Technical Letter No. 1110-2-547*, Department of the Army U.S. Army Corps of Engineers, September 30, 1997.

12. U.S. Army Corps of Engineers, "Risk Based Analysis in Geotechnical Engineering for Support of Planning Studies," *Circular No. 1110-2-554*, Department of the Army U.S. Army Corps of Engineers, 27 February 1998.

13. Dai, S.-H., & Wang, M.-O., *Reliability Analysis in Engineering Applications*, Van Nostrand Reinhold, New York, 1992.

14. Harr, M.E., *Reliability-Based Design in Civil Engineering*, McGraw-Hill, New York, 1987.

15. Folayan, J.I., Höeg, K., & Benjamin, J.R., "Decision Theory Applied to Settlement Predictions," *Journal of the Soil Mechanics and Foundations Division, ASCE*, Vol. 96, No. SM4, July 1970.

Managing to Avoid Congestion

The world's population is by no means decreasing and engineers have to come up with new, outside-the-box solutions to create a built environment that will healthily sustain more people.

BRIAN BRENNER

The plot of the movie, *The Truman Show,* concerns the life of a man who lives in a television show, but does not know it. The producers of the show constructed an imaginary village covered by a huge dome and populated this set with actors. Everyone except the star of the show, Truman, is a performer playing a scripted role. Truman lives his life not knowing that his wife, employer and neighbors are all actors working from the producer's script. The proceedings are cleverly filmed and presented to the voyeuristic public, which watches the show waiting to see each new development in the soap opera of Truman's life.

This movie is not a great one to see if you are paranoid.

The village that Truman lives in — the "set" — is supposed to be an idealized, sunny, perfectly-built place. Gentle waves lap the shore of this seacoast village, which has cheerful, inviting architecture, palm trees and friendly people. The village is presented as Utopian. In reality, the movie set is not a set at all, but an actual place. The movie was filmed at Seaside, Florida, a newly built town on the coast of the Gulf of Mexico. This village is at the vanguard of the New Urbanism movement. This uncommon village has certain zoning and design features that can be summarized as follows:

- Stores and offices are permitted in some areas along with houses and apartments. The design allows for mixed usage.
- The street grid has features that lead to pedestrian comfort, such as reduced street width, traffic "calming" devices, trees, sidewalks and benches.
- Garages do not face the street, but are set back in alleys.
- The houses are built more densely, and are designed to shape the public street space, which is accomplished with relatively small front yards, front porches and cupolas that lead to a transition from outside to inside. Building position and massing helps the street to feel like an outside room and not a speedway.

The New Urbanism design guidelines that were in place for the building of Seaside are illegal in much of the U.S. Most towns and cities have strict zoning guidelines that separate stores from offices from housing. Even the types of housing are strictly separated by area: apartments from townhouses from single-family homes from really exclusive single-family homes. Required lot sizes and setbacks lead to today's standard suburban housing developments, strip malls and office parks. Today's dominant form of urban design is sprawl. One of the ramifications of sprawl is traffic congestion. Because everything is separated and widely spaced, you have to drive large distances to go shopping, to go to work, to do anything. You cannot walk, and there is usually not a subway or bus system near the 1-acre zoned lots.

Yet, the utopian world of *The Truman Show* wasn't filmed at Levittown or at a strip mall. When the movie producers needed an idealized place for their imaginary world, they selected a town that violates all of today's suburban development guidelines. It is ironic that, at the end of the movie, Truman escapes from his fishbowl existence and chooses to live in the outside world. What the movie does not show is Truman's subsequent life in a housing subdivision with a ninety-minute one-way commute in heavy traffic.

Probably most people suspect that there is something wrong with the present development scheme. They muse in bumper to bumper traffic, and are uneasy cruising by dreary strip malls and the vast parking lots that define modern suburban spaces. They go to visit Main Street at Disney World and marvel at what a great place it is, not really understanding why they cannot live around Main Street in real life.

The public at large may be uncomfortable and dissatisfied, and not understand why. Civil engineers have a greater responsibility. It is our business to design and shape the built environment. Therefore, we need to better understand how the design pieces fit together, and act on this knowledge. In February 1999, the U.S. Environmental Protection Agency (EPA) sponsored a day-long conference, "Smart Growth Strategies for New England." Speakers discussed strategies for containing sprawl and focusing urban development. Even here in New England, which is arguably in the best shape of any region in the country when it comes to sprawl, the landscape is being plowed over by strip malls and subdivisions. Dealing with this problem will require the skills and participation of engineers as well as planners.

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Hydraulic Engineering in The Netherlands: A Visit by the Tufts ASCE Student Chapter, Fall 1992, Vol. 7, No. 2, pp. 75–90

Hydrologic Sensitivity to CO2-Induced Global Warming, R.T. Wetherald & S. Manabe, Spring 1992, Vol. 5, No. 1, pp. 33–36

The Limited Benefits of Flood Control: An Interview With Lu Qinkan, Chen Kexiong, Spring/Summer 1997, Vol. 12, No.1, pp. 99–103

Long-Range Surface Water Supply Planning, Richard A. Vogel & David I. Hellstrom, Spring 1988, Vol. 3, No. 1, pp. 7–26

Mamaroneck Effluent Pumping Station Wet Well Model Study: Necessity or Redundant Design Precaution?, Peter J. Barthuly & Mahadevan Padmanabhan, Spring 1990, Vol. 5, No. 1, pp. 69–84

The New York City Water Supply: Past, Present & Future, Edward C. Scheader, Fall 1991, Vol. 6, No. 2, pp. 7–20

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The Role & Contributions of Hydraulic Testing Labs: Part I, Industrial Revolution to World War I, George E. Hecker, Albert G. Ferron & Bruce J. Pennino, Spring/Summer 1999, Vol. 14, No. 1, pp. 5-28

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The Three Gorges Project: Key to the Development of the Yangtze River, Zhu Rulan, Yao Jianguo, Chen Deji, Guo Yu, Fang Ziyun, Zhao Shihua & Cheng Shoutai, Spring/Summer 1997, Vol. 11, No.1, pp. 39–72

The Three Gorges Project & Sustainable Development in China, Dai Qing, Spring/Summer 1997, Vol. 11, No.1, pp. 73–92

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Bridge Rehabilitation, Frank Stahl, Fall 1990, Vol. 5, No. 2, pp. 7–40

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Launching Gantries for Bridge Erection in Difficult Terrain, W. Scott McNary & John Harding, Fall/Winter 1993, Vol. 8, No. 2, pp. 53-64

The Performance of Highway Bridges in the Northridge, California, Earthquake, National Center for Earthquake Engineering Research, Fall/Winter 1995, Vol. 10, No. 2, pp. 5-26

Major Engineered Structures in Boston, Edmund G. Johnson, Spring 1989, Vol. 4, No. 1, pp. 89–99

Massachusetts Earthquake Design Codes, S.A. Alsup & K.E. Franz, Spring 1989, Vol. 4, No. 1, pp. 79–82 [Discussion by William Weiler, Fall 1989, Vol. 4, No. 2, pp. 85–86. Response by author, Fall 1989, Vol. 4, No. 2, pp. 90–91.]

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A Model Coastal Zone Building Code for Massachusetts, Ad Hoc Committee on Coastal Zone Building Codes of the BSCES Waterway, Port, Coastal & Ocean Engineering Technical Group, Fall 1991, Vol. 6, No. 2, pp. 21–30

Modern Marina Layout & Design, Duncan C. Mellor, Spring 1992, Vol. 7, No. 1, pp. 87–102

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