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75th anniversary of strong motion observation—A historical review

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ABSTRACT

This review describes the experience accumulated in the field of recording earthquake motions up to the early 1900s, and then it discusses the key players who contributed to the first successful strong motion observation program in earthquake engineering in the 1930s. It begins by summarizing the accomplishments of the preceding seismological observations, which provided the stepping-stone ideas on how to construct the first strong motion accelerograph. Next, it describes the lack of optimism among the engineers in the early 1900s, who doubted that structural response could ever be calculated for irregular earthquake ground motion—this was, of course, half a century before the appearance of fast digital computers—but also their realization that something needed to be done to reduce the hazards from earthquakes. The roles of the two pioneers Kyoji Suyehiro and John Freeman, whose vision, leadership, and perseverance launched the strong motion observation program in 1932, are then briefly discussed. Finally, the mechanical characteristics of the first strong motion accelerograph are outlined. The review is completed by illustrating the growth of the strong motion observation programs in selected seismic areas of the world and the fruits of these programs—the cumulative number of uniformly processed strong motion records in southern California.

Contents

Strong motion accelerograms properly interpreted are the nearest thing to scientific truth in earthquake engineering. [1]

1. Introduction

In the context of its contemporary theoretical foundation (the Response Spectrum Method—RSM) and of its experimental and observational basis (strong motion recordings in epicentral regions of destructive earthquakes), modern earthquake engineering was born 75 years ago, in 1932 and 1933. Biot [2–6]

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introduced the concept of the response spectrum in June 1932, and 9 months later, on March 10, 1933, the first strong motion accelerogram was recorded, during the Long Beach, California Earthquake ($M_L = 6.3$; e.g., [7]). A review of the theoretical work that led to the development of the RSM concept has been addressed elsewhere [8]. Here, we examine the factors that contributed to the establishment of the strong motion observation program in the Western United States, thus initiating the development of the experimental basis for earthquake engineering. Our aim is to explain and illustrate the interaction between the goals of early 1900s society, which recognized the need to reduce the hazards associated with devastating earthquakes, and the accumulated knowledge in the related field of observational seismology, the difficulties faced by engineers in the age before digital computers, and the vision and energy of two pioneers of earthquake engineering (Suyehiro and Freeman), who organized and motivated others to carry out the work, thus creating the foundations of modern earthquake engineering. Their story is inspiring and shows how much an individual could accomplish then, before the time of present complexities, peer reviews, and research agenda often set by funding agencies rather than by the individual researchers.

Now established, recognized, and 75 years old, the strong motion observational branch of seismology, which deals with the recording of strong earthquake shaking, has again focused a significant portion of seismological observations on the proximity of the earthquake source, where research started almost 2000 years ago and stayed until the late 1800s. It was only after the development of modern and highly sensitive instruments toward the end of the 19th century that teleseismic observations could be initiated, opening possibilities of studying the Earth's interior in terms of the inverse theory based on earthquake waves and in terms of amplitudes and wavelengths, which are outside the realm of what is directly related to earthquake engineering. Thus, the development of strong motion instruments in the early 1930s for the purpose of characterizing the nature of near-source strong ground motion and their use in the engineering design of earthquake-resistant structures has brought us back to the subject of near earthquake shaking.

2. Evolution of seismometry

The desire to understand earthquake phenomena is as old as the classical civilizations [9], but it took many years for quantitative measurements to replace myths and folklore and for strong motion instruments to reach their present state of the development.

2.1. Seismoscopes

Possibly the oldest instrument for detection of strong motion is almost 1900 years old. In 136 AD, the Chinese scientist Chôko (also referred to as Chang Heng and Tyoko) designed a seismoscope that indicated the direction of a strong motion pulse by the tipping a vertical cylinder [10]. The falling cylinder, or some kind of a pendulum [11,12], would cause a ball to be released from the mouth of a dragon into the mouth of a waiting frog (Fig. 1). Depending upon the design, there were six or more dragon and frog pairs arranged in a circle, and it was assumed that the earthquake originated from the direction behind the dragon that dropped the ball.

In the early 1700s, Europeans believed that earthquakes were caused by explosions within the earth, and they tried to design earthquake-detecting instruments to respond to tilting rather than to horizontal wave motion. A bowl filled with mercury, for example, was used by de la Haute Feuille in 1703 to determine the direction of the shock [13–15]. The aim was also to predict strong earthquakes by detecting the small earthquakes that were assumed to precede the large ones.

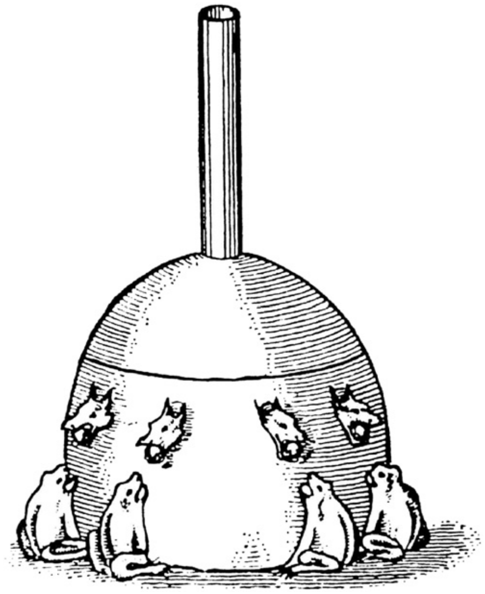


Fig. 1. Dragon seismoscope developed by Chinese philosopher/scientist Chôko in 136 A.D.

The first use of a pendulum to record earthquake motions appears to have occurred in Naples during a sequence of earthquakes in 1731 [16]. In one design by Bina, the pointer attached to the pendulum was used to record the movements in a tray of fine sand [17]. In 1783, after the devastating Calabrian earthquakes, the first "Earthquake Commission" was appointed to study the earthquake's effects. Liquid-filled containers and various metastable blocks were used for detection of the direction of the first strong motion [13,15]. The Calabrian disaster was followed by many other attempts to design more advanced instruments. In 1783, Salsano designed a *geo-sismometro*, a pendulum with a brush and ink, which recorded on an ivory slab. This pendulum may have responded to some earthquakes 300 km away and was equipped with a bell, which would ring when the motions were large. In 1785, Cavalli modified de la Haute Feuille's bowl filled with mercury by adding rotating platforms with cavities corresponding to hours and minutes. When the bowl filled with mercury would overflow during an earthquake into the cavities, it would show the hour and the minute of the earthquake. Then, in 1796, Duca della Torre added a hair to the pendulum of a *sismografo*. When the pendulum moved, the hair would start a clock [13].

During the New Madrid earthquakes of 1811 and 1812, Daniel Drake of Cincinatti, Ohio reported on "an instrument constructed on the principle of that used in Naples, at the time of the memorable Calabrian earthquake." This instrument "marked the direction of undulations from south–southwest to north–northeast" [18].

In 1839, a series of small earthquakes in Comrie, Scotland led to the establishment of a Special Committee of the British Association for Advancement of Science to develop instruments and to record earthquakes [19]. An instrument that resulted from this effort was described by Forbes [20]. A pencil on the top of an inverted pendulum wrote on a paper-lined spherical dome. The design of this pendulum was physically analogous to Wiechert's [21,22] inverted pendulum, which was constructed more than half a century later, in 1900, as well as to modern seismoscopes that would be used in engineering studies of strong motion a century later [23,24].

To measure velocities of elastic waves in surface rocks generated by explosions, Mallet [25,26] designed a seismoscope in which the image of a cross-hairs, reflected from the surface of mercury, would become blurred by arrival of the disturbance. This work was later continued by Abbot [27] and others, who used similar instruments.

Mallet also made use of fallen objects and the distribution of cracks in buildings to interpret earthquake effects [28]. He assumed that earthquake waves produced compression followed by dilatation, which would create transverse cracks in the buildings relative to the direction of wave arrival. This assumption was later shown to be invalid when seismometers capable of recording horizontal components of ground motion were built and when large transverse horizontal motions were recorded [29]. Milne and Omori [30] calculated accelerations necessary to overturn columns and blocks and verified their calculations experimentally. Omori then applied their results to interpret overturned gravestones in the epicentral region of the Mino-Owari earthquake of 1891 in Japan and found accelerations in excess of 0.4*g* [31].

To study the frequency content of earthquake waves, Cavalleri [32] used six pendulums with different periods and recorded their motion in fine powder. He assumed that the range of frequencies between two and four cycles per second was adequate to "embrace every undulation occasioned by any earthquake." He also assumed that the predominant period of earthquake motion would resonate with one of the pendulums showing larger amplitudes than the other pendulums. Possibly one of the first attempts to use multiple pendulums of different lengths (periods) to study earthquake motions was made by Brooks, from Louisville, Kentucky, to observe the New Madrid earthquakes of 1811 and 1812 [18]. A century later, the same approach was used by Suyehiro [33]. Cloud and Hudson [34] note that the Suyehiro's instrument "can be thought of as a direct way of measuring the earthquake response spectrum. It is perhaps unfortunate that at the time the Seismic Vibration Analyzer was developed the full implications of the device were not generally realized, and the advantages of the instrument were never fully exploited." Cloud and Hudson do not cite the studies of Brooks or Cavalleri, but *mutates mutandis* their comment applies to essentially all mechanical vibration analyzers consisting of multiple pendulums that were developed before 1932, when the concept of the RSM was introduced.

An instrument operating on the same principle as a mechanical vibration analyzer was also constructed in the late 1930s by the US Coast and Geodetic Survey (USC&GS), but the details for its application were never worked out [35]. A description of multi-pendulum instruments—AIS-1, which had two groups of pendulums recording in two mutually orthogonal horizontal directions; AIS-2, which had multiple spherical pendulums; and AIS-2p, a portable version of AIS-2—can be found in Nazarov [36]. AIS-2p consisted of four pendulums recording horizontal motion ($T = 0.15$, 0.30, 0.60, and 0.9 s) and three pendulums recording vertical motion ($T = 0.075$, 0.15, and 0.30 s). A multiple-pendulum recorder (the Structural Response Recorder or SRR) consisting of six pendulums having three sets of periods ($T = 0.40$, 0.75, and 1.25 s) and two sets of damping values (0.05 and 0.10 of critical) was also constructed in India [37,38].

An instrument designed to give the direction, intensity, and duration of an earthquake, the *seismografo-elettro-magnetico*, was designed in 1856 by Palmieri. It had a collection of "seismoscopes," each intended to record different parameters of an earthquake [39]. Threshold motions were detected by closing the horizontal and vertical gaps, which would close the electrical circuit, stop the clock, and show the time of the earthquake. Palmieri's *seismografo* was used to monitor volcanic tremors on Mount Vesuvius and in the nearby city of Naples, and it was also used for ten years in Japan [40]. After the development of true seismographs, Palmieri's circuit-closing system was often used as a triggering device to start the recording system of other instruments [41].

2.2. Seismographs

The first seismograph appeared in Italy in 1875 [42,43]. It had three pendulums to record NS, EW, and vertical motions, a device to measure rotations, and a magnification factor of about three. It recorded a large earthquake on the French-Italian border in 1887 [44].

In Japan, the work of British professors Milne, Ewing, and Gray contributed to the further development of seismographs and to their introduction into observational research in seismology [15,45]. Ewing's first seismograph employed a 21-foot-long pendulum, had a 5-s natural period, and magnified ground motion six times [46]. Ewing was also the first to successfully use a horizontal pendulum to record earthquake motions [47,48]. Both instruments recorded an earthquake in November 1980, giving the first long seismograph records of earthquake motion versus time [40]. Based on theoretical considerations, Perry and Ayrton [49] recommended the use of viscously damped pendulums. Gray [50] and Milne [51] intentionally used heavily damped seismometers, but as far as we know they employed solid friction only.

The next important development occurred in Europe as a result of the recognition that sensitive instruments could be constructed to record earthquake waves from events around the world. Up to the late 1800s, the instruments could record only local earthquakes. Their magnification was typically only up to one order of magnitude, and most recording systems could accommodate only relatively short records. The first successful seismographs [43,44,52,53] were thus in many respects closer to the instruments used in modern strong motion and engineering seismology than to the modern sensitive seismographs that would become essential tools for seismological research in the 20th century.

