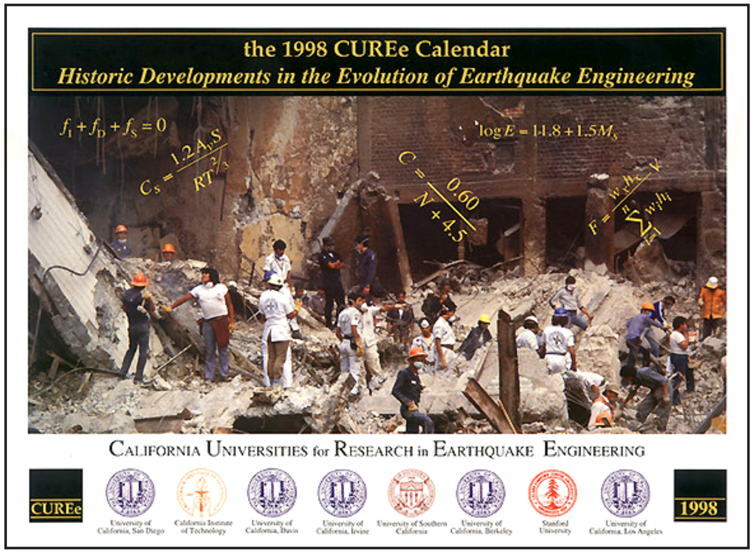


Historic Developments in the Evolution of Earthquake Engineering

adapted from the 1998 CUREE Calendar

illustrated essays by Robert Reitherman

Consortium of Universities for Research in Earthquake Engineering

1301 S. 46th Street, Richmond, CA 94804-4698 tel: 510-231-9557 fax: 510-231-5664

http://www.curee.org

Collapse of Struve Slough Bridge, Highway I, Loma Prieta Earthquake, California, October 17, 1989

The performance of newly designed or retrofitted bridges a few years later in the January 17, 1994 Northridge Earthquake in Los Angeles was excellent – none collapsed or was seriously damages, though some older, unretrofitted bridges collapsed – indicating the degree of improvement in performance that earthquake engineering is increasingly capable of providing.

Cover Equations

The miscellaneous assortment of earthquake engineering equations on the cover are identified below, along with a reference for each where more information may be obtained.

$$\log E = 11.8 + 1.5M_s$$

The energy released by an earthquake can be related to its magnitude, in this case the surface wave magnitude. (Bruce Bolt, Earthquakes: A Primer, San Francisco: W. H. Freeman and Co., 1978, Appendix G.)

$$f_I + f + f_s = 0$$

Dynamic equilibrium requires that the inertial force be balanced by the damping and the resisting forces. (Anil Chopra, Dynamics of Structures: A Primer, Oakland, CA: Earthquake Engineering Research Institute, 1980, p.19.)

$$F = \frac{w_x h_x}{\sum_{i=1}^{n} w_i h_i} V$$

In the equivalent static lateral force method of analysis, this equation provides an estimate of the vertical distribution of lateral forces in the fundamental mode of vibration. For uniform story weight and height, it gives the familiar inverted triangular lateral force distribution. (Int'l Conference of Building Officials, Uniform Building Code, Whittier, CA: ICBO, various editions.)

$$C = \frac{0.60}{N + 4.5}$$

In 1943, the city of Los Angeles building code was the first to introduce a factor into a seismic coefficient quantifying the load-reducing effect of building flexibility. (Glen Berg, "Historical Review of Earthquakes, Damage, and Building Codes," Proceedings of the National Structural Engineering Conference; Methods of Structural Analysis, New York: American Society of Civil Engineers, p. 393.)

$$C_s = \frac{1.2 A_v S}{R T^{2/3}}$$

The R or response modification factor was introduced into the seismic coefficient to account for the difference between elastically-calculated forces and the actual forces a structure inelastically experiences under strong shaking. (ATC and SEAOC, Tentative Provisions for the Development of Seismic Regulations for Buildings, ATC-3-06. Redwood City, CA: Applied Technology Council, 1978, p.335.)

CUREE

Cover Photo: The collapse of a structure, such as this tall building in Mexico City in the September 19, 1985 Michoacan Earthquake, is the catastrophe that has primarily motivated the development of earthquake engineering through much of its evolution over the past century. Currently, additional objectives aiming at higher levels of performance are commonly used in the seismic design of new construction. The level of knowledge and technology in the earthquake engineering field is rising to meet this demand for buildings, bridges, and other construction that can withstand strong earthquakes without costly damage, significant chance of injuries, or major functional interruption. (photo credit, cover and this page: Bob Reitherman)

1998

CONSORTIUM of UNIVERSITIES for RESEARCH in EARTHQUAKE ENGINEERING

Professor Omori of the University of Tokyo collaborated with his colleague Professor John Milne to simulate the behavior of objects in actual earthquakes by means of artificially shaking models. (John Freeman, Earthquake Damage and Earthquake Insurance, McGraw-Hill, New York, 1932, p.38) Omori's goal was to estimate the accelerations in an earthquake that had caused and were "recorded" by the toppling of stone lanterns.

F. J. Rogers, a Stanford physics professor, became interested in experiments to determine the response of soils to earthquake vibrations from discussions with a professor of geology and later president of the university, John Casper Branner. Rogers began testing in 1906 with the machine shown here (described by Rogers in "Experiments with A Shaking Machine," in *The California Earthquake of April 18, 1906: The Report of the State Earthquake Investigation Commission*, Washington, DC, Carnegie Institution, 1908, Vol. I, Part 2, 326-335, and reprinted in BSSA, Vol. 20, No. 3, September 30, 1930, 147-160). The soil-filled cart was cyclically driven by a DC-powered drive-rod while the recording drum was rotated by hand. After the 1925 Santa Barbara Earthquake, a shaking table was used in experiments at Caltech, while at Stanford, Professor Lydik Jacobsen, a mechanical engineering professor, at the suggestion of Bailey Willis, geology professor, constructed a machine with a steel platform actuated either by the impact of a heavy pendulum or by a rotating unbalanced flywheel driven by an electric motor. A series of tests was devoted to the sheathing materials used to brace woodframe buildings. ("Experimental Study of the Dynamic Behavior of Models of Timber Walls Subjected to an Impulsive, Horizontal, Ground Vibration," BSSA,Vol. 20, No. 3, September, 1930, 115-147). At the same time in Japan, Kyoji Suyehiro and Kotaro Sato of the University of Tokyo's Earthquake Research Institute also chose wooden residential construction for their first shake table tests because of the importance of earthquake-resistant housing, "and for this reason we have taken up the present problem in precedence of all others." They constructed an analytical model and compared results with their 1.5-meter-tall physical model (Freeman, 732-734,summarizes the report from the *Proceedings of the Imperial Academy*, Vol. VI, 1930, No. 7, 289-292).

