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Historical Review

# Early history of the response spectrum method

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**Contents**



*Once Einstein was asked …. what schools should emphasize. "In teaching history," he replied, "there should be extensive discussion of personalities who benefited mankind through independence of character and judgment*." (Isaacson, 2007) [1].

## 1. Introduction

Writing about the early history and formative ideas of a given subject can be interesting and educational in many different ways. It is also difficult, because the record is always incomplete, because we cannot interview all those involved, and because the risk of presenting yet another version of a "Rashomon" story is always present. Yet, it is useful to document what is known and to search for the key factors that led to the formulation of a new concept, to learn about the key players, their teachers, and the times in which they lived—and perhaps to discover the anatomy of the process that led to the new ideas. In this time, when we study such a broad spectrum of natural and societal phenomena, it should seem only natural and logical to try to research the origins and the conditions surrounding the development of a significant new concept.

The year 2007 marks the 75th anniversary of the formulation of the concept of the response spectrum method (RSM) in 1932. Since then, the RSM has evolved into the essential tool and the central theoretical framework—in short, a conditio sine qua non—for Earthquake Engineering. The mathematical formulation of the RSM first appeared in the doctoral dissertation of M.A. Biot (1905–1985) in 1932 and in two of his subsequent papers [2,3].

The RSM remained in the academic sphere of research for many years and did not gain widespread engineering acceptance until the early 1970s. There were two main reasons for this. First, the computation of the response of structures to earthquake ground motion led to "certain rather formidable difficulties" [4], and, second, there were only a few well-recorded accelerograms that could be used for that purpose. This started to change in 1960s with the arrival of digital computers and the commercial availability of strong-motion accelerographs. Before the digital

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computer age, the computation of structural response was time consuming, and the results were unreliable [5]. By the late 1960s and early 1970s, however, the digitization of analog accelerograph records and the digital computation of ground motion and of the response spectra were developed completely and tested for accuracy. Then, in 1971, with the occurrence of the San Fernando, California, earthquake, the modern era of RSM was launched. This earthquake was recorded by 241 accelerographs, and by combining these data with all previous strong-motion records it became possible to perform the first comprehensive empirical scaling analyses of response spectral amplitudes [6,7].

In the following, we focus only on the early history of the RSM. The description and analyses of the modern developments in the RSM are beyond the scope of this work. The reader can find papers that describe many contemporary uses of the RSM in the special issue of the *Indian Society of Earthquake Technology* (*ISET*) *Journal*, vol. 44, no. 1, published in 2007.

## 2. Engineering mechanics in the 19th and early 20th centuries

Solution of the type of differential equations that describe the dynamic response of structures can be viewed in terms of (1) waves (D'Alembert (1717–1783) first described this method of solution in a memoir of the Berlin Academy in 1750), or (2) using a vibrational approach in terms of the characteristic functions (mode shapes) (Bernoulli (1700–1782), first wrote about this method in a memoir of the Berlin Academy in 1755). The related problem of the vibrating string was solved analytically by Lagrange (1736–1830) in a memoir of the Turin Academy in 1759, which established the existence of a number of independent frequencies equal to the number of interconnected particles. Mathematical principles and the methods associated with the latter approach have been researched and described extensively by Rayleigh [8] (the first edition of the *Theory of Sound* was published in England in 1877. It took 68 years for the first American edition of the *Theory of Sound* to appear, as a Dover publication, in New York, in 1945).

Lord Rayleigh was born John William Strutt, the eldest son of the Baron Rayleigh of Terling Place. In 1861, at the age of nearly 20, he went to Cambridge and entered Trinity College, where he profited greatly from the lectures of Sir George G. Stokes. In 1866, he made a trip to the United States, during the period of reconstruction after the Civil War, and the first pages of the *Theory of Sound* were written on a houseboat during a trip up the river Nile, late in 1872. Rayleigh was a modest man. When he received the Order of Merit, he remarked that the only merit of which he was personally conscious was that of "having pleased himself by his studies, and any results that may have been due to his researches were owing to the fact that it had been a pleasure to him to become a physicist."