One of the first recordings of a distant earthquake was made in 1889 with a horizontal pendulum designed to measure small tilt [54]. Von Rebeur-Paschewitz also used the first photographic system for continuous recording, and encountered problems similar to those that persisted through many later designs, and that are common in most analog accelerographs recording on film [55,56]. In Italy, Agamennone and Cancani made improvements to the long, common-pendulum seismometer [57], and Cancani [58] and Oldham [59] presented detailed studies and interpretations of teleseismic waves.

In 1898, Wiechert introduced viscous damping of the pendulum [21], using the resistance of air in a piston and cylinder to provide the damping. It could be controlled by a valve that regulated the air going in and out of the piston. Wiechert's first seismograph used a horizontal pendulum and photographic recording, and his second seismograph was designed as an inverted pendulum, had a mass of 1000 kg and mechanical magnification of 200, and recorded on smoked paper.

Electromagnetic seismographs were introduced by Galitzin [60], who wrote a comprehensive treatise on the theory of electromagnetic recording [61]. Many strong motion recording systems in buildings in the former Soviet Union, especially those with central recording systems and multiple sensors, used such electromagnetic systems [62].

Forbes [20] published one of the first mathematical theories of a seismograph subjected to non-oscillatory ground motion, and the theory of seismograph response to arbitrary ground motion was presented by Perry and Ayrton [49]. Poincaré [63] and Lippman [64] wrote the early notes on how to integrate seismograms to compute ground displacements. Further contributions to the subject of calculating ground displacements from recorded seismograms started to appear a decade later [65–68].

The contribution of ground tilting to recorded seismograms was debated at length during late 19th century [58,65,69] before the introduction of seismoghaphs capable of recording vertical ground motion. Later experiments with the seismograms of vertical ground motion showed that the role of ground tilting in linear-wave motion is usually small. Galitzin [70], who doubted the conclusions based on those experiments, formulated the theory of transducer response when subjected simultaneously to tilts and displacements. However, he found this theory so complicated that he was forced to neglect the effects of tilts [66]. It took another half century before the complete theory and a quantitative description of the relative role of three translations and three rotations acting simultaneously on a simple transducer were published [71,72].

Thus, by the early 1900s all of the elements of the theory and the design of transducers, recording systems, and triggering devices were developed and published in the seismological literature. However, it would take another thirty years for the first strong motion accelerographs to be built and for the first strong earthquake ground motion recordings to be made. It took this long because of the doubts among the leading engineers that it was even possible to conquer the difficult tasks of computing and analyzing the response of structures to strong ground motion. Then it would take an additional four decades (until the early 1970s) before the engineers would start to use dynamic response analysis in design.

3. Engineering education in early 1900s

The teaching of engineering mechanics and applied mathematics started to expand in Europe toward end of 19th and the beginning of 20th centuries [73–75], but at most universities in the early 1900s engineering curricula did not include advanced mathematics and mechanics, which are essential for teaching analysis of the dynamic response of structures. This deficiency in theoretical preparation is reflected in the often-cited view of C. Derleth [76], civil engineering professor and Dean of the College of Engineering at the University of California, Berkeley, who commented after the 1906 San Francisco earthquake that while earthquake stresses in framed structures could be calculated, "such calculations lead to no practical conclusions of value".

In 1938, when G. Housner approached his advisor R. Martel about doing Ph.D. research in earthquake engineering, Martel responded

> Well, that is a very interesting subject, but I don't know if it will ever amount to anything. We have tried and tried to get things done but it has been very difficult to get anything accomplished; people seem not to be interested in the earthquake problem [77].

A comment by Ruge [78], the first professor of engineering seismology at the Massachusetts Institute of Technology, that "the natural tendency of the average design engineer is to throw up his hands at the thought of making any dynamical analysis at all," further shows that the progress was slow [79].

Such views, however, started to change gradually toward the end of the 1920s. In 1929, at the University of Michigan in Ann Arbor, the first lectures were organized at the Summer School of Mechanics by S. Timoshenko (1878–1972) [73], with the participation of A. Nádai, R.V. Southwell, and H.M. Westergaard. "After the first session of the summer school in 1929, the number of doctoral students in mechanics…started rapidly to increase".

4. Seismic coefficient and design codes

Several earthquake disasters in densely populated areas in the early 20th century showed that defensive mechanisms needed to be developed to prevent future loss of life and property from destructive earthquakes. The first steps, which initiated the engineering work on the design of earthquake-resistant structures, are associated with the introduction of the *seismic coefficient* and started to appear following the destructive earthquakes in San Francisco, California in 1906, Messina-Reggio, Italy in 1908 [80], and Tokyo, Japan in 1923. The first seismic design code was introduced in Japan in 1924, and Suyehiro [81] describes the use of the "static load of the intensity given by the mass of the building multiplied by the horizontal acceleration of the seismic vibration." In New Zealand, Ford [82] wrote one of the earliest books in English on seismic engineering. In California, work on earthquake code development started in 1920s, but it was not until after the Long Beach earthquake in 1933 that the Field Act was finally adopted in 1934.

Benioff [83] comments on the seismic coefficient method in the introduction to his paper on seismic destructiveness as follows: "…engineers have been forced to proceed on an empirical basis. From past experience…it has been found that buildings, which are designed to withstand a constant horizontal acceleration of 0.1 gravity are, on the whole, fairly resistant to seismic damage…. We know that seismic motions do not exhibit constant accelerations; that instead they are made up of exceedingly variable oscillatory movements. A formula based upon constant acceleration may thus lead to large errors, especially when applied to new types of structures, which have not been tested in actual earthquakes."

In California, work on developing building design codes began after the Santa Barbara earthquake of 1925 [84], and in 1927 the "Palo Alto Code," developed with the advice of Professors Willis and Marx of Stanford University, was adopted in the California cities of Palo Alto, San Bernardino, Sacramento, Santa Barbara, Klamath, and Alhambra. It specified the use of a horizontal force equivalent to 0.1, 0.15, and 0.2g acceleration on hard, intermediate, and soft ground, respectively.

"Provisions Against Earthquake Stresses," contained in the *Proposed US Pacific Coast Uniform Building Code*, was prepared by the Pacific Coast Building Officials Conference and adopted at its 6th Annual Meeting in October 1927, but these provisions were not generally incorporated into municipal building laws [84]. The code recommended the use of horizontal force equivalent to 0.075, 0.075, and 0.10 g acceleration on hard, intermediate, and soft ground, respectively. Following the 1933 Long Beach earthquake, the Field Act was implemented, and Los Angeles and many other cities adopted an 8 percent g base shear coefficient for buildings and a 10 percent g for school buildings. In 1943, the Los Angeles Code was changed to indirectly take into account the natural period of vibration. The reader can find a brief review of modern code development in the paper by Freeman [85].

5. Two pioneers—Kyoji Suyehiro and John Freeman

In 1929, during an engineering conference in Tokyo, John Freeman met Prof. Kyoji Suyehiro, was impressed with his research in earthquake engineering, and invited him to come to America and give lectures. Suyehiro accepted the invitation, and in the fall of 1931 he traveled to the United States and presented a series of lectures on engineering seismology [81] (Fig. 2). The lectures were given at Berkeley, Stanford, Caltech, and M.I.T and were very successful. Suyehiro's third lecture (III), entitled "Vibration of Buildings in an Earthquake," was of particular interest for earthquake engineering, and it seems that the term "engineering seismology"—*Jishin Kogaku*—was first used at this time [86]. In the lectures, which were subsequently published in the Transactions of the ASCE, Suyehiro emphasized the importance of recording strong earthquake motion, both on ground and in structures, and described the measurements carried out at the Earthquake Research Institute of Tokyo University. He recommended development and deployment of strong motion instruments and suggested that the Wood-Anderson seismometer, which had been designed in 1921 at the Carnegie Seismological Laboratory in Pasadena, California [87], could be modified for this purpose [88].

5.1. Suyehiro

Kyoji Suyehiro (1877–1932) was a member of the Japanese Imperial Academy and Professor of Applied Mechanics at Tokyo Imperial University. After the Tokyo earthquake of 1923, when the Japanese government set up the Earthquake Research Institute at Tokyo University, Kyoji Suyehiro was appointed its first director. By training he was a ship-building engineer, but he had mastered some of the most intricate aspects of earthquake engineering through careful study, observation, and analysis.

Suyehiro's work on his multi-pendulum recorder [33] is sometimes cited as being the first appearance of the idea of representing earthquake excitation by a response spectrum ([89, p. 24]). However, as we have already noted, such multi-pendulum recorders had been used as early as 1811 by Brooks to observe the New Madrid earthquakes [18] and in 1860 by Cavalleri to study the frequency content of earthquake waves. Suyehiro [81] refers to his multi-pendulum recorder as a "seismic vibration analyzer," and he describes the record at Hongo and how that site has a natural period of about 0.3 s. Suyehiro's aim was to analyze the periodic content in the recorded motion, as is done in general with vibration analyzers (Fig. 3). Post facto, the recordings of Brooks, Cavalleri, Suyehiro, and others can be viewed as mechanical means of measuring the Response Envelope Spectra [90], but at the time—well before the concept of the RSM was introduced in 1932—these authors considered their instruments only in the context of seismic vibration analysis.

In his third lecture, Suyehiro [81] discussed the response and the observed damage of "rigid," "medium rigid," and "weak" buildings situated on "soft" (loose clay) and "rock" ground. He explained how the "rigid" building "moved as a rigid body on the ground-bed" and suffered little or no damage. In contrast, the "weak" buildings on "rock" ground were either damaged or destroyed. Searching for an explanation, Suyehiro states that "very probably the primary cause is the yielding of the ground-bed due to oscillation of the foundation…." He concluded that "such cushioning action of the ground at the time of an earthquake may serve more or less to relieve the destructive action of a strong earthquake in the case of masonry [i.e., rigid] buildings." These remarkable observations have been confirmed many times by earthquake damage patterns seen since 1932, and the recent observations of damage following the Northridge, California earthquake of 1994 are no exception. Readers may peruse the papers by Trifunac and Todorovska [91,92] to see how insightful and meaningful were Suyehiro's comments 62 years prior to the Northridge earthquake. Suyehiro also describes microtremor measurements performed by Professor Ishimoto in 1929 at the Earthquake Research Institute, both in the building and on the adjacent ground (see Fig. 55 on page 91 of Suyehiro's lectures).

In Fig. 57 (p. 93), Suyehiro [81] shows the records of an earthquake on November 26, 1930, taken on the roof and at ground level adjacent to the Earthquake Research Institute Building. After about 7 s of recording, this record goes off scale. From the similarity of the recorded motions at the roof and on the ground, Suyehiro concludes that the relative

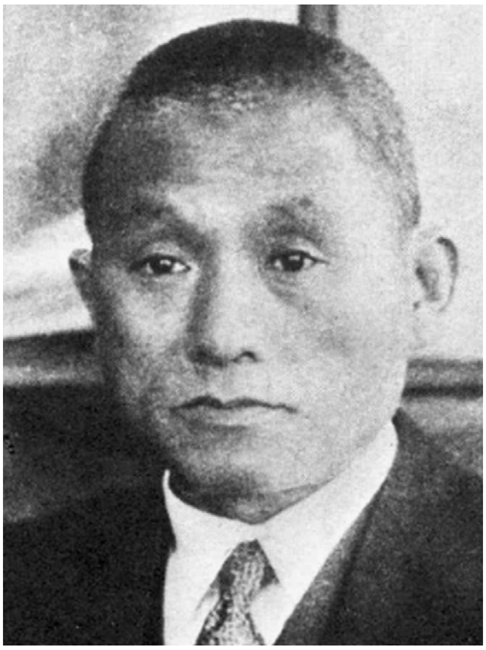


Fig. 2. Kyoji Suyehiro (1877–1932).