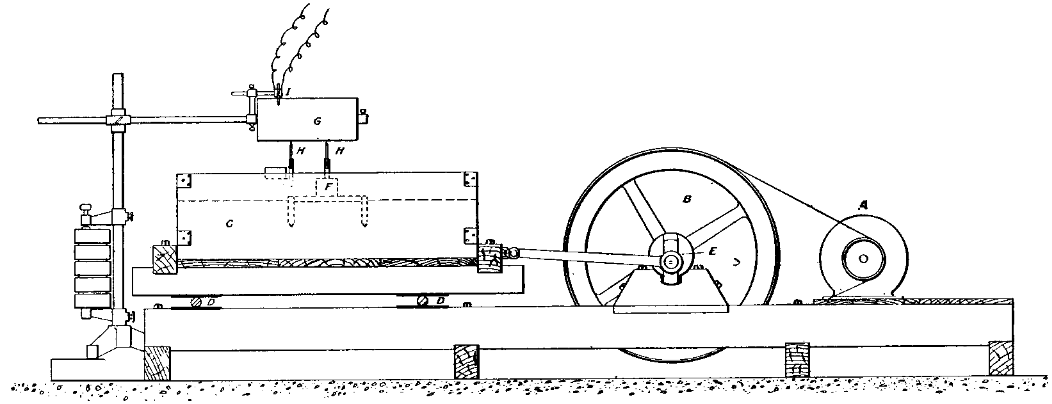


Diagram of F. J. Rogers' shaking machine from "The California Earthquake of April 18, 1906", Vol. I, Part 2, p.327.

The modern shaking table is heavily indebted to the development of computers for control of the electrohydraulic drive apparatus, processing of actual or synthetic earthquake records, and data acquisition and analysis. The UC Berkeley Earthquake Engineering Research Center table that was completed in 1972 represents a dividing line between the first generation of simulators and contemporary machines. The 20-ft. square table at UC Berkeley was called the "medium-scale shaking table" in the original planning study by R. W. Stephen, J. G. Bouwkamp, R. W. Clough, and J. Penzien (*Structural Dynamic Testing Facilities at the University of California, Berkeley*, EERC Report No. 69-8, 1969), because the planned but never funded "large-scale" table was 100 ft. by 100 ft. (with three translational degrees of freedom, 52 hydraulic actuators, and a maximum test structure mass of 4 million pounds). (Penzien, Bouwkamp, Clough, and Rea, *Feasibility Study: Large-Scale Earthquake Simulator Facility*, EERC Report 67-1, 1967). Today, there are five major shake tables in the USA (UC Berkeley, SUNY Buffalo, University of Illinois at Urbana-Champaign, US Army Construction Engineering Research Lab, and UC San Diego) and 14 elsewhere in the world, 12 of which are in Japan. (Earthquake Engineering Research Institute, Assessment of Earthquake Engineering Research and Testing Capabilities in the United States, September 1995).

CUREE

1893: Shaking Table Experiments by Fusakichi Omori and John Milne and the Development of Modern Simulators

Following the Mino-Owari Earthquake of 1891, Professors Fusakichi Omori and John Milne conducted surveys of the falling or fracturing of stone lanterns and similar objects, which led to experiments between 1893 and 1910 with brick columns on a shaking table.

1998

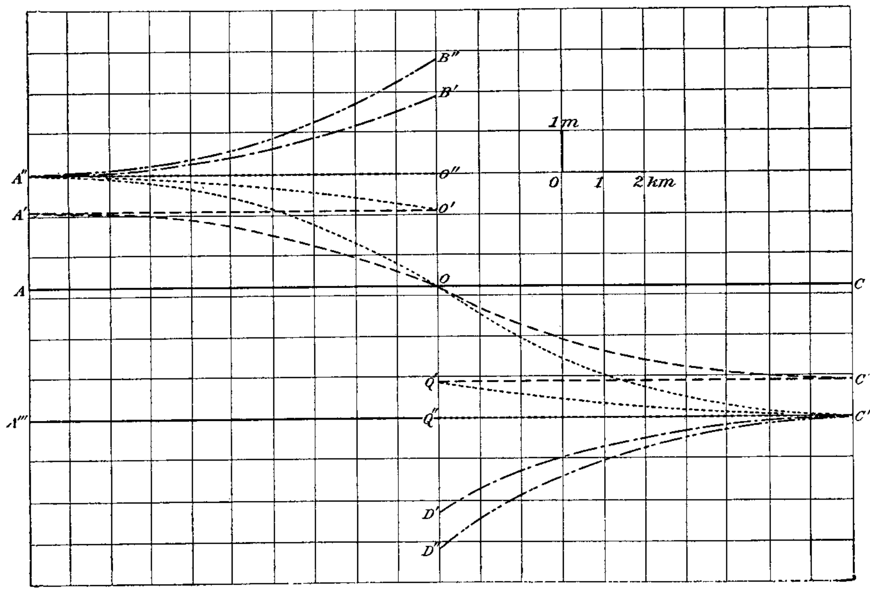
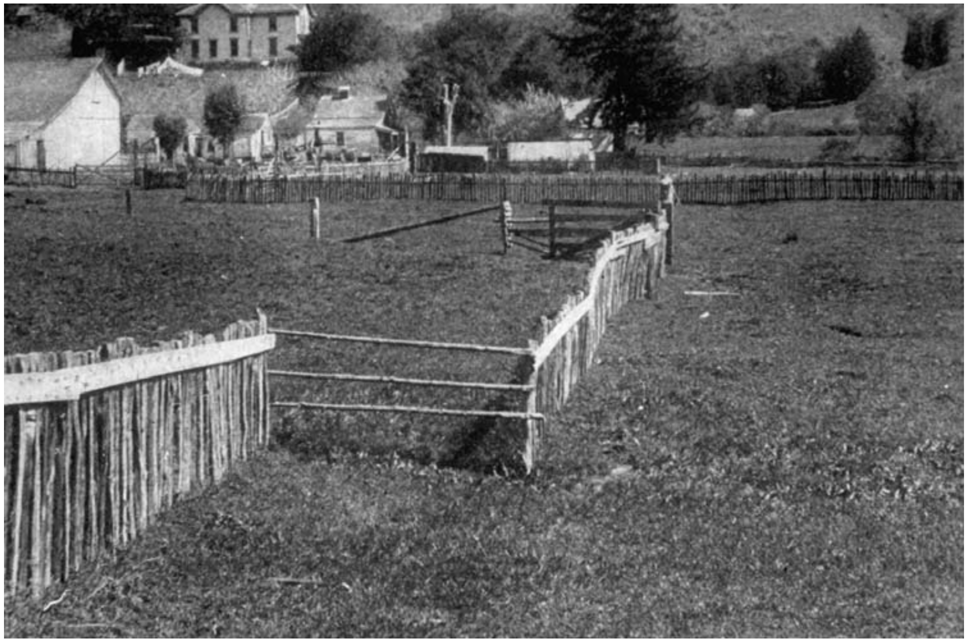


Figure from H. F. Reid's explanation of elastic rebound

"We know that the displacements which took place near the fault-line occurred suddenly, and it is a matter of much interest to determine what was the origin of the forces which could act in this way....external forces must have produced an elastic strain in the region about the fault-line, and the stresses thus induced were the forces which caused the sudden displacements, or elastic rebounds, when the rupture occurred....We can determine the force necessary to hold the two sides together before the rupture, which must exactly have equaled the stress which caused the break....We can also determine the work done at the time of the rupture; it is given by the product of the force per unit area of the fault-plane multiplied by the area of the plane and by half the slip." *(Reid, pp. 18-22, in Lawson, editor, vol. II, 1908).*

The degree to which Reid's theory was innovative is indicated by the fact that only a generation earlier in 1872, the most prominent geologist in California, Josiah Whitney, surveyed the fault scarp of the Owens Valley Earthquake, which had up to 50 feet of offset, and concluded that the earthquake had caused the ground rupture, rather than the other way around. The modern view elucidated by Reid underlies many subsequent developments in the earth sciences in understanding earthquakes, including regional seismic hazard assessments based on long-term strain rates, the concept of moment magnitude, plate tectonic explanations for the concentration of earthquakes at plate boundaries, and source-path-site modeling, which is founded on the fact that the earthquake vibrations emanate from a rupture surface of definable geometry.