The RSM is based on the vibrational representation of the solution, in which each mode shape and its natural frequency are associated with one equivalent single-degree-of-freedom (SDOF) system. Then, for linear systems the response is represented as a superposition of the responses of those equivalent SDOF systems. Therefore, the analysis of the linear response of an $n$-degree-of-freedom system can be reduced to a study of individual SDOF systems, one at a time.

A comprehensive review of the conditions that prepared and enabled the key players to formulate the concept of the RSM is beyond the scope of this work. In the following, I will mention only a few examples. The first is that the teaching of physics, and particularly of engineering mechanics and applied mathematics, started to expand in Europe around the end of 19th and the beginning of 20th century [9–11]. The second was the arrival of leading scientists and engineers in earthquake-prone areas (e.g., Milne in Japan, Compte de Montessus de Ballore in Chile, and Millikan, Gutenberg, and Von Kármán in Southern California). Their organizational abilities, interest, and curiosity to examine yet another challenging group of physical phenomena created new critical mass, which in turn attracted the next generation of talented students.

At many universities in the early 1900s, engineering curricula did not include advanced mathematics and mechanics, both essential for teaching analysis of the dynamic response of structures. This deficiency in theoretical preparation is reflected in the view of C. Derleth (1874–1956), civil engineering professor and Dean of the College of Engineering at U.C. Berkeley, who commented after the 1906 earthquake [12]:

> Many engineers with whom the writer has talked appear to have the idea that earthquake stresses in framed structures can be calculated, so that rational design to resist earthquake destruction can be made, just as one may allow for dead and live loads, or wind and impact stresses. Such calculations lead to no practical conclusions of value.

A comment by Ruge [13], 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," shows that the progress was slow [14].

Such views, however, had started to change gradually toward the end of 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), 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" [9]. In the summer of 1932, M.A. Biot was among the young postdoctoral students who took part in Timoshenko's summer school [15,16].

In southern California, studies of earthquakes and research in theoretical mechanics were expanded and energized by the arrival of R. Millikan (1868–1953), who became the first president (chair of the executive council) of the California Institute of Technology in 1921. Millikan had completed his Ph.D. studies in physics at Columbia University in 1895, and following the recommendation of his advisor M. Pupin (1854–1935) spent a year in Germany, in Berlin and Göttingen. This visit to Europe appears to have influenced many of Millikan's later decisions while recruiting the leading Caltech faculty members two decades later. In 1921, H.O. Wood (1879–1958) invited Millikan to serve on the Advisory Committee in Seismology [17]. The work on that committee and Millikan's interest in earthquakes were also significant for several subsequent events. In 1926, J. Buwalda (1886–1954) was asked to set up the division of geological sciences at Caltech, and C. Richter (1900–1985) and B. Gutenberg (1889–1960) joined the seismological laboratory in 1926 and 1930, respectively. In the area of applied mechanics, Millikan invited Theodore Von Kármán (1881–1963) to join the Caltech faculty, and in 1930 Von Kármán became the first director of the Guggenheim Aeronautical Laboratory. An engineer, applied scientist, teacher, and visionary, Von Kármán had a remarkable talent for getting people together across professional, national, and language barriers, and he became one of the foremost leaders in the world of aviation and space technology (see, for example, [10]). But it was Millikan's vision and his ability to anticipate future developments that brought so many leading minds to a common place of work, creating an environment that made the first theoretical formulation of the concept of the RSM possible.