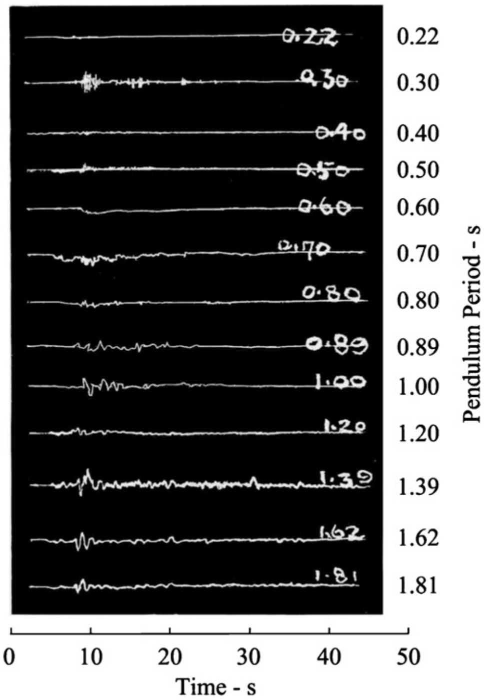


Fig. 3. Record from Suyehiro's seismic vibration analyzer (redrawn from Freeman [84]).

deformation of the building was small: "From these facts, it can be inferred that the dynamic stress induced in a strongly constructed rigid building by an earthquake is likely to be equal to the static stress which would be induced, had the building been subjected to the static load of the intensity given by the mass of the building multiplied by the horizontal acceleration of the seismic vibration." These and two other examples of vibrations caused by earthquakes (in the Marounochi Building, Fig. 59 on page 96, and in Yurakukan Building, Fig. 60 on page 97 of Suyehiro [81] appear to be the first full-scale records of building motions caused by earthquakes.

It is interesting to read how Suyehiro describes the scattering of short waves from a "rigid" foundation and the resulting averaging (smoothing) action of the foundation. "According to observations made by Professor Imamura on the vibration of the Diet Building during construction, some very rapid ripples, having a period of about 0.1 s, disappeared in the motion of the foundation although the foundation moved about as much as the neighboring ground."

Professor Ishimoto's investigation of the velocity of ripples on the ground is very useful in this connection. According to him, "...on the surface of the ground where our Institute building stands, the P-wave has a velocity of above 120 m. per sec. And the S-wave about 65 m. per sec. Therefore, very probably, the wavelength of ripples having a period of 0.1 s, is between 6.5 to 12.0 m.; hence, they are less than the linear dimensions of the building. Consequently, a building on soft ground is not sensitive to those quick and short ripples. It may also be mentioned that this fact may be attributed to a certain extent to another behavior of the vibration of soft ground, in which the amplitude of the component of a seismic vibration of very short period decreases quickly with depth. Therefore, foundations at some depth below the surface will be less affected by the rapid components of seismic vibrations."

In his published lectures, Suyehiro does not use the modern term "soil-structure interaction," but it is obvious that that is in fact one of the topics of his lecture III. Of course, from today's viewpoint, his observations were intuitive and for the most part qualitative, but his insight and ability to interpret observations were remarkable.

Perusal of Suyehiro's lectures will show his keen awareness that the motion of ground and of structures must be recorded before one can begin to understand the nature and the consequences of strong earthquake shaking. Suyehiro and his colleagues at ERI did record the weak earthquake motions in 1929 and 1930 before he came to America to lecture, but it was not until March 10, 1933, during Long Beach earthquake in California, that the first *strong* motion was recorded. It is interesting that Suyehiro's ideas and recommendations would lead to success, only a year after his death in 1932, in America, while it would be almost two decades before Japan actively started to build strong motion accelerographs, in early 1950s.

5.2. Freeman

John Ripley Freeman (1855–1932) (Fig. 4), an American civil and hydraulic engineer who received his undergraduate degree from the Massachusetts Institute of Technology in 1876, was born in West Brighton, Maine. He is noted for his efforts to design and build the Charles River Dam, advising the government on dam and lock foundations for the Panama Canal, consulting on the Hetch-Hetchy water project for the City of San Francisco and the silting of the Yangtse River in China, and for his influence on the design of the new MIT campus. Freeman served on the National Advisory Board on Aeronautics during World War I and was founder and

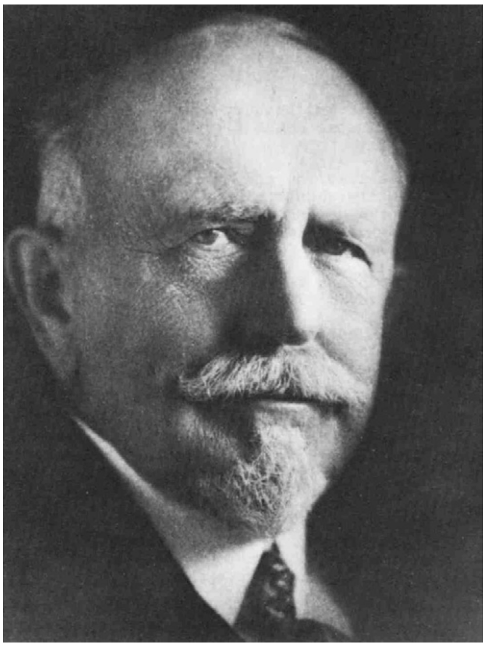


Fig. 4. John Ripley Freeman (1855–1932).

president of the Massachusetts Mutual Fire Insurance Company, where he did research on the hydraulics of fire hoses and the design of fire nozzles. He served as president of both the American Society of Mechanical Engineers and the American Society of Civil Engineers. He also influenced the US Army Corps of Engineers to set up a laboratory for hydraulics research, and he lobbied Congress for appropriations, which resulted in the eventual establishment of a laboratory in Vicksburg, Mississippi. Today, this laboratory is well known as the US Army Engineer Waterways Experiment Station. He also endowed scholarships for young engineers to go to Europe for a year to study at the hydraulics laboratories there.

Freeman became interested in earthquakes at the age of 70, following the Santa Barbara, California earthquake of 1925 and an earthquake in Quebec, Canada, also in 1925, which was felt in Boston area, where Freeman lived. Having examined the contemporary books on structural engineering, he found only three that mentioned earthquakes forces, and he concluded that the subject was in "real bad shape" ([84], p. 709).

To learn about earthquakes, and to document all he could gather at the time, Freeman wrote a book entitled *Earthquake Damage and Earthquake Insurance*, which was published in 1932 by McGraw-Hill. In this book, he emphasized the need to develop and deploy accelerographs to measure strong earthquake ground motion, and he described the characteristics such accelerographs should have (e.g., they should record on a continuous belt of paper that moves about one centimeter per second). In Japan, Freeman saw a tiltmeter and Suyehiro's vibration analyzer, both of which impressed him, and subsequently he bought a tiltmeter for monitoring earthquake precursors and convinced the USC&GS to build a multi-pendulum Mechanical Vibration Analyzer [35].

Freeman [84] gives the expanded title of his 904-page-long book as *Studies of a Rational Basis for Earthquake Insurance and Studies of Engineering Data for Earthquake-Resisting Construction.* Detailed commentary on this fascinating book is beyond the scope of this review, but it provides a wealth of information and shows Freeman's exceptional ability to present data and observations clearly and unambiguously and with a rare physical insight.

Freeman corresponded extensively with N.H. Heck, the chief seismologist at the USC&GS [93]; Captain Patton, who was in charge of the USC&GS; Mr. Lamont, the Secretary of Commerce; R.R. Martel, Professor of Civil Engineering at Caltech; and occasionally with President Herbert Hoover. He emphasized to all of them the need for doing something about earthquakes. The following excerpts from a letter Freeman wrote in January 1930 to Martel [77] illustrates this: "… in America no particular study has been given to effects within the epicentral area or within the area of damage to structures, all of their [seismological] studies in considering their elastic waves commonly begin a hundred miles or more away from this disturbed area, and with their instruments for nearby study all set on solid rock and of such great delicacy as to be utterly incapable of reproducing the effects in a destructive earthquake; on the other hand the Japanese were concentrating their efforts within epicentral areas and to the territory within which buildings had been injured".

In his efforts to disseminate the methods for earthquake-resistant design, which were then evolving in Japan, Freeman distributed partial copies of translations from the book written by Naito on earthquake-resisting structures. He asked Martel to contribute to the introduction of the translation of Naito's book: "…try your hand at writing a preliminary introductory chapter to this book, making plain that it is not forbidding or incomprehensible, as quick turning of the pages might lead the ordinary non-mathematical prodigy of an engineer to suspect." Freeman wrote to Martel about having lunch in Pasadena with Prof. and Mrs. Millikan, making it plain that "the engineer could hope for little from the geophysical organization" and stating, "I urged that we got to arouse research on the practical side, particularly among the engineering schools of California…." Freeman also describes his discussions with H. Wood at the Seismological Laboratory, for whom he outlined the situation "as I had found it in Japan, and asked if it were not in some way practicable to interest the geological laboratory and the Carnegie Institute on the practical side of the field." When Wood said that the research funds were limited, Freeman concluded that "we must seek funds from those engaged in the structural arts."

After his visit to the Bureau of Standards in Washington, where he met Burgess and Wenner, Freeman informed Martel that he had "urged the importance of an instrument which would measure accurately the vertical motion which accompanies the horizontal motion, and which Suyehiro seemed to think played an important part in overturning moments." In another letter, Freeman said, "I think we're making headway, I am getting a letter from Captain Patton almost every day." Freeman "kept after the USC&GS until the accelerograph was developed" [77].

6. First strong-motion accelerograph

The strong motion instrumentation program in America started in 1931 as a result of the personal efforts of Freeman and a few other engineers and businessmen who were impressed with the advances in the design of earthquake-resistant structures in Japan and who recognized that further progress could not be made without recording the destructive earthquake shaking. With Suyehiro's lectures providing technical background and ideas, and with Freeman's vision and persistence, Federal aid was enlisted, and Congress approved funds for the USC&GS to start the program. N.H. Heck described the opinion held at the time:

> The chief purpose of the work is for the benefit of engineers and architects. It has been felt that they should say what they want, and the general consensus of opinion obtained from them is that recording should start at a point where slight damage begins and that such records should have sufficient amplitude for interpretation. The upper limit should be the recording of acceleration for as wide a range as the design of the instruments permits, and the upper bound should exceed 0.2 the acceleration of gravity. The information desired includes the acceleration, the period, and the amplitude of ground motion [94].

The work on the development of the first accelerograph was a cooperative venture, carried out at the USC&GS, the National Bureau of Standards, MIT, and the University of Virginia.

