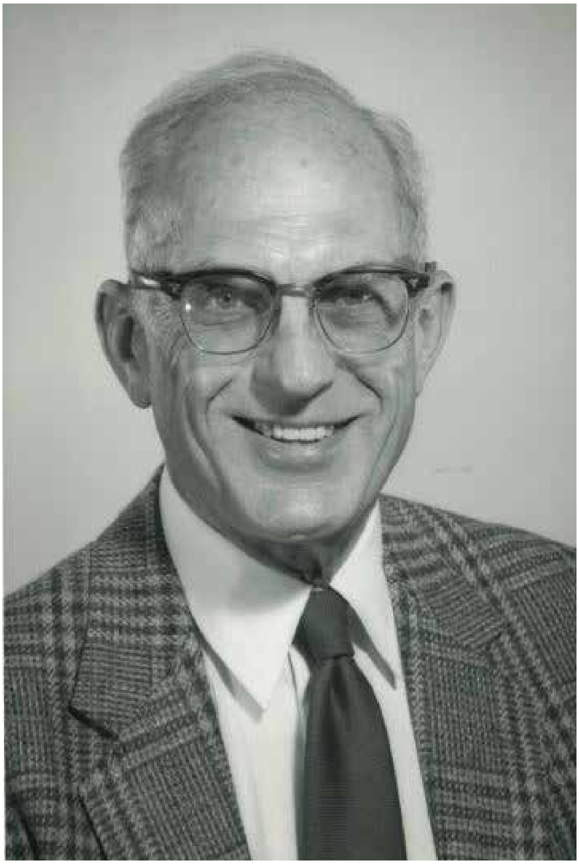

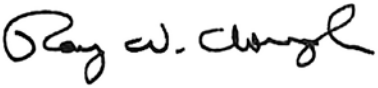

RAY W. CLOUGH

1920–2016

Elected in 1968

"Analysis, design, and applications of structures for dynamic loadings, including earthquakes."

BY EDWARD L. WILSON AND JACK P. MOEHLE

RAY WILLIAM CLOUGH, recognized as one of the world's most accomplished engineers and scientists, died October 8, 2016, at the age of 96.

He was born July 23, 1920, in Seattle, the third child of Mildred Nelson, from North Dakota, and Ray W. Clough, from Vermont. Ray Clough Sr. had earned a PhD at the University of Washington in food chemistry and was responsible for the quality of salmon that came down from Alaska. The other Clough children, from oldest to youngest, were Ralph, Harriet, and Phyllis.

Ray met his future wife, Shirley Potter, who was a year younger than he, at Roosevelt High School. Later they both studied at the University of Washington, where they shared their experiences of hiking and skiing in the Cascades and on Mt. Rainier with college friends. They married in October 1942.

Also in 1942, Ray graduated from the University of Washington with a degree in civil engineering 6 months after the start of World War II. He attempted to enlist in the Naval Construction Battalions (the Seabees) where he could use his engineering education, but was rejected because of his poor eyesight.

He went to work at Boeing engineering in Seattle, in a job that would guarantee a deferment until the end of the war. But he found the work menial and did not consider it a productive way to spend the war years. He learned that the Army Air Force had a shortage in meteorology and would accept him because it was a noncombat position. After basic training, he obtained a master's degree in meteorology at the California Institute of Technology, where he became an instructor in meteorology until June 1944. By that time, the Army Air Force had a surplus of meteorologists and Ray was transferred to be in charge of an airfield construction crew.

In July 1945 Ray's construction battalion was on a troop ship traveling from Hawaii to join the war in the Pacific and participate in the invasion of Japan. Not long after they left Hawaii in the convoy, the Hiroshima bomb was dropped (August 6). As they continued toward Japan, the Nagasaki bomb was dropped (August 9). On August 15 Japan surrendered, ending the war.

Ray continued to Japan and was part of the occupying force on the island of Okinawa. Ironically, having been rejected earlier by the Seabees, when his Air Corps construction battalion arrived at Okinawa he was immediately reassigned to a Seabee unit working on the construction of an airfield runway and the aircraft control tower.