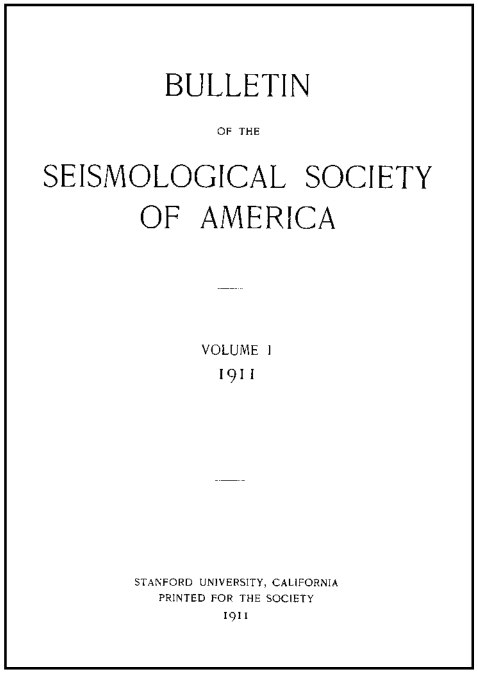


Displacement of the San Andreas Fault in 1906
photo by G. K. Gilbert; Steinbrugge Collection, EERC Library, UC Berkeley

1908: The Elastic Rebound Theory

In Volume II of the *Report of the State Earthquake Investigation Commission on The California Earthquake of April 18, 1906* (Andrew Lawson, ed., published by the Carnegie Institution in 1908), Harry Fielding Reid clearly described the elastic rebound theory whereby strain energy, accumulated in the form of geologic deformation along a fault, is released as vibrational energy by sudden fault slippage.

The first meeting of the thirteen people who formed the Seismological Society of America was held August 30, 1906 in San Francisco. The organization was a direct result of the San Francisco Earthquake that had occurred four months previous. At the Board of Directors meeting on December 15, 1910, the Board decided that the Society should regularly publish a journal, although at that time and for a number of years thereafter, the finances of the organization remained at the margin of stability; only good fortune such as an anonymous contribution of $5,000 from a Harvard geology professor allowed the journal to continue. S.D. Townley was the first *BSSA* editor, aided by J. C. Branner and A. C. Lawson. Townley and Branner were professors at Stanford, and thus Stanford University Press became the publisher.


BULLETIN

OF THE

SEISMOLOGICAL SOCIETY OF AMERICA

VOLUME I

1911

STANFORD UNIVERSITY, CALIFORNIA
PRINTED FOR THE SOCIETY
1911

While today there are dozens of earthquake periodicals, for many decades in the USA this single journal was the publication of choice for authors as well as the single source to which both researchers and practitioners could turn to find the latest information. The term “seismology” in 1911 included “earthquake engineering” within its scope, as is evident from the breadth of topics covered by Andrew C. Lawson’s “Seismology in the United States” article in the first issue. Lawson noted the difficulties under which the first generation of earthquake researchers and practitioners labored: “In the present state of public opinion in California it is impossible to secure state aid for the study of earthquakes....It is believed such discussion will advertise the state as an earthquake region, and so hurt business.”

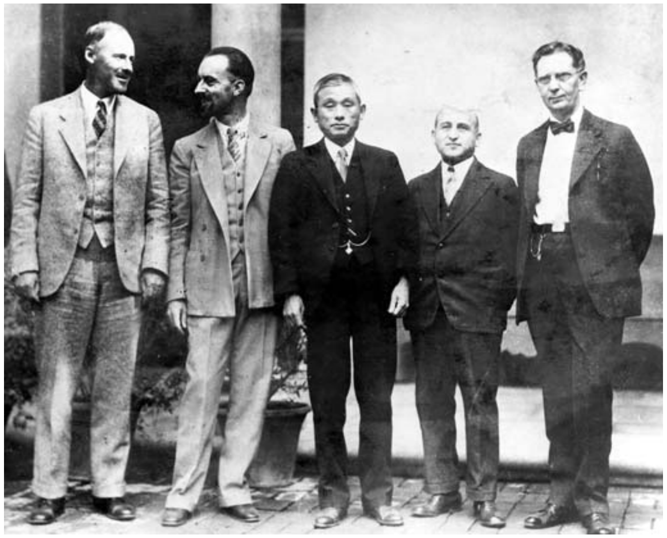
In 1958 when Charles Richter published *Elementary Seismology* (San Francisco: W. H. Freeman and Co.), he included a large amount of material intended for engineers, including chapters on “Earthquake Effects on Buildings and Other Construction,” “Earthquake Risk and Protective Measures,” and an appendix on “Earthquake-Resistant Construction.” Today’s seismology text is more likely to include only a few sidebars on earthquake engineering, and likewise, earthquake engineering texts typically include only passing reference to seismology by way of introduction.

In 1988, C. Allin Cornell in his SSA Presidential Address, “On the Seismology-Engineering Interface,” predicted, “I shall be the last engineer to be President of the SSA. Personally, I hope the future will prove me wrong, but I see at least the following three forces at work reducing the active involvement of engineers in the Society. First, in the last decade, strong motion recording and prediction (both empirically and theoretically) have become interesting to seismologists and geophysicists, gradually relieving the engineers of that responsibility.... Secondly, the evolution of engineering practice away from ‘worst case’ design criteria and the now widespread use by professional earth science firms of probabilistic seismic hazard analysis (with its resulting continuous spectrum of ground motion levels and probabilities) eliminate the previously critical need for engineers to get involved ‘up front’ in the seismic input characterization for a project....Thirdly, and perhaps most significantly, in the last twenty years rapid growth in funding and interest in earthquake engineering research has led to many organizations, conferences, and journals that provide engineers a more specialized forum. “ (BSSA,vol. 78, no. 2, April 1988, 1020-1026).

Among the many papers of historic interest published in BSSA in the early years are “Modified Mercalli Intensity Scale of 1931,” by Harry O. Wood and Frank Neumann (vol. 21, no. 4, December 1931), “An Instrumental Earthquake Magnitude Scale,” by Charles F. Richter (vol. 25, no. 1, January, 1935), and the over 200-page volume containing all the modern elements of a post-earthquake report, “An Engineering Study of the Southern California Earthquake of July 21, 1952 and Its Aftershocks,” by Karl V. Steinbrugge and Donald F. Moran (vol. 44, no. 2B, April, 1954).

1911: The Bulletin of the Seismological Society of America

In the USA, the issuance of the first edition of the *Bulletin of the Seismological Society of America (BSSA)* in 1911 was a significant step toward unifying and developing the embryonic field of earthquake studies. As is the case in many fields, specialization accompanies evolutionary development, and after several decades of serving as the prime US journal of both engineering and earth sciences studies of earthquakes, it began to specialize in the latter.