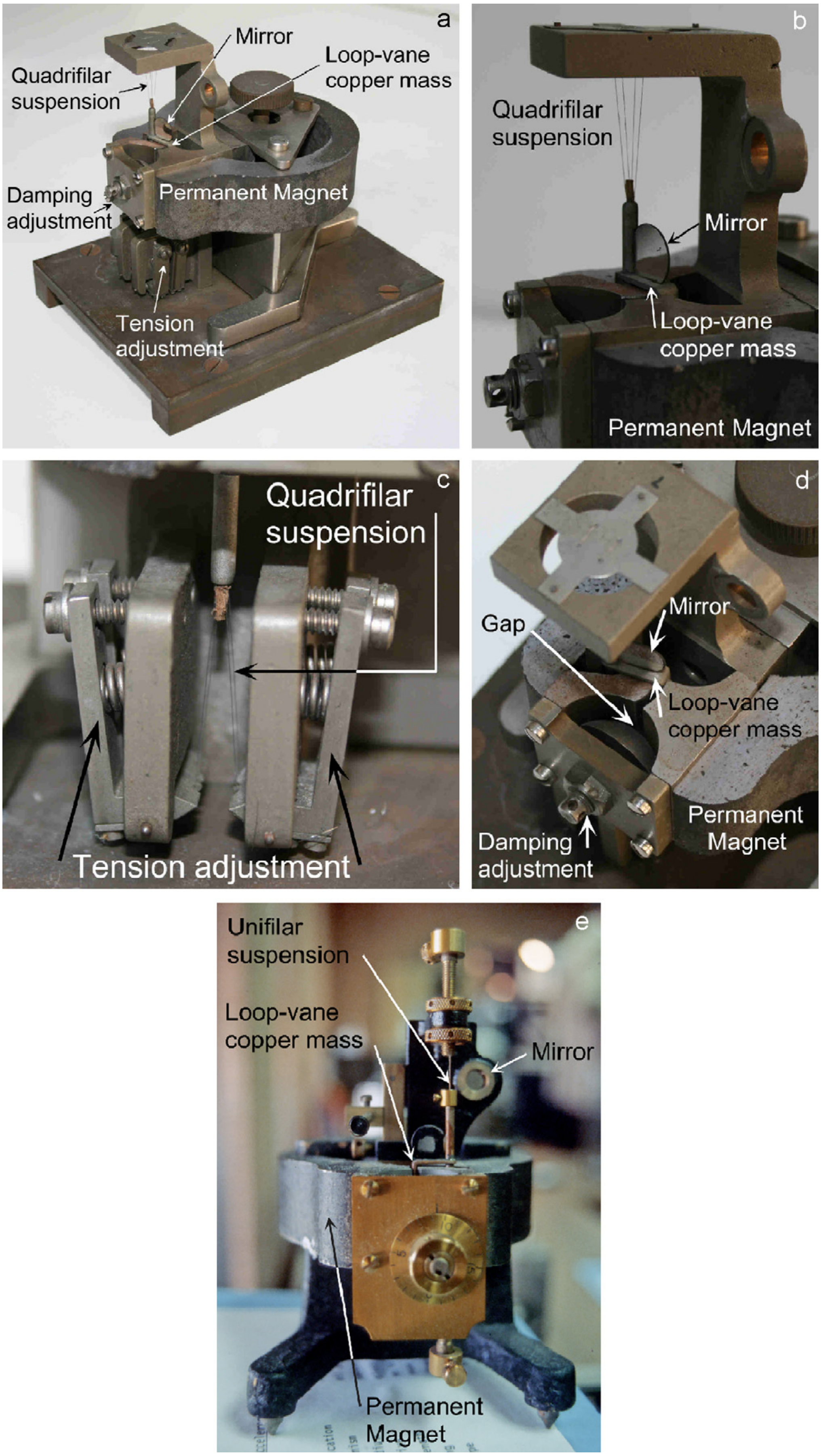
Wenner [95], at the Bureau of Standards, designed a transducer that was based on the principles used in the Wood–Anderson torsional seismometer, developed in 1921 [87]. It had a natural frequency of 10 Hz, or somewhat less, a mass of 4 g, and it consisted of a loop-vane copper mass supported by quadrifilar suspension (Fig. 5a–c, and Fig. 1 in [95]. Quadrifilar suspension provided lateral stiffness, which essentially eliminated excitation of higher mode shapes of the transducer mass and its suspension system, but which also made it difficult to adjust equal tension in all four wires (Fig. 5c) in field conditions. The mass would move through a field created by the permanent magnet, which provided viscous damping, critical or less, as desired. The damping was adjusted by changing the gap between the permanent magnet and a large hemispherical head of a screw opposite the gap in the permanent magnet (Fig. 5d). With the recording paper at a distance of 50 cm from the transducer mirror, the trace moved approximately 4 cm, for an acceleration of 0.2*g*.

The quadrifilar suspension was abandoned in 1933 because of the difficulties in adjusting the four wires to equal tension. It was replaced by a pivot and spring stabilized suspension (see Fig. 2 in [96], and Fig. 3 in [97]). The pivot suspension was later also abandoned because its zero position shifted during earthquakes [94]. In 1947, the pivot suspension was replaced by a unifilar torsional wire (Fig. 5e).

The first recording system (Fig. 6b), designed at the USC&GS, was a drum holding 6-inch-wide photographic paper. The drum, which was designed by D.L. Parkhurst, H.E. McComb, and E.C. Robison, was translated along a screw to separate the recorded traces. The speed of drum rotation was set so as to produce a record with a speed of 1 cm/s. A clock operated a flag to interrupt the light beam at 0.5-s intervals to record time, which appeared on the record as a dashed straight line. The recording drum was later replaced by a 12-inch-wide paper magazine and a take-up roll mechanism [88] (Fig. 6c).

The first starters were designed by M.W. Braunlich at MIT and consisted of undamped, inverted pendulums with electrical contacts at each end (Fig. 7). A pair of starters, oriented in two orthogonal horizontal directions, was used in the first strong motion accelerograph (see Fig. 1 in [96], and Fig. 1 in [97]) and in the Weed seismograph (see Fig. 5 in [96]). No starters sensitive to vertical motion were used. The Braunlich starters were sensitive to extraneous vibrations and malfunctions and were eventually replaced by a vertical pendulum starter designed by H.E. McComb (Fig. 6b, c, and Fig. 8). With minor modifications, the McComb starter (Fig. 6.8 in [98]) was used for many years, up to the early 1960s, and in the first commercially produced AR-240 strong motion accelerograph. It was sensitive to tilt, and on a few occasions produced long, continuous records, until the photographic paper supply would be spent (e.g., [99,100]). Its starting sensitivity decreased with the period of the triggering pulse (Fig. 6.9 in [98]), and its overall field performance was very good.

Because the primary recording was made of ground acceleration (with neither digital nor analog computers being available at the time), it was clear from the beginning of the strong motion program that it would be very difficult to compute ground displacements from the recorded accelerograms. To solve this


a
Mirror
Quadrifilar suspension
Loop-vane copper mass
Damping adjustment
Permanent Magnet
Tension adjustment
b
Quadrifilar suspension
Mirror
Loop-vane copper mass
Permanent Magnet
c
Quadrifilar suspension
Tension adjustment
d
Gap
Mirror
Loop-vane copper mass
Permanent Magnet
Damping adjustment
e
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Loop-vane copper mass
Mirror
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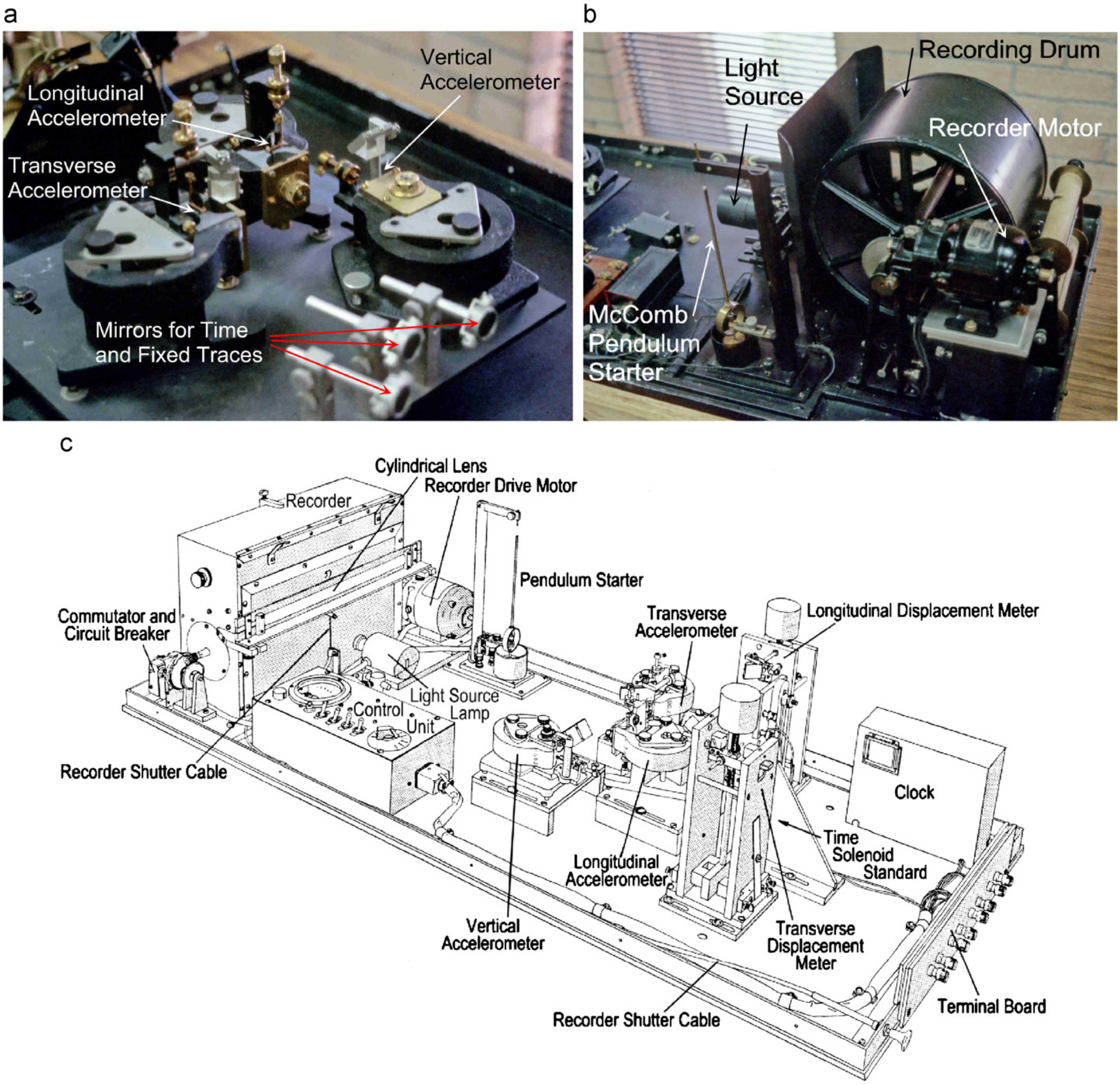


Fig. 6. (a) Placement of three transducers in the original USC&GS strong motion accelerograph, to record longitudinal, transverse, and vertical motions. (b) Light source, recording drum for 6-inch wide photo paper, and the vertical pendulum starter in the original USC&GS strong motion accelerograph. (c) USC&GS accelerograph (later model) equipped with a 12-inch-wide paper magazine, an McComb pendulum starter, and two "displacement" meters. The distance from accelerometer mirrors to photo paper was about 1 m.

problem, long-period displacement meters were constructed at USC&GS with two horizontal pendulums, unit magnification, and 10-s natural periods. The damping was by vanes moving in oil, and registration was photographic (see Figs. 3 and 4 in [96]). Later, smaller displacement meters—inverted pendulums—with a 5-s natural period were designed by D.S. Carder and added to the standard USC&GS accelerograph in 1950s (Fig. 6c and Fig. 9). Then, after the introduction of the first commercially built strong motion accelerograph (the AR-240), the appearance of digital computers in the early 1960s, and the development of digital data processing of strong motion accelerographs [101], the use of displacement meters was discontinued.

Fig. 5. (a) Wenner strong motion acceleration transducer with quadrifilar suspension. (b) Top quadrifilar suspension of a horizontal accelerometer, and eccentric mirror, mounted on the loop-vane transducer mass to record its torsional deflections. (c) Bottom quadrifilar suspension of a horizontal accelerometer, and four independent screws for adjusting tension in the four wires. (d) Damping in the Wenner accelerometer was achieved by moving the copper loop-vane in the magnetic field. The strength of the field, and the fraction of critical damping, was adjusted by moving a hemi-spherical metal piece closer or further from the permanent magnet. (e) Wenner strong motion transducer with unifilar suspension.

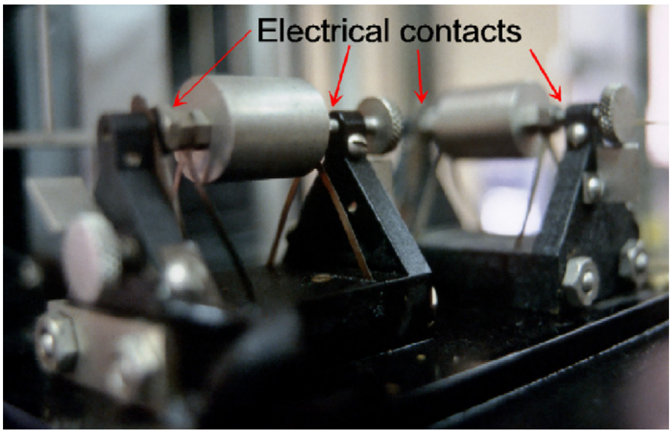


Fig. 7. Braunlich starters.