Ray was discharged in 1946 in time to enter the graduate program at the Massachusetts Institute of Technology. While working for his doctoral degree he took an advanced aerodynamics course from Raymond L. Bisplinghoff that influenced him for the rest of his life. He completed his thesis on experimental and theoretical analyses of buckling of arches.

After receiving his degree in 1949, Ray was hired by the Civil Engineering Department at the University of California, Berkeley. Over the next 38 years, until he retired, his courses were very popular, attracting students from structural engineering and multiple other disciplines. According to retrospective reports from several of his students, he was always well prepared and very effective in presenting a significant amount of practical information in a short period of time.

During the summers of 1952 and 1953, he was employed at a dynamics analysis research group with the Boeing Aircraft

Company in Seattle. The work involved modeling the delta wing with three-dimensional strut elements (connected to two joints) and the wing surfaces with triangular or quadrilateral triangular membrane elements (connected to three or four joints). His research involved the development of elements that accurately predicted displacements compared to experimental results. Boeing referred to this work as the direct stiffness method, a standard method of structural analysis where the joint displacements were the unknowns.

At Berkeley Ray was asked to develop a dynamics course that would enable civil engineers to design earthquake-resistant structures. No additional funding was provided for him to conduct earthquake engineering research, but in October 1955 he published "On the Importance of Higher Modes of Vibration in the Earthquake Response of a Tall Building" (*Bulletin of the Seismological Society of America* 45(4)).

In 1956 he received a Fulbright Fellowship to spend a year in Trondheim, Norway, at the Ship Research Institute, where there was interest in calculating stresses due to ship vibrations in order to predict fatigue failures at stress concentrations. This is when he realized his element research should be called the finite element method (FEM), which could solve many different types of problems in continuum mechanics. The FEM was a direct competitor to the finite difference method, which was being used to solve many problems in continuum mechanics.

When Ray returned from Norway in fall 1957 he put a note on the student bulletin board asking students to contact him if they were interested in conducting finite element research for the analysis of plate and shell structures. He did not have funding for such research, but a few graduate students who had other sources of funds responded.

At the time, the only digital computer in the College of Engineering was an IBM 701 that was produced in 1951 and used vacuum tube technology. The maximum number of linear equations it could solve was 40. Consequently, when Ray presented his first FEM paper in September 1960, "The Finite Element Method in Plane Stress Analysis," at ASCE's

2nd Conference on Electronic Computation in Pittsburgh, the coarse mesh results were not impressive.

After improvements in the speed and capacity of the computers on the Berkeley campus, Ray's second FEM paper, "Stress Analysis of a Gravity Dam by the Finite Element Method," presented at a conference in Lisbon in September 1962, had a more significant impact on the engineering profession. The paper was republished in *RILEM Bulletin* 10 (June 1963), which had a very large circulation.

The paper reported on the finite element analysis of the 250-foot-high Norfork Dam in Arkansas, which had developed a vertical crack during construction in 1942. The finite element analysis correctly predicted the location and size of the crack, which apparently was due to temperature changes, and produced realistic estimates of displacements and stresses in the dam and foundation for both gravity and several hydrostatic load conditions. Because of this publication, many international students and visiting scholars came to the Berkeley campus to work with Professor Clough.

It is well documented that from 1957 to 1963 Ray and his students created the simple and powerful finite element method as a replacement for the finite difference method. He is the father of the modern FEM and coined the term many years before the creation of the term computational mechanics. Yet he did not capitalize on his success. He returned to the task of building the earthquake engineering program at Berkeley—the task he was given when he was hired in 1949.

In the early 1960s Ray and Joseph Penzien led a group of faculty at Berkeley in establishing the university's Earthquake Engineering Research Center. Ray was very involved in the design and construction of a 20′ × 20′ shaking table that was capable of testing large structures subjected to realistic earthquake motions. This was the most sophisticated earthquake simulator in the world at the time, and it continues as an important earthquake simulator today.

A remarkable aspect of Ray's earthquake engineering research was his balanced approach of conducting physical experiments, both in the laboratory and in the field, to verify and improve the development of more accurate analytical methods. Notable among his laboratory studies are several shaking table tests to explore the nonlinear dynamic response of multistory building models (including the first-ever tests on rocking buildings), structure-fluid dynamics, and dynamic response of dams.