## 3. First steps

Several earthquake disasters in densely populated areas in the early 20th century made it clear that defensive mechanisms needed to be developed to prevent future loss of life and property from destructive earthquakes. The first practical steps, which initiated the engineering work on the design of earthquake-resistant structures, accompanied the introduction of the *seismic coefficient* (known as *shindo* in Japan and *rapporto sismico* in Italy) and started to appear following the destructive earthquakes in San Francisco, California in 1906, Messina-Reggio, Italy in 1908 [18], and Tokyo, Japan in 1923. The first seismic design code was introduced in Japan in 1924. 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 [14].

Benioff [19] 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.

Suyehiro [20] also discussed the "static load of the intensity given by the mass of the building multiplied by the horizontal acceleration of the seismic vibration", and we can speculate that Frank Lloyd Wright may have used it in his design of the Imperial Hotel in Tokyo, especially in the analysis of its "floating" foundation.

In Italy, work on developing building design codes began in 1908, following the Messina disaster, in which more than 100,000 persons were killed; in Japan following the 1923 Tokyo disaster, in which more than 150,000 perished; and in California after the Santa Barbara earthquake of 1925 [20,21]. In 1927, the "Palo Alto Code," developed with the advice of Professors Willis and Marx of Stanford University, was adopted in the cities of Palo Alto, San Bernardino, Sacramento, Santa Barbara, Klamath, and Alhambra, all in California. It specified the use of a horizontal force equivalent to 0.1, 0.15, and 0.2$g$ acceleration on hard, intermediate, and soft ground, respectively.

"Provisions Against Earthquake Stresses," contained in the *Proposed U.S. 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 [21]. 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% $g$ base shear coefficient for buildings and a 10% $g$ 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 [22].

In the fall of 1931, Professor Kyoji Suyehiro visited the United States and presented a series of three lectures on engineering seismology [20], and his third lecture (III) entitled "Vibration of Buildings in an Earthquake" is of particular interest for earthquake engineering. It seems that the term "engineering seismology"—*Jishin Kogaku*—was first used at this time [23]. Suyehiro was a member of the Japanese Imperial Academy, a Professor of Applied Mechanics at Tokyo Imperial University, and Director of the Earthquake Research Institute. He died on April 9, 1932, but his lectures made strong and lasting impressions on many American seismologists and engineers who later contributed to the development of earthquake engineering.

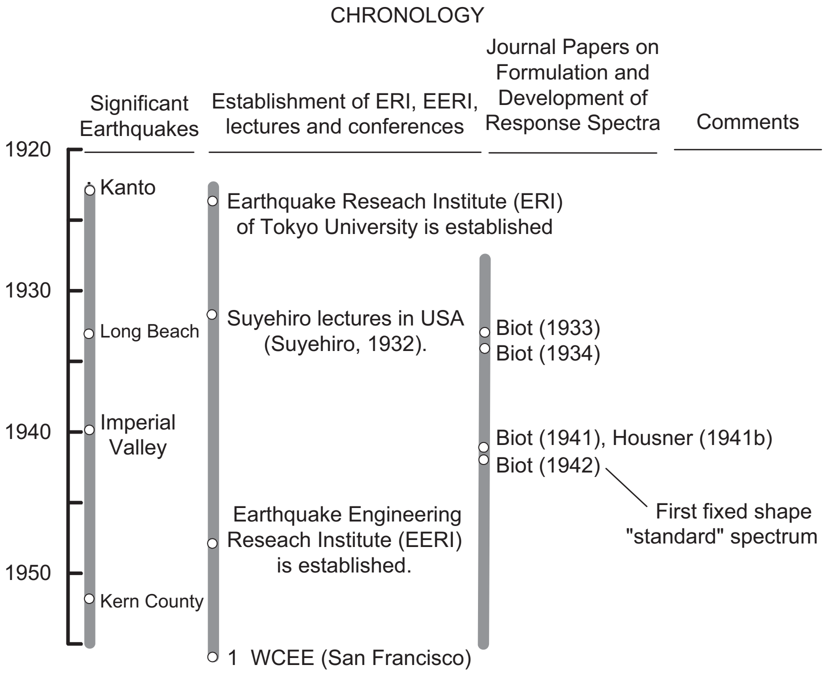


Fig. 1. Relative chronology of significant earthquakes for earthquake engineering, establishment of ERI and EERI, the Suyehiro lectures, the First World Conference on Earthquake Engineering, and journal papers dealing with formulation of the response spectrum method, between 1920 and 1955 [2,3,26,28,68].