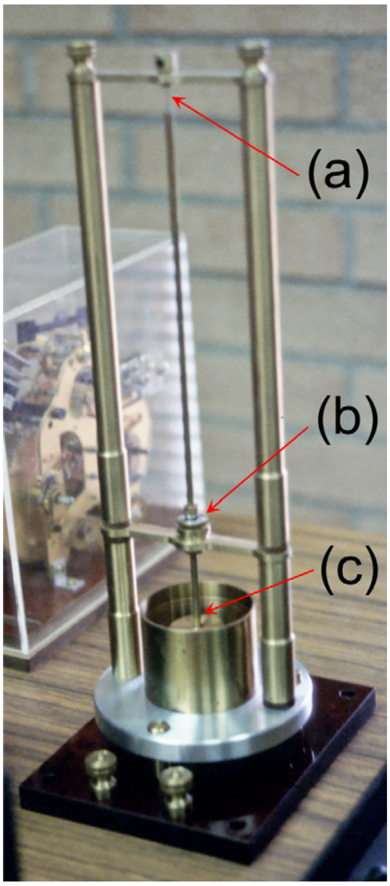


Fig. 8. McComb pendulum starter: (a) suspension wire, (b) platinum cup-and-cone contacts (spacing 0.05 cm), and (c) oil damping (S.A.E. 10).

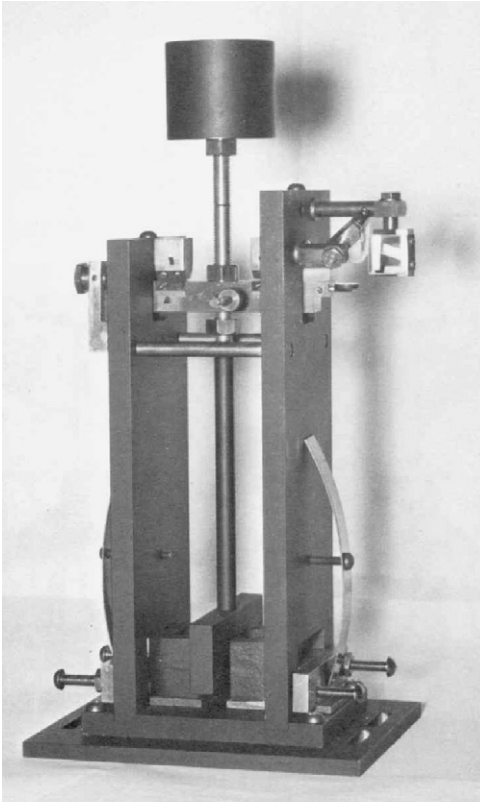


Fig. 9. Carder displacement meter used in USC&GS accelerograph.

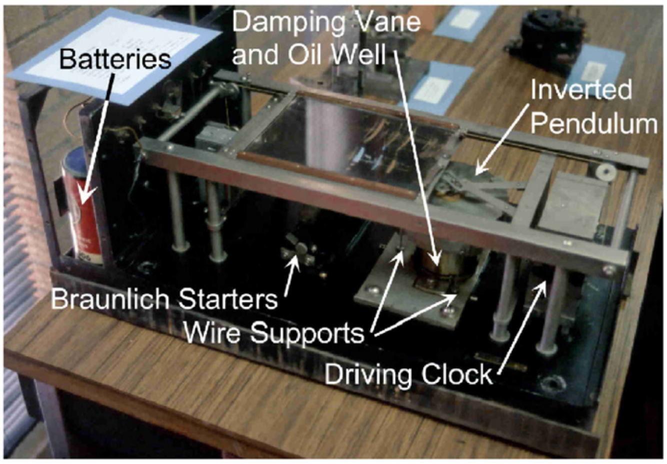
With digital data processing, it became possible to compute displacements from carefully corrected digitized accelerograms [102]. By the early 1960s, the standard USC&GS strong motion instrument was phased out and replaced by more compact designs, which first recorded on light-sensitive paper (AR-240) and then on 70-mm (SMA-1) or 35-mm film (MO-2) [88]. Carder displacement meters (Fig. 9) played an important role in (1) the assessment of the useable frequency band of strong motion accelerographs, (2) the provision of an independent information source that could be used to better describe the signal-to-noise ratio in the digitization of older accelerograms recorded on light-sensitive paper, and (3) the overall assessment of the accuracy of the displacements computed from digitized accelerograms [103].

A simpler, lower-cost, but not-too-accurate strong motion recorder, designed by A.J. Weed of the University of Virginia, was also developed in the early 1930s (Fig. 10a, b; [96]). It had an inverted pendulum, a 6-lb mass supported by three stiff vertical wires, and a natural frequency of 5 Hz. It recorded two horizontal components of the relative motion of the mass by two mechanical levers, which scratched the records (in a cylindrical coordinate system) onto a smoked glass plate. The instrument was set in motion by Braunlich starters, and the plate was translated by a clock system through a total distance of 7 inches, along the time axis. Ten Weed seismometers were deployed in the field by early 1934, but the advances in other accelerographs soon made them obsolete [88].

7. Long beach earthquake

The Long Beach, California earthquake ($M_L = 6.3$) occurred on March 10, 1933, at 17:54 P.S.T. The epicenter was at 33°34.5′N and 117°59′W, about 5.6 km (3.5 miles) southwest of Newport Beach [104]. Its focal mechanism can be described by slip direction of 45°, dip of 80°, and rake of 170°, and the seismic moment was estimated at 5×10^{25} dyne-cm. The rupture was unilateral and propagated from the hypocenter toward the northwest, along the Newport–Inglewood fault, causing right-lateral strike slip motion with a minor normal component [105]. The aftershock zone extended from Newport Beach to Long Beach, and analysis of teleseismic data indicates that the duration of the main event was about 5 s, which is in agreement with reported duration of strong shaking (5–10 s in Pasadena; [104].

a



b

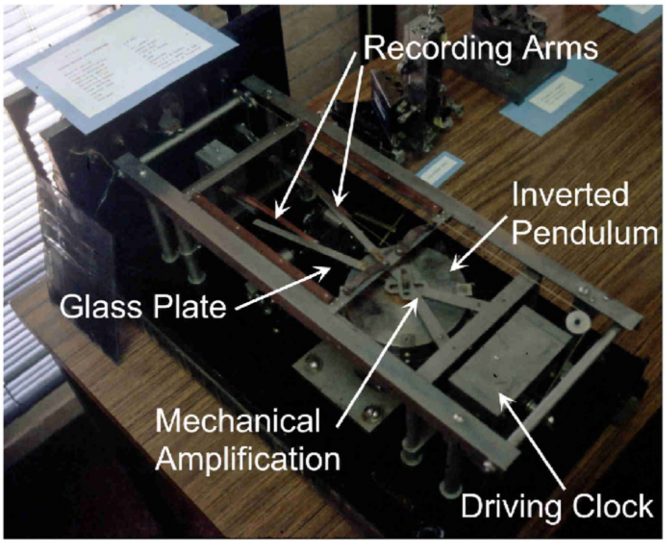


Fig. 10. (a) Side view of Weed seismograph. (b) Top view of Weed seismograph.

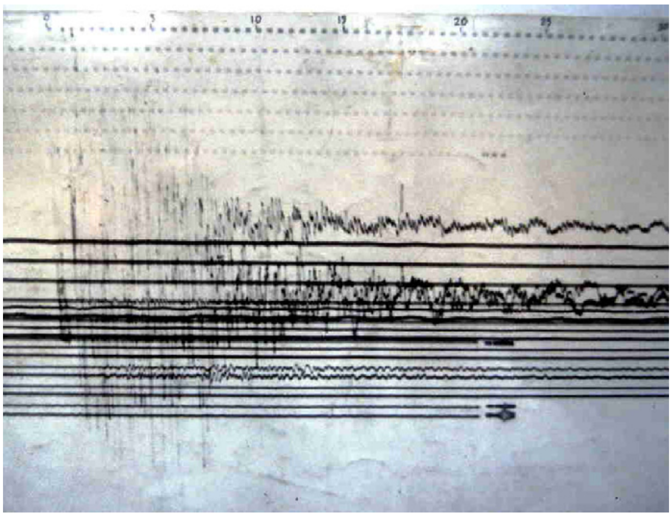


Fig. 11. Strong motion accelerogram—Long Beach Public Utilities Building.

7.1. Strong motion data

The installation of strong motion accelerographs started in the summer of 1932, with instruments being installed in Long Beach, Vernon, El Centro, and San Diego in July. In August, instruments were installed in the Los Angeles subway terminal building and on the Suisan Bay Bridge, and in September they were installed in the basement and on the 13th floor of the San Jose Bank of America Building. On December 20, 1932 a magnitude 7.3 earthquake occurred in Western Nevada. It triggered the accelerograph and was recorded at Long Beach, but because the earthquake was some 350 miles away the amplitudes of the record were very small. This was the first recording by the USC&GS accelerograph. The first *strong* motion was recorded on March 10, 1933 during the main event of the Long Beach Earthquake by three accelerograph stations at (1) the Long Beach Public Utilities Building, (2) the Vernon CMD Building, and (3) the Los Angeles Subway Terminal. Instrument and baseline-corrected strong motion data from these sites are presented in [106,107]. The largest peaks were recorded at Long Beach on the vertical component of strong motion (279 cm/s^2, 29.5 cm/s, and 26.4 cm for acceleration, velocity, and displacement, respectively). The significance of this strong-motion accelerogram is that it represents the first strong motion recording in the history of earthquake engineering. The number of recording stations and their positions relative to the causative fault were not adequate to allow inverse source mechanism studies of this event, but the closest station, at the Long Beach Public Utilities Building, could be used qualitatively to infer the most elementary spectral features of the source [7].

The first accelerograms, which were recorded on light-sensitive paper, were often exposed to stray light, and during large and high-frequency accelerations (optical density of the trace would decrease due to shorter exposure caused by the faster-than-average speed of the light beam per unit length of the acceleration trace) they were difficult to interpret and digitize. The first strong motion accelerogram, shown in Fig. 11, and many other difficult but important records, such as at El Centro during the Imperial Valley earthquake of 1940 [108] and at the Pacoima Dam during the San Fernando earthquake in 1971 [109], were all manually digitized, corrected, and processed by the author. All modern digital data collections with strong motion accelerograms include his digitized versions of these records [110].

7.2. Earthquake damage

The Long Beach earthquake was not a major earthquake, but because of its location in a settled region with poorly constructed buildings it was one of the most destructive earthquakes in US history. The damage was estimated at 41 million dollars, and the area affected was 75,000 sq mi (192,000 km^2) [7,111,112]. Many hundreds of people were injured, and about 120 died. It was reported that up to 19 fires resulted from strong shaking.

8. Subsequent developments

Following the Long Beach earthquake, plans for further investigations were formulated at a series of conferences in San Francisco and in Southern California. These plans called for a crash instrumentation program, which started in 1934 under the supervision of F.P. Ulrich. During this program, the number of strong motion stations was increased to 51, and the periods of 292 buildings were measured with portable instruments developed by H.E. McComb, F. Neumann, R. McLean, and H. Benioff [94]. A ground and building vibrator was developed at Stanford University by J.A. Blume and L.S. Jacobsen [113], and damage to type III masonry buildings during Long Beach earthquake was studied [111]. Double integration of strong motion accelerograms was investigated by F. Neumann at the USC&GS [114].