Kyoji Suyehiro (center) on his lecture tour in the USA with (left to right): John Buwalda, R.R. Martel, Beno Gutenberg, and John Anderson
photo credit: Caltech

Kyoji Suyehiro (1877-1932) was the first Director of the Earthquake Research Institute at the University of Tokyo, which was established in response to the destructive 1923 Kanto or Tokyo Earthquake. The Earthquake Research Institute which Suyehiro directed grew out of the Earthquake Investigation Committee of 1892, established to investigate the October 28, 1891 Mino-Owari Earthquake. Even earlier, following the February 22, 1880 Yokohama Earthquake, the Seismological Society of Japan, the world's first, was founded (T. Usami, "Presidential Address: Future Prospects for Earthquake Engineering," BSSA, Vol.78, no.6, Dec. 1988, 2110-2113). J.A. Ewing, John Milne, C.G. Knott, T.C. Mendenhall, Thomas Gray, John Perry, and William Ayrton were professors in Japan recently arrived from Europe who were active in SSJ. Perry and Ayrton of the Imperial College of Engineering in Tokyo, who wrote a paper in 1879 ("On a Neglected Principle That May Be Employed In Earthquake Measurements," *Phil. Mag*. 8 (46) 30-50) are cited by Donald Hudson as "so far ahead of their time that they scarcely influenced their contemporaries." (D. E. Hudson, "A History of Earthquake Engineering," Proc. IDNDR Int'l Symposium on Earthquake Disaster Reduction Technology, Tsukuba, Japan, 1992, 3-13). Hudson notes that Ewing, Gray, and Milne produced "the world's first true seismographs."

Three pioneering University of Tokyo Japanese professors preceded Suyehiro. Seikei Sekiya produced a wire diagram of the motion of the ground in an 1877 earthquake and occupied the first professorship of seismology from 1886-1897, when he was succeeded by Fusakichi Omori, who with John Milne conducted shaking table experiments and field tests of building vibrations by pulling on them with ropes and winches and rapidly letting go. Following Omori's death two months after the 1923 Kanto Earthquake, Akitune Imamura became Director and investigated the great disaster and studied how local geology affected intensity. Engineering practice was advanced by Riki Sano, author of *Theory of Earthquake Resistant Building* in 1915, a practicing engineer and University of Tokyo professor who studied the 1906 San Francisco Earthquake and was the father-in-law of Dr. Kiyoshi Muto, who was to become famous as an engineering professor at the University of Tokyo and also in his practice with Kajima Corporation. ("Japan Designing Against Disaster," *Mosaic*, National Science Foundation, Nov.-Dec. 1977). Tachu Naito, whose large buildings designed with the then-novel equivalent lateral static force method performed well in the 1923 earthquake, was a professor of architecture at Waseda University and became father-in-law to Takuji Kobori, who is today one of Japan's most senior earthquake engineering experts, a professor at Kyoto University and prominent engineer in Kajima Corporation. Glen Berg ("Historical Review of Earthquakes, Structural Analysis, ASCE, 1976, 387-402) cites the influence of Naito in the USA via his work and writings, such as "Earthquake-Proof Construction," published in BSSA in June, 1927. Suyehiro, a professor of naval architecture at the University of Tokyo, developed concepts of soil-structure interaction and of a characteristic soil period for a given site. (John Freeman, Earthquake Damage, New York: McGraw-Hill, 1932, p.44)

In his 1931 lecture across the USA sponsored by the American Society of Civil Engineers he advocated use of accelerographs to measure the ground shaking in order to rationally devise earthquake-resistant design criteria. (Scientific and Technical Papers, Suyehiro Memorial Committee, Tokyo, 1934, includes his 1931 ASCE lectures.) Along with the advocacy of John Freeman, the new thinking introduced to the United States by Suyehiro helped lead to the installation of accelerographs in the USA in time for the 1933 Long Beach Earthquake.

1926: The Suyehiro Vibration Analyzer

In 1926 Kyoji Suyehiro published "A Seismic Vibration Analyzer and the Records Obtained Therewith" in the *Bulletin of the Earthquake Research Institute*, vol. 1, August, 1926. Suyehiro's instrument consisted of 13 unidirectional oscillators with natural periods of vibration from 0.22 to 1.81 seconds. During an earthquake the displacements of the compound pendulums were recorded on a rotating drum and indicated a response spectrum for very small damping.

John Ripley Freeman was a very bright and energetic engineer who received the BSCE degree from MIT in hydraulic engineering. After graduating he worked for 10 years for Hiram F. Mills, an eminent consulting hydraulic engineer. After 10 years of employment with the Factory Mutual Insurance Company he was appointed President of the Company and served in that position for 36 years. At the same time he served as consultant on numerous projects including the Panama Canal, the Yellow River flooding problem in China, the Los Angeles Owens Valley Aqueduct System, the San Francisco Hetch-Hetchy Water project, the MWD Colorado River aqueduct to Los Angeles, and the water supply system of New York City. Freeman is the only person to have been elected as President of the American Society of Mechanical Engineers (1905) and also of the American Society of Civil Engineers (1922), using the latter position to strongly advocate the establishment of hydraulic laboratories in the US against entrenched political resistance.

John Ripley Freeman
photo credit: Caltech

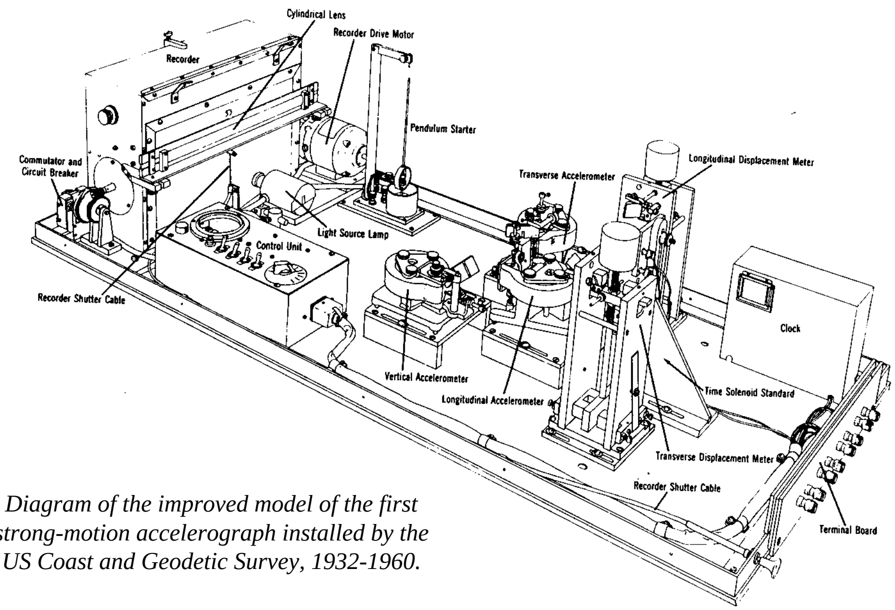


Diagram of the improved model of the first strong-motion accelerograph installed by the US Coast and Geodetic Survey, 1932-1960.

In 1925, at the age of 70, Freeman became interested in earthquake engineering because of the Santa Barbara Earthquake. He visited Japan in 1929 to attend the World Engineering Congress and was disappointed to find no accelerographs. He convinced the Secretary of Commerce of the need for strong motion recordings, who then directed the US Coast and Geodetic Survey to develop and maintain these instruments.

A modification of the Wood-Anderson seismograph was produced and installed in 1932, in time for the March 10, 1933 Long Beach Earthquake. In 1950 it cost $4,000 (about $40,000 in 1998 dollars) to have an instrument maker construct an accelerograph from design drawings provided by the Seismological Field Survey, which was a great deterrent to expanding the network. In 1998 a small portable accelerograph, much better than the original models, can be purchased for about $2,500. In 1932, Freeman wrote the encyclopedic *Earthquake Damage and Earthquake Insurance: Studies of A Rational Basis for Earthquake Insurance, also studies of Engineering Data for Earthquake-Resisting Construction* (New York: McGraw-Hill). In its 904 pages, Freeman summarized the state of the art and went on to recommend shake table research, post-earthquake investigations, international exchanges of researchers, development of improved accelerographs, better communication of seismological and geological findings to the structural engineering profession, introduction of earthquake engineering courses into civil engineering curricula, adoption of seismic provisions in building codes, and many other things we take for granted today.