In 1975 he and Penzien published *Dynamics of Structures* (McGraw-Hill). The book was widely adopted and had a major impact in the education of generations of structural and earthquake engineers. The second edition is still in demand.

Ray traveled extensively as a pioneer in earthquake engineering, and surveyed the damage caused by the Agadir (Morocco) and Valdivia (Chile) earthquakes of 1960 and the Skopje (Yugoslavia) earthquake of 1964. He was a member of the UNESCO Seismology and Earthquake Engineering Mission to the Mediterranean Area in 1962, the US delegation to the UNESCO Governmental Meeting on Seismology and Earthquake Engineering in Paris in 1964, and the US delegation to inspect earthquake engineering research and construction in the USSR in 1969.

Ray's research and professional contributions have been recognized by many organizations in the United States and internationally; only a partial list of his honors is presented here. He was elected to the National Academy of Engineering in 1968 and the National Academy of Sciences in 1979. In 1994 President William Clinton awarded him the National Medal of Science and in 2006 he received the Benjamin Franklin Medal—at the time he was the only engineer to receive either medal. His international awards include the Fulbright Fellowship (1956–57); an Overseas Fellowship from Churchill College, Cambridge University (1963–64); honorary doctor of technology degrees from both Chalmers University, presented by the King of Sweden (1979), and the Norwegian Institute of Technology, Trondheim (1982); and the International Association of Computational Mechanics (IACM) Congress Medal (the Gauss-Newton Medal) (1986).

He represented the technical areas of earthquake engineering and structural dynamics in service on many governmental advisory panels and boards, including the Committee Advisory to the Earth Systems Science Agency (ESSA), the Panel Advisory to the Building Research Division of the National Bureau of Standards (now NIST), and the US Army Corps of Engineers Structural Design Advisory Board. He was appointed to a number of National Research Council activities, as a member of the Committee on Earthquake Engineering Research (1981–83), Advisory Committee on the USSR and Eastern Europe (1981–85), Committee on Earthquake Engineering (1985–91), and Panel on Evaluation of US-PRC Earthquake Engineering Program (1989–93), among others, and as chair of the Panel on Earthquake Engineering for Concrete Dams (1986–90).

He was also active in professional societies, as chair of the American Society of Civil Engineers Engineering Mechanics Division executive committee, and as a member of the board of directors of the Structural Engineers Association of Northern California, Seismological Society of America, and Earthquake Engineering Research Institute. In addition, he was the founder and first editor of *Earthquake Engineering and Structural Dynamics*, the journal of the International Association for Earthquake Engineering.

In addition to his academic career, Ray consulted on a number of complex structural problems in the design of power stations, ships, dams, multistory buildings, transmission towers, offshore drilling platforms, aerospace projects, and fluid structure interaction problems.

As a teenager, Ray was attracted to the hiking and mountain activities of the Boy Scouts. However, the Boy Scout group did not attempt climbing high mountain peaks, so Ray and his friends decided to form their own climbing club, naming it the Ptarmigan Climbing Club after the little mountain birds found in the Pacific Northwest and other mountain regions. The major objective of the club was to develop safe techniques to climb mountains where the surfaces were a combination of bare rock, snow, and/or ice. The club had 20 or 30 members and they would form small climbing groups using their new and safe techniques. Pitons and ropes were used for safety only.

In 1938 Ray and three other young friends planned and completed an approximately 10-day, 35-mile mountain climbing trip in the Northern Cascades range, including six mountain peaks that had not been climbed previously. Nearly 80 years later, the Seattle mountaineering community refers to this trip as the Ptarmigan Traverse and it is still considered a challenging trip using modern equipment.

Members of Ray's family and his close friends believe the impression made on Ray as a member of the Ptarmigan Club was profound. After his remarkable success as a teenager he set his sights on greater objectives, "climbing" ever higher and delighting in the friendship of his students and colleagues. They all joined him in solving complex problems in many different fields of engineering.

Ray's wife Shirley preceded him in death on April 17, 2016. They are survived by their son Douglas, daughters Allison and Meredith, five grandchildren, two great-grandchildren, and many nephews and nieces.