By 1964, the number of strong motion stations grew slowly to 71, mainly because the standard USC&GS accelerograph was not mass-produced and was expensive, costing up to $8000 each. Then, after the 1964 Alaska Earthquake renewed interest in earthquake investigations, the first commercially produced accelerograph (the AR-240) was developed, and following the ordinance passed in 1965 by Los Angeles and Beverly Hills requiring owners of new buildings higher than six stories to buy three accelerographs for each building, the number of strong motion stations started to grow rapidly [94,115].

The AR-240 accelerograph, manufactured by United GeoMeasurements (UGM), a division of United Electrodynamics, which later became Teledyne/Geotech, appeared in 1963. The first strong motion accelerograph to use 70 mm film was Mark II, intended to supplant the USC&GS standard instrument. It was spearheaded by C. Langer of USC&GS in Albuquerque, and UGM was asked to manufacture it. In addition to three accelerometers, Mark II had also two Carder type displacement meters. In Japan, the Strong-Motion Observation Committee developed the SMAC accelerograph (models A, B, C, D, and E) and started to deploy the first instruments in 1952 [116]. In 1967, Teledyne/Geotech introduced the RFT-250 accelerograph, which recorded on 70-mm film, and in 1970 Kinemetrics launched the SMA-1, also recording on 70-mm film [117]. Design of SMA-1 employed the same optical system of double reflection mirrors, previously used by Wood and Anderson. This meant that SMA-1 could be much smaller than any preceding acelerographs. In New Zealand, strong motion measurements started in the mid-1960s and were based on the MO-2 accelerograph recording on 35-mm film [118].

Strong-motion measurements were also made using devices with electro-dynamic registration [61]. In the former Soviet Union, structural vibrations were recorded with the help of multi-channel systems based on transducers such as the VEGIK (Vibrograph, Electrodynamic, Geophysical Institute, Kirnos), the SPM-16 (Seismo-transducer, Mechanical), and the VBP (Vibrograph for Big Displacements), and galvanometers of the GB type [23]. A variety of techniques were used to control the response of these systems [119]. Early strong-motion instruments used in China were often RDZ-type devices that also featured galvanometers [120].

There were certain advantages in using coupled systems as compared with single-degree-of-freedom devices: (1) the ability to get a broad range of amplifications, (2) the ability to separate recording and measuring locations, and (3) the ability to gather and write on the same medium (film, paper, magnetic tape) the response of several transducers attached at different places to the object being studied (this simplified time matching of the different records, [56]. It is important to process the records obtained by such devices in such a way that they are as representative of the ground (or structural) motion as possible and in as broad a frequency band as possible. This can be accomplished by careful digitization of these records and application of data-processing and correction procedures [62].

The field of strong motion observation was dominated by analog recording instruments until 1980s, when digital recording accelerographs gradually started to be introduced. Today, essentially all new instruments are digital, and the older analog models are being phased out [115].

Strong-motion observation in Japan began in 1951 [121], and by 1970 there were 500 SMAC and DC-2 accelerographs installed [117]. As of the end of 1980, there were about 1700 accelerographs in the United States (1350 of those in California), and by January 1982 there were over 1400 accelerographs in Japan. Fig. 12 illustrates the growth in the number of strong motion instruments in selected parts of the world and the growth in the number of uniformly processed strong motion acceleration records in the EQINFOS database that contains strong motion data in the western United States [110]. By the turn of the 21st century, this database had more than 2000 uniformly processed records, which made it possible to perform numerous empirical scaling regressions of amplitudes, spectral content, and duration of strong ground motion (e.g., [122,123].

9. Summary and conclusions

The observational experience of seismological research and the necessary applied engineering mechanics were developed in the early 1900s to a point that it became feasible to initiate the production of instruments for recording strong earthquake shaking and to record strong motion close to faults, in the zones where the man-made structures get damaged. However, there were two major obstacles. First, the digital computers, which are essential for processing the recorded strong motion accelerograms and for computation of the response of structures to the time-dependent excitation, were not available. Without computers, it was almost impossible to analyze the dynamic stresses in buildings shaken by earthquake ground motion. Unfortunately, it would take another half century, until 1960s, for the computers to finally appear and become widely accessible. The second obstacle was the view of the leading engineers of the period that computation of the response was too complicated to be included in the practical engineering design process [76,78,80]. When major earthquake disasters in California, Italy, and Japan occurred in the early 1900s, and when it finally became obvious that something had to be done to protect lives and property, engineers opted for a solution based on the seismic coefficient approach, which approximated complex earthquake effects in a rough but simple way, in terms of a statically applied horizontal load equal to about 10 percent of the total weight of the structure. Considering such obstacles, it is remarkable how much Suyehiro and Freeman were able to accomplish by combining the rational analysis of limited data with vision and persistence—and essentially alone.

The contemporaneous development of the theoretical basis of modern earthquake engineering, which produced the RSM in 1932, was up against the same obstacles, but it had the advantage that it did not require major funding. It was formulated as a part of the more general interest, M. Biot had in the maxima of transient dynamic problems [8,124]. Recording of the first strong motion accelerogram in March 1933, less than a year after the RSM was introduced, stimulated the search for ways to calculate spectral amplitudes from the recorded strong motion accelerograms. From among the different methods that were considered, analog simulation of the governing differential equations, first based on the mechanical analog (torsional pendulum, [5] and later on the electrical analog (analog computers, [125]), prevailed and was used until the arrival of digital computers in early 1960s [126].

The appearance of the RSM in 1932 had little effect on the further development of the design of strong motion accelerographs, but it revived interest in the use of single-pendulum seismoscopes (e.g., [23,34]) and especially in their further extension to multi-pendulum models (e.g. [36,37]).

The birth of the strong motion observational program in California and its immediate success (on March 10, 1933; Fig. 11) were the fruits of the vision and persistence of two remarkable men, Kyoji Suyehiro and John Freeman. Following his appointment as the first director of the Earthquake Research Institute of Tokyo University in 1924, Suyehiro organized a comprehensive theoretical and observational program to study strong earthquake

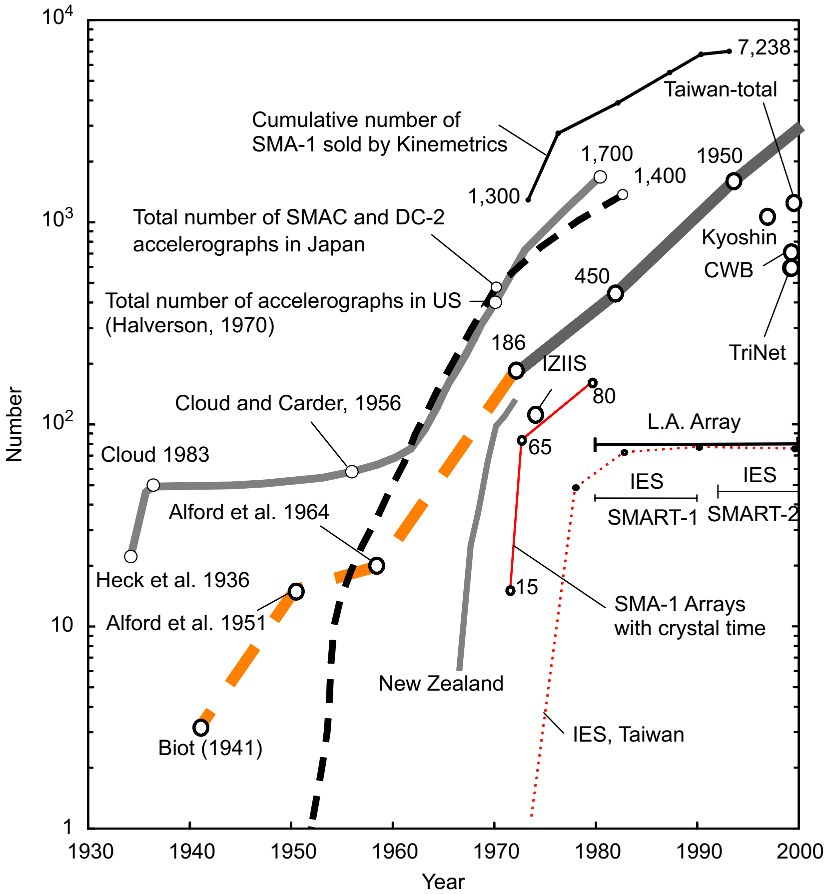


Fig. 12. Cumulative number of analog strong motion accelerographs in California and in Japan up to 1980, and of SMA-1 accelerographs sold worldwide. The wide dashed line, which continues as a solid gray line after 1972, shows the number of records in the uniformly processed EQINFOS strong motion database for California earthquakes [110]. Also shown are selected special-purpose arrays in California (SMA-1 arrays with crystal time, and the L.A. Array), Taiwan (SMART-1, SMART-2, and CWB), Japan (Kyoshin), and former Yugoslavia (IZIIS) (see [5,93,94,115,117,127,135]).

motion of the ground and in structures. His lectures in America in 1931 [81] summarized only what he and his associates had been able to decipher in the course of 5 years, but Suyehiro's exceptional ability to interpret observations, his systematic approach, his conviction that strong motion needed to be recorded systematically, and his vision left a lasting impression on his American colleagues. In this sense, he should be viewed today as one of the founding fathers of the strong-motion recording program in earthquake engineering. John Freeman, who recognized the importance of recording strong motion, who invited Suyehiro to America to give the lectures, and whose persistent lobbying finally convinced the US Congress to appropriate funds in 1931 for the strong motion program, should be recognized as the founding father of America's strong motion observation program [77]. After successful installation of the first accelerographs in the summer of 1932, the successful recording of the Long Beach earthquake in March 1933, and the crash instrumentation program in 1934–1935, during which the number of strong motion accelerographs grew quickly to 51 (Fig. 12; [94,127], the USC&GS continued to add accelerographs until a total of 71 had been installed by 1964. After the Alaska earthquake of 1964, the passing of ordinances in 1965 by the cities of Beverly Hills and Los Angeles requiring owners of buildings higher than six stories to install three accelerographs, and the very successful recording of the San Fernando earthquake in 1971, strong motion measurement programs began to grow rapidly in many parts of the world (Fig. 12; [115].

The impressive accomplishments of K. Suyehiro and of J. Freeman, and the remarkable speed with which they produced the results, may serve as examples for the next generations of earthquake engineers to emulate. Their success also shows that when there is clear and strong will combined with dedication and timely relevance, age is not an obstacle, but an advantage, because of the experience and wisdom it brings into the process. Quantitative studies of scientific productivity tend to show that the average productivity of scientists and engineers begins to decline after the age of about 40 [128,129]. Suyehiro, who was 54 in 1931 when he lectured in America, and Freeman, who was 77 when his book about earthquakes was published in 1932, lived and worked well before the modern era, which is covered and quantified by the ISI database [130], but their productivity and accomplishments in terms of a broad set of other general indicators were obviously far above the average trends.

I close this review by considering a hypothetical question. Could such a success story be repeated, and so quickly, today? Could present and future leaders like John Freeman succeed in today's conditions? I explore the answer by assuming that they would not find any opposition among earthquake engineers and that because today's digital computers are more than capable of handling all the needed calculations the computational obstacles would also not be present. The answer, however, still depends upon whether they could overcome other complexities, such as peer reviews, competitive aspirations of different institutions engaged in earthquake research, and the funding constraints.

At present, the funding agencies and the research centers tend to dictate the research priorities, and they favor “big science” initiatives, while the original and unsolicited initiatives and ideas of individual scientists—“small science” [131]—receive less attention and support. In addressing this question, we must also keep in mind that earthquake engineering, after its many accomplishments during the past 75 years, has approached what might be viewed by some as a mature stage, in which many problems have already been addressed and to a degree solved. While the seismic risk is increasing at an accelerating rate, due to the rapid growth of mega-cities and of the population density in general, other contemporary challenges in the areas of medicine, genetics, advanced materials, and information technology, for example, are coming into focus, and by their size and ubiquity these fields tend to dominate what are perceived to be the research priorities of the 21st century. The relative insignificance of the “earthquake problem” in the context of all other contemporary scientific research, and the attention it may receive, especially after long periods of low seismicity, might be illustrated symbolically by an anecdote involving Albert Einstein. In January 1933, Einstein arrived in Pasadena as a guest of the Oberlaender Trust, a foundation seeking to promote German-American cultural exchange. His visit was organized and hosted by Robert Millikan, the President of Caltech. On March 10, 1933, in the garden of the Athenaeum on the Caltech campus, Einstein was interviewed by Evelyn Seely of the *New York World Telegram*. Just as Seely was completing her interview, several minutes before 6 PM, Los Angeles was shaken by the devastating Long Beach earthquake—but Einstein barely seemed to notice. Seely ended her article with a metaphor: “As he left for the seminar, walking across campus, Dr. Einstein felt the ground shaking under his feet” [132].