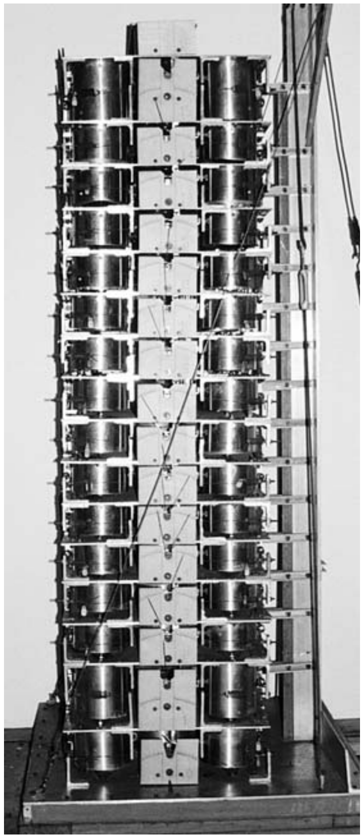
1932: John R. Freeman and the Strong Motion Accelerograph

John R. Freeman (1855-1932) played a key role in the early development of earthquake engineering. He was principally responsible for the development and installation of the first strong motion accelerographs, originally called the Montana Accelerograph, in 1932. He was also instrumental in the establishment of the Seismological Field Survey of the US Coast and Geodetic Survey, which installed and maintained the accelerographs.

Assembly Bill 2342, better known as the Field Act after Don Field, the Glendale, California legislator who introduced the bill, was signed into law as an emergency measure by the Governor on April 10, 1933, exactly a month after the disastrous Long Beach Earthquake. The Field Act mandated seismic requirements for public school buildings and empowered the state's Division of Architecture (now the Division of the State Architect) to carry out the regulations. The legal framework of the act was based on the model of the 1929 State Dam Act, another historic piece of legislation, also motivated by a disaster, in that case the collapse of the St. Francis Dam in 1928 in Southern California. (*Meeting the Earthquake Challenge: The Final Report to the Legislature, State of California, by the Joint Committee on Seismic Safety*, January 1974, Appendix B). Also passed in 1933 after the Long Beach Earthquake was the Riley Act, which required that most buildings in the state except houses be designed for lateral forces, leaving the enforcement up to local jurisdictions. The seismic design provisions that fleshed out the Field and Riley Acts were adapted from work that had been underway in California since the 1925 Santa Barbara Earthquake, including some efforts funded by the California Chamber of Commerce and the 1927 (first edition) Uniform Building Code, which contained optional seismic requirements in an appendix. (Glen Berg, "Historical Review of Earthquakes, Damage, and Building Codes," *Proceedings of the National Structural Engineering Conference: Method of Structural Analysis*, American Society of Engineers, 1976, 387-402). These laws used the equivalent static force procedure then in use in Japan, where in 1924, following the 1923 Kanto or Tokyo Earthquake, a 10% seismic coefficient was adopted in the Tokyo building regulations. This was a codification of the theory of Dr. Riki Sano (and hence the coefficient was referred to at that time as "Sano's coefficient"), which was validated by the good performance in the earthquake of large buildings which were designed by Tachu Naito. (Yukio Otsuki, "Development of Earthquake Building Construction in Japan," *Proceedings of the First World Conference on Earthquake Engineering*, 16-1 - 16-17). The Field Act used a maximum coefficient of 10% (applied to the building's live-plus-dead load) and for most buildings, coefficients in the range of 2% to 5% were applicable, based on soil type (bearing capacity).

Main Street, Compton, California, Long Beach Earthquake of 1933
photo credit: Los Angeles Public Library

In California, "pre-'33" is often used as a synonym for "pre-seismic-code," and all other seismic codes that were later adopted in California and elsewhere in the United States are descendants of the Field and Riley Acts. The engineers in the Division of Architecture began to accumulate a collection of proven construction details for earthquake-resistant buildings (Harry W. Bolin, "Earthquake-Resistant Design for New School Buildings," *Engineering News-Record*, March 18, 1937), and the need for good detailing in addition to accurate structural analysis has remained a basic principle of earthquake engineering to this day. Much higher-than-average plan review and construction quality control requirements also pertained. In the first major test of the Field Act in the 1940 Imperial Valley Earthquake, in which the famous El Centro strong motion accelerogram was recorded, none of the Field Act schools had damage over 1% of construction value, while the non-Field Act schools aggregated a 29% loss. (Donald K. Jephcott, "50-Year Record of Field Act Seismic Building Standards for California Schools," *Spectra*, Earthquake Engineering Research Institute, vol. 2, no. 3, 1986, 621-629). In 1939, the Garrison Act was passed, which incrementally achieved by the 1980s seismic retrofit of any seismically deficient pre-Field Act public school buildings. The historic precedent of the Field Act in the USA is thus twofold: the first enactment of seismic building code regulations, and the first mandatory retrofit program.



The dynamic model of the 15-story Alexander Building, constructed by John Blume and Harry Hesselmeyer.

Source: Helmut Krawinkler

Professor Lydik S. Jacobsen, who became the first President of the Earthquake Engineering Research Institute in 1949, developed Stanford's Vibration Laboratory in the 1930s, which included a field-deployed shaker for structures, built in 1934 by John A. Blume, then a graduate student, and a shaking table. The shaker was used by Blume during 1934 and 1935 for forced-vibration experiments on numerous buildings, dams, and bridges, as well as the ground itself (Coast and Geodetic Survey Special Publication No. 201, *Earthquake Investigations in California 1934-1935*, 1936) A model of a proposed Olympic Club building in San Francisco, the world's first multistory dynamic building model for shaking table experiments, was designed and constructed in 1930 and 1931 by Jacobsen and his students (Jacobsen and Ayre, 1938) In their 1934 thesis under Prof. Jacobsen, "The Reconciliation of the Computed and Observed Periods of Vibration of a Fifteen-Story Building," (the 15-story Alexander Building at the corner of Bush and Montgomery Streets in San Francisco), John Blume and Harry Hesselmeyer tackled enough problems for several theses, including pioneering calculations of fundamental and second mode periods from construction drawings, the effect on rigidity of nonstructural elements and floor system flexure, and the relative importance of cantilever deflection of the building as compared to story shear translation. In a paper for the *Proceedings of the First World Conference on Earthquake Engineering* in 1956, "Period Determinations and Other Earthquake Studies of A Fifteen-Story Building," Blume's subheadings indicate the encyclopedic nature of his work: Building Periods As Originally Recorded (1931), The Original Mathematical Study (1933-1934), Wind Vibration Records (1934), Earthquake Response (1934-1956), Dynamic Model Experiments (1934-1938), Forced Vibration (1935), and some miscellaneous categories taking the reader up to the then present, including doing his original 1930s analyses over again based on the more accurate 1950s state-of-the-art.

Blume has recently related how the dynamic model was built: "This kind of work had never been done before. Having five degrees of freedom per story made it very complex to design and to build. We finally made the model using aluminum plates for the floors, and steel springs for the wall stiffness. For the rotational stiffness about the horizontal axes we provided thin-gauge steel plates resting on aluminum tubing. On top of these steel plates was a steel ball bearing, which allowed the floor to roll. The bending of the steel plate provided the flexibility for overall flexure of the structure." (Stanley Scott, ed., The EERI Oral History Series: John A. Blume, Earthquake Engineering Research Institute, 1994) The model included an additional basement story to allow soil-structure interaction to be simulated.