We may not be able to find a definitive answer to our question, even by performing a *gedankenexperiment* (thought experiment), but by loose analogy to other, much larger programs it seems that what Suyehiro and Freeman accomplished could not be repeated today. We illustrate the plausibility of this view by three examples, referring first to the much larger and far more complex Inter-Continental Ballistic Missile (ICBM) program, which started in the mid-1950s. Ramo [133] describes how the ICBM program was formulated by a small group of experts in a meeting with President Eisenhower and how it was launched with only a few members of Congress being fully informed. Ramo also describes how, in 1954, the defense bureaucracy was already “so strong that it was difficult to speed the project through. It is far worse in the late 1980s.” He goes on to illustrate many obstacles that would be expected to occur today and concludes that “launching a huge crash program without controversy and delay is now impossible.” The second and third examples, both also very large, are the development of the atomic bomb (the Manhattan Project) and the Apollo Space Program [134]. General Groves managed the entire Manhattan Project with just four staff members. As Kao says, “Given the hopes riding on his leadership, he was arguably, if briefly, more *heavyweight* than the president himself.” James Webb controlled $6 billion (in 1966 dollars) of Apollo Program funding, which represented about 5 percent of all federal spending. “Groves and Webb succeeded because they were free to use vast resources and their own judgment in mobilizing the talent and tools needed to accomplish the missions hugely important to the United States. Today, getting large-scale things done is incalculably harder than it was forty years ago. In the current political climate, consensus is the exception rather than a rule, and even the challenge of hiring the finest experts for vital missions is usually politicized.” Finally, because of “today's paucity of creativity” [134], it may take a longer time before society is blessed with visionary researchers as capable as Suyehiro and Freeman.

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References

[1] Duke CM, Luco JE, Carriveau AR, Hradilek PJ, Lastrico R, Ostrom D. Strong earthquake motion and site conditions: Hollywood. Bull Seism Soc Am 1970;60(4):1271–89.
[2] Biot MA. Vibrations of buildings during earthquake. In: Ph.D. thesis no. 259, Transient oscillations in elastic systems, Chapter II. Pasadena, CA: Aeronautics Department, California Institute of Tech; 1932.
[3] Biot MA. Theory of elastic systems vibrating under transient impulse with an application to earthquake-proof buildings. Proc Natl Acad Sci 1933;19(2): 262–8.
[4] Biot MA. Theory of vibration of buildings during earthquakes. Z Angew Matematik Mech 1934;14(4):213–23.
[5] Biot MA. A mechanical analyzer for the prediction of earthquake stresses. Bull Seism Soc Am 1941;31:151–71.
[6] Biot MA. Analytical and experimental methods in engineering seismology. ASCE Trans 1942;108:365–408.
[7] Trifunac MD. Nonlinear soil response as a natural passive isolation mechanism, Paper II—The 1933 Long Beach, California earthquake. Soil Dyn Earthquake Eng 2003;23(7):549–62.
[8] Trifunac MD. Early history of the response spectrum method. Report CE 07-01. Los Angeles: Department of Civil Engineering,University of Southern California; 2007a. Available at http://www.usc.edu/dept/civil_eng/Earthquake_eng/.
[9] Vitaliano DB. Legends of the earth. Bloomington, IN: Indiana University Press; 1973.
[10] Needham J. Science and civilization in China, vol. 3. Cambridge, UK: Cambridge University Press; 1959. pp. 624–635.
[11] Milne J. Earthquakes and other earth movements. New York: Appleton; 1886.
[12] Imamura A. Tyoko and his seismoscope. Jpn J Astron Geophys 1939;16:37–41.
[13] Baratta M. Richerche storiche sugli apparechi sismici. Ann Uff Cent Met Geodin Ital 1895; 17 (ser 2, part 1): 3–37.
[14] Favaro A. Contribuzioni alla storia della microsismologia. Atti Inst veneto Sci 1884;6(2):91–103.
[15] Davison C. Founders of seismology. Cambridge, UK: Cambridge University Press; 1927.
[16] Cirillo N. The history of an earthquake which shook Apula and almost the whole kingdom of Naples, in 1731. Philis Trans 1747;8:682–4.
[17] Agamennone G. L'inventore del sismografo a pendolo. La Meteorol Pratica 1926;7:264–6.
[18] Fuller ML. The New Madrid earthquake. Bull US Geol Surv 1912; 494.
[19] Milne D. Report of a committee appointed at Glasgow meeting for obtaining instruments and registers to record shocks of earthquakes in Scotland and Ireland. Rep Br Assoc Adv Sci, 1842; 1841: 46–9.
[20] Forbes JD. On the theory and construction of a seismometer, or instrument for measuring earthquake shocks, and other concussions. Trans R Soc Edinburgh 1844;15:219–28.
[21] Wiechert E. Seismometrische Beobachtungen im Göttinger Geophysikalischen Institut. Nachr Ges Wiss Göttingen 1899;1889:195–208.
[22] Wiechert E. Ein astatisches Pendel höher Empfindlichkeit zur mechanichen Registrierung von Erdbeben. Beitr Geophys 1904;6:435–50.
[23] Medvedev SV. Elementary seismology. Jerusalem: Israel Program for Scientific Translations; 1965.
[24] Hudson DE. The Wilmot survey type strong-motion recorder, EERL. Pasadena, CA: Califonia Institute of Technology; 1958.
[25] Mallet R. Second report on the facts of earthquake phenomena. Rep Br Assoc Adv Sci 1852; 1851: 272–320.
[26] Mallet R. Account of experiments made at Holyhead to ascertain the transit velocity of waves, analogous to earthquake waves, through the local rock formation. Philos Trans R Soc 1861 (1862a);151:655–79.
[27] Abbot HL. On the velocity of transmission of earth waves. Am. J. Sci. 1878;115:178–84.
[28] Mallet R. The first principles of observational seismology. London: Chapman and Hall; 1862.
[29] Milne J. Seismic experiments. Trans Seism Soc Jpn 1885;8:1–82.
[30] Milne J, Omori F. On the overturning and fracturing of brick and other columns by horizontally applied motion. Seism J Jpn 1893;1:59–85.
[31] Milne J. Earth pulsations in relation to certain natural phenomena and physical investigations. Seism J Jpn 1893;1:87–112.
[32] Cavalleri PGM. Description of a new seismometer constructed in the college at Monza. Philos Mag 1860;4(19):102–16.
[33] Suyehiro K. A seismic vibration analyzer and the records obtained therewith. Bull Earthquake Res Inst, Tokyo Univ 1926;1:59–64.
[34] Cloud WK, Hudson DE. A simplified instrument for recording strong earthquakes. Bull Seism Soc Am 1961;51(2):159–74.