"A Reserve Energy Technique for the Design and Rating of Structures in the Inelastic Range," (*Proceedings*, *Second World Conference on Earthquake Engineering*, 1960), "An Engineering Intensity Scale for Earthquakes and Other Ground Motion," (*BSSA*, Vol. 60, No. 1, 1970), and *Design of Multistory Reinforced Concrete Buildings for Earthquake Motions*, co-authored with Nathan Newmark and H. L. Corning (Portland Cement Association, 1961) are among his influential contributions, along with numerous studies of ground motion from underground nuclear testing in Nevada. The "gap" problem he identified ("On Instrumental Versus Effective Acceleration and Design Coefficients," *Proceedings of the Second US National Conference on Earthquake Engineering*, 1979) is still a central building code issue being studied and debated by engineers and seismologists.

1934: John A. Blume's Thesis and the Use of Computations, Field Measurements, and Model Testing to Predict Response

In a series of studies beginning in the 1930s, Professor Lydik Jacobsen of Stanford and his student John Blume began to combine a theoretical model of a building, considering such complexities as damping and inelasticity, with field observations of a building's periods and shake table model testing to produce a new level of understanding of building response.

Charles Frances Richter (1900-1985) was a great benefactor to earthquake engineers when he invented the Magnitude Scale, for this gave a relatively consistent method of describing the size of an earthquake and the area covered by strong ground shaking. When Richter first published his magnitude scale in the *Bulletin of the Seismological Society of America* in 1935, its usefulness was not perceived by either engineers or seismologists, and it was not until after 1950 that its value began to be appreciated. His brilliant idea came to him when he read a paper in a European journal which commented on the peculiarities of earthquakes in the Southwestern United States. It said that the large, destructive Long Beach earthquake of 1933 wrote a small record in Europe whereas the small, nondestructive Nevada earthquake of 1932 wrote a large record. Richter said that the author had it backwards, for the earthquake that wrote a larger record must be a bigger earthquake. Actually, the Long Beach earthquake rated M6.3 and the Nevada earthquake rated M7.3 on the scale that Richter subsequently developed. Undoubtedly, now every earthquake engineer in the world understands Richter's magnitude scale and uses it for making hazard assessments, and many know his 768-page book published in 1958, *Elementary Seismology*. (San Francisco: W. H. Freeman.)

Richter was Professor of Seismology at the California Institute of Technology, where he became a faculty member in October of 1930, but he also had a great interest in astronomy. It occurred to him that just as astronomers rank stars according to their magnitudes one could rank earthquakes similarly. The magnitude of a star is ranked according to the intensity of the light waves it sends forth, and the earthquake is ranked according to the intensity of seismic waves it sends forth, assuming that the recording seismograph is at a large distance compared to the length of the slipped fault so it can be viewed as effectively a point source; both are on a logarithmic scale. This enables one to compare the sizes of different earthquakes, estimate slipped length of fault from seismograms (for example, from the seismograms recorded during the 1964 Alaska earthquake, M8.4, we know that the slipped length of fault must have been 400 or more miles), and the seismicity of a region is described by the historical frequency of occurrence of earthquakes of various magnitudes. The foregoing are indications of how useful the concept of earthquake magnitude is.

As a person, Charles Richter was a sort of seismological curmudgeon and was quite outspoken in his criticism. In a paper he published in *BSSA* in 1977 he said, "Journalists and the general public rush to any suggestion of earthquake prediction like hogs toward a full trough. Prediction provides a happy hunting ground for amateurs, cranks, and outright publicity-seeking fakers. The vaporings of such people are from time to time seized upon by the news media who then encroach on the time of men who are occupied in serious research. Earthquake prediction is a particular annoyance to earthquake engineers, and it is still causing problems. Trying to get rid of earthquake prediction is like trying to kill a snake by chopping off its head and finding that the two parts then immediately grow back together again."

Charles F. Richter with the seismograph he operated in his living room.

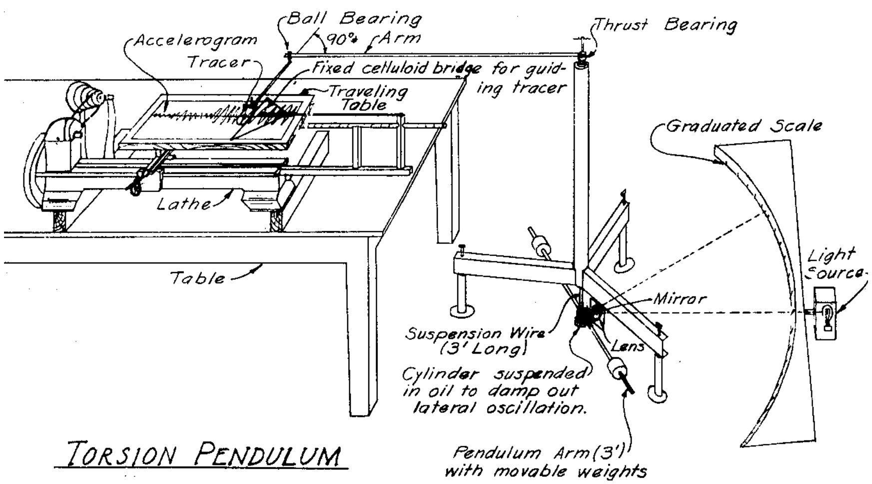
Source: Caltech

1935: The Magnitude Scale

A paper was published in the January, 1935 issue of the *Bulletin of the Seismological Society of America*, titled "An Instrumental Earthquake Magnitude Scale," by Charles F. Richter. The first sentence read: "In the course of historical or statistical study of earthquakes in any given region it is frequently desirable to have a scale for rating these shocks in terms of their original energy, independently of the effects which may be produced at any particular point of observation."

The Earthquake Response Spectrum and the Earthquake Design Spectrum have had a far-reaching influence on seismic design of structures. “It is important to recognize the distinction between a design spectrum...and a response spectrum....The jagged response spectrum is a plot of the maximum response of different oscillators to a given accelerogram, and hence, is a description of a particular ground motion. The smooth design spectrum, however, is a specification of the level of seismic design force, or displacement, as a function of natural period of vibration and damping level...the level of force prescribed by a design spectrum is to be associated with a specified level of material resistance, for example the allowable design stresses or strains. The resultant effect is, thus, a specification of the required earthquake resistance of the structure and its elements. If the material resistance is stated in terms of allowable stresses, the design spectrum is a specification of the strength of the structure; if the material resistance is expressed in terms of permissible ductile strains, the design spectrum becomes a specification of the capacity of the structure to deform, that is, the ductility it must have.” (Housner and Jennings, 1982, 58-61).

The 1933 Long Beach Earthquake provided the first recorded accelerograms of earthquake ground motions, and following that earthquake, efforts were made at California Institute of Technology to calculate the response spectrum from accelerograms. At this time, several professors at Caltech were discussing the problem of calculating dynamic seismic response: R. R. Martel (civil engineering), T. von Karman (aeronautics), H. Benioff (seismology), and M. A. Biot (aeronautics). George Housner obtained his M.S.C.E. in 1934 under Prof. Martel, then left Caltech for several years to work as a practicing engineer, later to return and obtain his Ph.D. in 1941 on this subject. The great difficulty was the very large amount of labor required to calculate the response of a single oscillator. The first attempt was with a hand-cranked mechanical calculator; the second attempt was to do it graphically; the third attempt was to do it with a torsion-pendulum analog, pictured here; the fourth attempt was using a special electric-analog computer; and the fifth attempt was using the large IBM digital computer in the 1970s. Over these years the time required to calculate a single response spectrum curve went from several months to less than one minute, and now with modern computers and programs it is possible to compute five different spectrum curves for various amounts of damping in just a fraction of a minute. The advent of nuclear electric power facilities in the 1960s and the high degree of safety required for them made it necessary for many structural engineers to learn about the response spectrum, design spectrum, and dynamic analysis, and this knowledge gradually diffused into the practice of earthquake engineering. Now, every earthquake engineer knows about these matters.