[35] Ulrich FP. Progress report for 1939 of the seismological field survey of the United States Coast and Geodetic Survey. Bull Seism Soc Am 1941;31:107–19.
[36] Nazarov AG. Metod Inzenernogo Analiza Seismicheskih Sil, Izdatelstvo A.N. Armyanskoi S.S.R., Erevan, 1959.
[37] Krishna J, Chandrasekaran AR. Structural response recorders. Proceedings of the third world conference on earthquake engineering, vol. III, New Zealand, 1965. p. 143–50.
[38] Trifunac MD. Statistical analysis of the computed response of structural response recorders (SRR) for accelerograms recorded in the United States of America. Proceedings of the sixth world conference on earthquake engineering, New Delhi, India, v ol. III, 1977. p. 2956–61.
[39] Palmieri L. The electromagnetic seismograph. Rep Smithson Ins 1871; 1870: 425–8.
[40] Dewey J, Byerly P. The early history of seismometry (to 1900). Bull Seism Soc Am 1969;59(1):183–227.
[41] Holden ES. A catalogue of earthquakes on the Pacific Coast, 1769 to 1897. Smithson Misc Collns 1898;1087:17–22.
[42] Cecchi PF. Sismografo elettrico a carte affumicate scorrevoli. Atti Acad Pontiff Nouvi Lincei 1876;29:421–8.
[43] Agamennone G. La Registrazione dei Terremoti, Casa Editrice "L'Ellettricista," 1906.
[44] Denza PF. Osservazioni fatte all'Osservatorio di Moncalieri sul terremoto del 23 febbrario 1887. Boll Mensuale dell' Osservatorio Centrale Moncalieri 1887;2(7):68–70.
[45] Ewing JA. Earthquake measurement. Memoires of the Science Department, University of Tokyo, 1883; 9.
[46] Ewing JA. A new form of pendulum sesmograph. Trans Seism Soc Jpn 1880;1:38–43.
[47] Ewing JA. On a new seismograph for horizontal motion. Trans Seism Soc Jpn 1880;2:45–9.
[48] Ewing JA. On a new seismograph. Proc R Soc 1881;31:440–6.
[49] Perry J, Ayrton WE. On a neglected principle that may be employed in earthquake measurement. Philos Mag Ser 1879;5(8):30–50.
[50] Gray T. Instruments for measuring and recording earthquake-motions. Philos Mag 1881;5(12):199–212.
[51] Milne J. Experiments in observational seismology. Trans Seism Soc Jpn 1881;3:12–64.
[52] Ewing JA. Notes on some recent earthquakes. Trans Asiat. Soc. Jpn 1881;9:40–8.
[53] Milne J. Seismic science in Japan. Trans Seism Soc Jpn 1880;1(1):3–34.
[54] Von Rebeur-Paschwitz E. The earthquake of Tokyo, April 18, 1889. Nature 1889;40:294–5.
[55] Trifunac MD, Markus DK, Moslem K. A note on controlling the optical density of analog film records in strong motion accelerographs. Soil Dyn Earthquake Eng 1985;4(1):31–4.
[56] Trifunac MD, Todorovska MI, Lee VW. Common problems in automatic digitization of strong motion accelerograms. Soil Dyn Earthquake Eng 1999;18(7):519–30.
[57] Agamennone G. I terremoti di lontana provenieza registrati al Collegio Romano. Atti Accad Naz Lincei Rc 1894; 5, 7, sem. 1: 265–71.
[58] Schlüter W. Schwingungsart und Weg der Erdbebenwellen. Beitr Geophys 1903;5:314–59. 401–65.
[59] Oldham RD. On the propagation of earthquake motion to great distances. PhilosTrans R Soc (Ser A) 1900;194:135–74.
[60] Galitzin B. Zur methodik der sesmometrischen beobachtungen. Izv Imp Akad Nauk 1903;5(19):xxx–xxxi.
[61] Galitzin, B. Lekcii po seismometrii, Tipografiya Imperatorskoi Akademii Nauk, S. Peterburg, 1912.
[62] Novikova EI, Trifunac MD. Instrument correction for the coupled transducer-galvanometer Systems. Los Angeles: Department of Civil Engineering, Report CE 91-02, University of Southern California, 1991, Available at http://www.usc.edu/dept/civil_eng/Earthquake_eng/.
[63] Fouqué F. Les Tremblements de Terre. Paris: Bailliere; 1888.
[64] Lippman G. Sur la theorie et la mode d'emploi des appareils seismographiques. C. r. hebd. Séanc. Acad Sci, Paris 1890;110:440–4.
[65] Wiechert E. Theorie der automatischen Seismographen. Abh K Bes Wiss Göttingen, Klasse N F 2, 1902–1903 (1903): 1–128.
[66] Galitzin B. Zur methodik der seismometrischen beobachtungen. Izv Postoyann Tsent Seism Komm 1904;1(3):1–112.
[67] Reid, HF. The mechanics of the earthquakes. Report, vol. 2, Sacramento, CA: California Earthquake Commission; 1910.
[68] McComb HE, Ruge AC. Tests of earthquake accelerometers on a shaking table. Bull Seism Soc Am 1937;27:325–9.
[69] Milne J. A note on the great earthquake of October 28, 1891. Seism J Jpn 1893;1:127–51.
[70] Galitzin B. Uber seimometrische beobahtungen. Izv Postyann Tsent Seism Komm 1902;1(1):101–83.
[71] Graizer VM. On the determination of displacement from strong-motion accelerograms. Proceedings of the seventh world conference on earthquake engineering, Istanbul, vol. 2, 1980. p. 391–4.
[72] Trifunac MD, Todorovska MI. A note on the useable dynamic range of accelerographs recording translation. Soil Dyn Earthquake Eng 2001;21(4):275–86.
[73] Timoshenko SP. As I remember. Princeton, NJ: Van Nostrand Co.; 1968.
[74] Von Kármán T, Edson L. The wind and beyond. Boston: Little, Brown and Co.; 1967.
[75] Cornwell J. Hitler's scientists. New York: Penguin Books; 2003.
[76] Derleth C. The effects of the San Francisco earthquake of April 18th, 1906 on engineering constructions. Transactions of the American Society of Civil Engineers, vol. LIX, December, 1907.
[77] Housner GW. Earthquake engineering—some early history. In: DE Hudson, editor. Proceedings of the golden anniversary workshop on strong motion seismometry. Report. Los Angeles: Department of Civil Engineering. University of Southern California, 1983. p. 7–16. Available at http://www.usc.edu/dept/civil_eng/Earthquake_eng/.
[78] Ruge AC. Ruge on earthquakes and structures. Transactions of the American Society of Civil Engineers, vol. 105, 1940.
[79] Reitherman R. The effects of the 1906 earthquake in California on research and education. Earthquake Spectra 2006;22(S2):S207–36.
[80] Sorrentino L. Early entrance of dynamics in earthquake engineering—Arturo Danusso contribution. Indian Soc Earthquake Technol J 2007;44(1):1–24.
[81] Suyehiro K. Engineering seismology notes on American lectures. Proc ASCE 1932;58(4):1–110.
[82] Ford CR. Earthquakes and building construction, Auckland, 1926.
[83] Benioff H. The physical evaluation of seismic destructiveness. Bull Seism Soc Am 1934;24(4):398–403.
[84] Freeman JR. Earthquake damage and earthquake insurance. New York: McGraw-Hill; 1932.
[85] Freeman S. Response spectra as a useful design and analysis tool for practicing structural engineers. Indian Soc Earthquake Technol J 2007;44(1): 25–37.
[86] Kanai K. Engineering seismology. Tokyo: University of Tokyo Press; 1983.
[87] Anderson JA, Wood HD. Description and theory of torsion seismometer. Bull Seism Soc Am 1925;15(1):1–72.
[88] Hudson DE. History of accelerograph development. In: Hudson DE, editor. Proceedings of the golden anniversary workshop on strong motion seismometry. Los Angeles: Department of Civil Engineering Report, University of Southern California, 1983. p. 29–56. Available at http://www.usc.edu/dept/civil_eng/Earthquake_eng/.
[89] Earthquake Engineering Research Institute. Connections, the EERI oral history series: GW Housner, Stanley Scott (Interviewer). EERI, Oakland, CA, 1997.
[90] Trifunac MD. Response envelope spectrum and interpretation of strong earthquake ground motion. Bull Seism Soc Am 1971;61(2):343–56.
[91] Trifunac MD, Todorovska MI. Nonlinear soil response as a natural passive isolation mechanism—The 1994 Northridge, California earthquake. Soil Dyn Earthquake Eng 1998;17(1):41–51.
[92] Trifunac MD, Todorovska MI. Reduction of structural damage by nonlinear soil response. J Struct Eng, ASCE 1999;125(1):89–97.
[93] Heck NH, McComb HE, Ulrich FP. Strong-motion program and tiltmeters. In: Earthquake investigations in California 1934–1935, Special Publication No. 201. Washington, DC: US Department of Commerce, Coast and Geodetic Survey; 1936. p. 4–30.
[94] Cloud WK. Early days of strong motion seismometry in the United States. In: DE Hudson, editor. Proceedings of the golden anniversary workshop on strong motion seismometry. Los Angeles: Department of Civil Engineering Report, University of Southern California; 1983. p. 25–28. Available at http://www.usc.edu/dept/civil_eng/Earthquake_eng/.
[95] Wenner F. Development of seismological instruments at the Bureau of Standards. Bull Seism Soc Am 1932;22:60–7.
[96] Ulrich FP. The California strong-motion program of the United States Coast and Geodetic Survey. Bull Seism Soc Am 1935;25:81–95.
[97] Ruge AC, McComb HE. Tests of earthquake accelerometers on a shaking table. Bull Seism Soc Am 1943;33(1):2–12.
[98] Hudson DE. Ground motion measurements. In: Weigel RL, editor. Earthquake engineering. Englewood Cliffs, NJ: Prentice-Hall; 1970.
[99] Trifunac MD. Stress estimates for San Fernando, California earthquake of February 9, 1971: main event and thirteen aftershocks. Bull Seism Soc Am 1972;62(3):721–50.
[100] Trifunac MD. Tectonic stress and source mechanism of the Imperial Valley, California earthquake of 1940. Bull Seism Soc Am 1972;62(5): 1283–302.
[101] Trifunac MD, Lee VW, Routine computer processing of strong-motion accelerograms. Earthquake Engineering Research Laboratory, EERL 73-03. Pasadena, CA: California Institute of Technology; 1973.
[102] Trifunac MD. Zero baseline correction of strong-motion accelerograms. Bull Seism Soc Am 1971;61(5):1201–11.
[103] Trifunac MD, Lee VW. A Note on the accuracy of computed ground displacements from strong-motion accelerograms. Bull Seism Soc Am 1974; 64(4):1209–19.
[104] Wood HO. Preliminary report on the Long Beach earthquake Bull Seism. Soc Am 1933;23(2):43–56.
[105] Hauksson E, Gross S. Source parameters of the 1933 Long Beach Earthquake. Bull Seism Soc Am 1991;81(1):81–98.
[106] Trifunac MD, Brady AG, Hudson DE. Strong-motion earthquake accelerograms, II, Corrected accelerograms and integrated ground velocity and displacement curves. Earthquake Eng. Res. Lab., Report EERL 72-50. Pasadena, CA: California Institute of Technology; 1973. Available at http://www.usc.edu/dept/civil_eng/Earthquake_eng/.
[107] Trifunac MD, Hudson DE, Brady AG. Strong-motion Accelerograms, II. Corrected acceleration and integrated velocity and displacement curves. Earthquake Engineering Research Laboratory, Report EERL 75-52. Pasadena,

CA: California Institute of Technology; 1975. Available at http://www.usc.edu/dept/civil_eng/Earthquake_eng/.

[108] Tifunac MD, Brune JN. Complexity of energy release during the Imperial Valley, California earthquake of 1940. Bull Seism Soc Am 1970;60(1):137–60.

[109] Tifunac MD, Hudson DE. Analysis of the Pacoima Dam accelerogram, San Fernando, California earthquake of 1971. Bull Seism Soc Am 1971;61(5):1393–411.

[110] Lee VW, Trifunac MD. Strong earthquake ground motion data in EQUINFOS: Part I. Los Angeles: Department of Civil Engineering, Report CE 87-01, University of Southern California, 1987. Available at http://www.usc.edu/dept/civil_eng/Earthquake_eng/.

[111] Martel RR. A report on earthquake damage to type III buildings in Long Beach. In: Earthquake investigations in California 1934–1935. Washington, DC: US Department of Commerce, Coast and Geodetic Survey, Special Publication; 1936. p. 143–62.

[112] Neumann F. United States earthquakes. Washington, DC: US Department of Commerce, Coast and Geodetic Survey, Serial No. 579, 1935. p. 9–14, and 25–35.

[113] Blume JA. The building and ground vibrator. In: Earthquake investigations in California 1934–1935, Special Publication No. 201, Washington, DC: US Department of Commerce, Coast and Geodetic Survey; 1936.

[114] Neumann F. An appraisal of numerical integration methods as applied to strong-motion data. Bull Seism Soc Am 1943;33(1):21–60.

[115] Trifunac MD. Recording Strong earthquake motion—instruments, recording strategies and data processing. Report CE 07-01. Los Angeles: Department of Civil Engineering, University of Southern California; 2007b. Available at http://www.usc.edu/dept/civil_eng/Earthquake_eng/.

[116] Strong-Motion Earthquake Observation Committee. Strong-motion earthquake records in Japan, vol. 1. Tokyo: Earthquake Research Institute, University of Tokyo; 1960.

[117] Halverson HT. Modern trends in strong movement (strong-motion) instrumentation, dynamic waves in civil engineering. In: DA Howells, DA Haigh, C. Taylor, editors. Proceedings of the conference organized by the society for earthquake and civil engineering dynamics, Swansea. London: Wiley-Interscience; 1970.

[118] Skinner RI, Stephenson WR, Hefford RT. Strong-motion earthquake recording in New Zealand. Bull New Zealand Soc Earthquake Eng 1971;4(1):31.

[119] Borisevich ES, editor. Katalog Geofizicheskoi Apparaturi. Moscow: Nauka; 1981 (in Russian).

[120] Lee VW, Wang YY. On the instrument correction of the RDZ-1 strong-motion pendulum galvanometer in China. Earthquake Eng Eng Vibr 1983;3(4):25, (in Chinese).

[121] Takahashi R. The SMAC strong-motion accelerograph and other latest instruments for measuring earthquakes and building vibrations. Proceedings of the first world conference on earthquake engineering., Berkeley, CA, vol. 3, 1956, p. 1.

[122] Lee VW. Empirical scaling of strong earthquake ground motion—Part I: Attenuation and scaling of response spectra. Indian Soc Earthquake Technol J 2002;39(4):219–54.

[123] Lee VW. Empirical scaling of strong earthquake ground motion—Part II: Duration of strong motion. Indian Soc Earthquake Technol J 2002;39(4):255–71.

[124] Trifunac MD. Biot response spectrum. Soil Dyn Earthquake Eng 2006;26(6–7):491–500.

[125] Caughey TK, Hudson DE, Powell RV. The CIT Mark II electric analog type response spectrum analyzer for earthquake excitation studies. Pasadena, CA: Earthquake Engineering Research Laboratory, California Institute of Technology; 1960.

[126] Trifunac MD. Brief history of computation of earthquake response spectra. Soil Dyn Earthquake Eng 2006;26(6–7):501–8.

[127] Cloud WK, Carder DS. The strong-motion program of the Coast and Geodetic Survey In: Proceedings of the first world conference on earthquake engineering. Berkeley, CA, vol. 2, 1956. p. 1.

[128] Lehman HC. Age and achievement. Princeton, NJ: Princeton University Press; 1953.

[129] Pelz D, Andrews FM, editors. Scientists in organizations: productive climate for research and development. Ann Arbor, MI: Institute for Social Research; 1976.

[130] Trifunac MD. On citation rates in earthquake engineering. Soil Dyn Earthquake Eng 2006;26(11):1049–62.

[131] Kanamori H. Small science and unexpected discoveries in seismology, Presidential Address. Bull Seism Soc Am 1986;76(5):1501–3.

[132] Isaakson W. Einstein—his life and universe. New York: Simon and Schuster; 2007.

[133] Ramo S. The business of science—winning and losing in the high-tech age. New York: Hill and Wang; 1988.

[134] Kao J. Inovation nation. New York: Free Press; 2007.

[135] Alford JL, Housner GW, Martel RR. Spectrum analysis of strong-motion earthquakes. Pasadena, CA: Earthq. Eng. Res. Lab., Calif. Inst. of Tech. (originally published in 1951, revised in 1964).