The torsion pendulum spectrum analyzer,
reproduced from George Housner's 1941 Ph.D. thesis.

Selected References

H. Benioff, “The Physical Evaluation of Seismic Destructiveness,” Bulletin of the Seismological Society of America, vol. 24, 1934, 398-403.

M.A. Biot, “Theory of Elastic Systems Under Transient Loading With An Application To Earthquake Proof Buildings,” Proceedings of the National Academy of Sciences, vol, 19, 1933, 262-268.

George Housner, “Calculating the Response of an Oscillator to Arbitrary Ground Motion,” Bulletin of the Seismological Soc. of America, vol 31, 1941, 143-149, contained along with other papers in Selected Earthquake Engineering Papers of George W. Housner, New York: American Society of Civil Engineers, 1990.

George Housner and Paul Jennings, Earthquake Design Criteria, Oakland, CA: Earthquake Engineering Research Institute, 1982.

Donald E. Hudson, “A History of Earthquake Engineering,” Proceedings of the IDNDR International Symposium on Earthquake Disaster Reduction Technology, Tsukuba, Japan, 1992, 3-13.

1941: Calculation of the Earthquake Response Spectrum

Professor George Housner at Caltech, beginning with his Ph.D. thesis in 1941, began publishing calculations of response spectra from accelerograms. The response spectrum computed from an accelerogram is an informative way of assessing the impact of ground motion on vibrating structures. The design spectrum specifies the level of seismic design force or displacement as a function of natural period of vibration of the structure and its damping level.

The one-volume *Proceedings of the World Conference on Earthquake Engineering* (Earthquake Engineering Research Institute and UC Berkeley, 1956) does not self-consciously refer to the "First" World Conference, though that is the historic precedent the1956 conference set. The growth in the field of earthquake engineering has been mirrored by the growth in the size of the WCEE events and proceedings, with the last event's proceedings, 11WCEE in Mexico, distributed only via compact disc because of the number of papers (over 2,000), while the *10WCEE Proceedings* had over 7,000 pages. The *Proceedings* of the first World Conference were distributed by the Secretary of EERI, Karl Steinbrugge, who kept boxes of the volumes under drafting tables at his office at the Pacific Fire Rating Bureau (later Insurance Services Office). The price was $8.50, which included postage. While the events and proceedings of the following World Conferences grew greatly in size, they have remained true to the original type: State-of-the-art or overview papers by leading experts from countries around the world are presented along with papers on more detailed topics, and although the field has matured, it has kept the sense of purpose from its early days that was articulated in the Preface to the 1WCEE *Proceedings* by EERI President George Housner: "Bringing together the scientists and engineers from major seismic areas of the world in order that their knowledge of earthquakes and developments in the science and art of earthquake resistant design and construction might be pooled for the benefit of all mankind." The organizing committee for the 1WCEE was Rube W. Binder, John A. Blume, William K. Cloud, Ray W. Clough, Henry J. Degenkolb, C. Martin Duke, A. L. Miller, H. C. Powers, and John E. Rinne.

World Conference on Earthquake Engineering

1WCEE, 1956:	Berkeley, USA
2WCEE, 1960:	Tokyo and Kyoto, Japan
3WCEE, 1965:	Auckland and Wellington, New Zealand
4WCEE, 1969:	Santiago, Chile
5WCEE, 1974:	Rome, Italy
6WCEE, 1977:	New Delhi, India
7WCEE, 1980:	Istanbul, Turkey
8WCEE, 1984:	San Francisco, USA
9WCEE, 1988:	Toko and Kyoto, Japan
10WCEE, 1992:	Madrid, Spain
11WCEE, 1996:	Acapulco, Mexico
12WCEE, 2000:	Auckland, New Zealand
13WCEE, 2004:	Vancouver, Canada

Participants in the First World Conference on Earthquake Engineering on the steps of Wheeler Hall at the University of California at Berkeley.
- Source: Earthquake Engineering Research Institute

Key organizational events preceding the 1WCEE include the founding of the Seismological Society of Japan in 1880, Seismological Society of Italy in 1895, and Seismological Society of America in 1907; the First Pacific Science Congress held in Honolulu in 1920 and initiatives of its Section of Seismology and Volcanology, and the World Engineering Congress held in Tokyo in 1929; the establishment of the Earthquake Research Institute of the University of Tokyo in 1926 and the Earthquake Engineering Research Institute in the USA in 1949.

CUREE

1956: The First World Conference on Earthquake Engineering

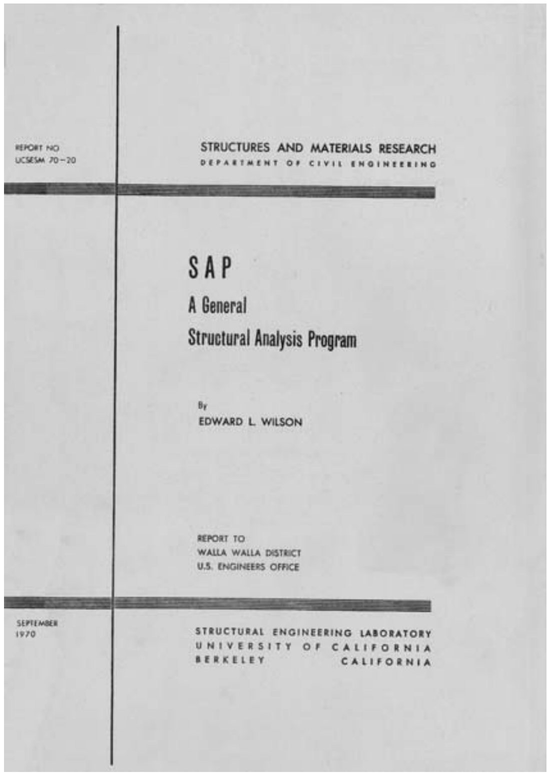
Fifty years after the 1906 San Francisco Earthquake, the First World Conference on Earthquake Engineering was held at the University of California at Berkeley, the first of the 11 World Conferences held to date. The conference was a major activity in the development of the Earthquake Engineering Research Institute, which was established in 1949.

1998

When John Freeman wrote *Earthquake Damage* in 1932, summarizing the earthquake engineering state of knowledge at that time, the word "computer" appeared on none of his book's 904 pages. After World War II and prior to the 1970s in earthquake engineering, the use of computers was rare and largely confined to university research. Even in the mid 1970s, desktop computers had not yet materialized and pocket calculators roughly equivalent to today's $20 models cost about $300 in today's dollars.

While SAP and other structural analysis software is applied to non-seismic as well as seismic analysis problems, it can be argued that modern computer programs and the ubiquitous desktop computers they run on are more essential for the latter—perhaps roughly quantified by saying they are more than twice as essential for earthquake analysis work: A seismic structural analysis must analyze the structure under both seismic and gravity loading, and often for several different earthquakes, rather than only for gravity; in addition, the transient dynamic loads of an earthquake are also more challenging to calculate than static gravity loads.

Edward L. Wilson wrote in the foreword to his *SAP: A General Structural Analysis Program* "Many computer programs for the analysis of large complex structures have been developed during the past several years. Each of these programs represents the result of large expenditures of energy and money. One of these programs required approximately 75 man-years and two million dollars before completion; however, the resulting program does not have modern structural elements and is not particularly efficient in operation. Also it is partially machine dependent. The computer program represented in this report is the result of over 10 years of research and development experience. However, the basic computer code was developed in a three-month period by a few engineers. In the past several months additional structural elements and a dynamic option have been added. The total development effort of the computer code to date has been approximately two man-years. In my opinion, however, the resulting program is one of the most powerful and efficient programs for the linear elastic analysis of complex structural systems that has been developed to date. Nevertheless, I am sure it will be obsolete within five years." As of 1998, the current generation of structural analysis software, although quite different from the original 1970 SAP, with the ability to import CAD drawings for model generation and advanced modeling and numerical features that are only possible in recent times, is evidence of the continuous evolution, rather than obsolescence, of the first version. Today, the researcher or practicing engineer can choose from a number of commercial and university-developed structural analysis programs that run efficiently on personal computers. Computers are also used in geotechnical engineering for site response analysis and in the field of engineering seismology to analyze site-specific seismic hazard and to simulate ground motions.



Cover of SAP - A General Structral Analysis Program

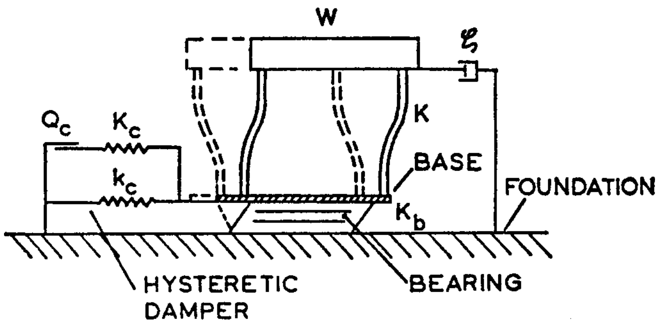
Wilson closed the foreword to his 1970 report by saying, "The slang name SAP was selected to remind the user that this program, like all computer programs, lacks intelligence. It is the responsibility of the engineer to idealize the structure correctly and assume responsibility for the results." John Blume made a similar comment on the effect of computers on earthquake engineering a few years later: "The more we use computers, the more precise we have to be in our criteria and instructions. We use less judgment in design today because (a) we rely more on computers; (b) because new generations brought up on computers may have less judgment to exercise (the reason for this being that judgment is not required so much and therefore is less developed); and (c) because society through its legal structure and current practice is making it risky to rely too much upon judgment where there are other means." ("An Overview of the State-of-the-Art in Earthquake Resistant Reinforced Concrete Building Construction in the United States of America," *Workshop on Earthquake-Resistant Reinforced Concrete Building Construction*, UC Berkeley, July 11-15, 1977, 119-137).

CUREE

1970: Edward L. Wilson's Development of SAP and the Growth of Modern Computer Programs for Structural Analysis

In 1970, Edward L. Wilson produced, "SAP: A General Structural Analysis Program." This program, continually under development and in use since then, is representative of the major importance computer analysis has played in the earthquake engineering field.

1998



Model of a Structure with Base Isolation.
illustration credit: Earthquake Engineering and Structural Dynamics (Skinner, Beck, and Bycroft, 1975.)

In 1974, R. Ivan Skinner, James L. Beck, and G. N. Bycroft submitted “A Practical System for Isolating Structures From Earthquake Attack” to *Earthquake Engineering and Structural Dynamics*, (published in vol. 3, no. 3, January-March 1975). Since then such systems have indeed become practical, if not also widespread. In conjunction with research on rubber-steel "sandwich" bearings, tests were made on other kinds of damping devices (R. I. Skinner, J. M. Kelly and A. J. Heine,"Energy Absorption Devices for Earthquake-Resistant Structures," *Proceedings of the 5th World Conference on Earthquake Engineering*, Rome, Italy, 1974). Earlier, Ivan Skinner's research on isolation extended back to the 1960's. Ian Buckle and Ronald Mayes noted in their paper on “Seismic Isolation: History, Application, and Performance—A World View” in the Seismic Isolation Theme Issue of the EERI *Spectra* journal (vol. 6, no. 2, May 1990), that there are three essential elements to “a practical base isolation system. These are: 1) A flexible mounting so that the period of vibration of the total system is lengthened sufficiently to reduce the force response; 2) A damper or energy dissipator so that the relative deflections between the building and ground can be controlled to a practical design level; 3) A means of providing rigidity under low (service) load levels such as wind and minor earthquakes.”

Prof. James Kelly (“Seismic Base Isolation: Review and Bibliography,” *Soil Dynamics and Earthquake Engineering*, vol. 5, 1986, 202-216) provides a survey of the early history of isolation inventions, approximately 100 schemes having been published or patented prior to 1960, though almost all remained only ideas on paper. One of the earliest concepts that was actually built was the room that John Milne, professor of geology and mining at the Imperial College of Engineering in Tokyo, erected next to his house in Japan in the 1880s. It “rested on pillar foundations but had a layer of cast-iron shot placed between the iron plates.” (A. L. Herbert-Gustar and P. A. Nott, *John Milne: Father of Modern Seismology*, Tenterden, England, Norbury Publications, 1980, p. 90) It has been claimed that the original Imperial Hotel in Tokyo, designed by Frank Lloyd Wright, performed brilliantly in the 1923 Tokyo Earthquake because it was a base isolated design, but in fact it had a relatively traditional spread footing foundation and also suffered more damage than larger neighboring buildings. (R. Reitherman, "The Seismic Legend of the Imperial Hotel," *AIA Journal*, June 1980). Non-engineers have also often mistakenly assumed that the Transamerica Pyramid in San Francisco is mounted on ball bearings, teflon, or some other kind of isolators, whereas actually it is sunk in the earth like a fence post, its sub-grade base made up of a three-story basement and a three-meter-thick reinforced concrete mat. (R. M. Stephen, J. P . Hollings, J. G. Bouwkamp, *Dynamic Behavior of a Multistory Pyramid-Shaped Building*, UC Berkeley EERC Report No. 73-17, 1974).

The William Clayton Buidling, Wellington, New Zealand, the first seismically isolated building of the modern era, designed in the 1970's and constructed in 1982.

photo credit: Ian D. Aiken

Buckle and Mayes counted slightly over 100 seismically isolated structures in the world in 1990. There are now 427 isolated buildings constructed or under construction just in Japan, with 225 building permits issued in 1996 alone. (M. Miyazaki and K. Saiki, “Current Trends of Isolated Buildings in Japan After 1995 Kobe Earthquake,’ *Int'l Post-SMiRT Conf. Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control*, Taormina, Italy, 1997) Seismic isolation has helped plant the seeds for other response control devices (e.g., active and passive control technologies), which, like isolation, are based on the strategy of reducing demand rather than increasing capacity.

1975: Seismic Isolation Design and Technology in New Zealand

The concept of isolating a structure from the shaking of the ground had long appealed to the imagination of inventors, but only in the mid-1970's in New Zealand did the elements of modern seismic isolation technology come together: quantitative ground motion and structural response criteria which could be met by a technology that reliably produced the necessary de-coupling of the structure from the foundation, increased damping, and shifting of periods of vibration.