Suyehiro's work on his multi-pendulum recorder is sometimes cited as reminiscent of and a predecessor to the concept of the response spectrum, but he (1932) refers to his pendula as a "seismic vibration analyzer" (p. 69, 7th line from top). A few lines later, he states that "each damper is so adjusted as to make the magnification of the amplitude of the resonance vibration of each stylus practically equal." Further down, on the same page, he describes the record at Hongo and how that site has a natural period of about 0.3 s. Suyehiro's discussion is directed toward analyzing periodic content in the recorded motion, as is done in general with vibration analyzers, but he presents no explicit or implicit meaning that could be related to the response spectrum concept. In discussing Suyehiro's work, Housner states (p. 24 of [24]) that the Suyehiro pendula "would give six points on the displacement spectral curve," but because the instrument did not have control of damping "the results could not be applied directly to buildings." It is interesting to note here that the torsional pendula then used by the U.S. Coast and Geodetic Survey (USC&GS), by Biot at Columbia, and by Housner at Caltech, all had the same problem—damping could not be controlled. The first spectra with controlled damping were computed with an electrical analog computer. Biot was aware of and followed Suyehiro's work, and on page 215 of Biot [3] he states, "According to recent observations (Suyehiro, Tokyo), there seem to exist characteristic frequencies of the ground at given locations. These frequencies would be given by the peaks in the spectral curves."

Fig. 1 outlines selected events in the early work on earthquake engineering, the years of "major" earthquakes (from the engineering point of view), and the year of the First World Conference on Earthquake Engineering, for the period 1920–1955.

## 4. Theodore Von Kármán and Maurice Biot

The mathematical formulation of the RSM first appeared in the doctoral dissertation of M.A. Biot in 1932 [25] and in two of his papers [2,3]. Biot defended his Ph.D. thesis at Caltech in June 1932 and presented a lecture on the method to the Seismological Society of America meeting, held at Caltech, the same month. Theodore Von Kármán, Biot's advisor, played the key role in guiding his student and in promoting his accomplishments. After the method of solution was formulated, Biot and Von Kármán searched for an optimal design strategy. A debate at the time was whether a building should be designed with a soft first floor or be stiff throughout its height, to better resist earthquake forces. An excerpt from the *New York Herald Tribune* in June 1932 illustrates this:

> **Shock Proof Buildings Sought by Scientists.**
> **Rigid or Flexible Materials, Their Difference in Theory**
> A building proof against earthquakes is the goal of Dr. Theodor von Kármán and Dr. M. Biot, of the California Institute of Technology. Dr. von Kármán described to the American Society of Mechanical Engineers, whose convention was held recently at Yale,

> studies of the amount of shock, which various types of buildings have undergone in Japan, South America, and California. Their researches are being conducted at the Institute's Guggenheim Aeronautical Laboratory.
>
> One of the principal problems is to decide whether a rigid or flexible structure is better. Some scientists contend the first is preferable; others would make the ground floor of tall buildings flexible.
>
> Pointing out that the reinforced concrete is superior to steel in absorbing the shocks, Dr. von Kármán's personal belief is that the building should be constructed to shake "with the rhythm of the earth's movements."

Another newspaper article, describing the same meeting, stated:

> **Quake Strains Discussed**
>
> **Von Kármán Tells New Haven Meeting Engineers Are Divided Between Rigid and Flexible Buildings**
>
> The most interesting piece of research now being conducted at the California Institute of Technology by Dr. M. Biot on the calculation of stresses occurring in buildings during an earthquake was described informally this morning by Dr. T. von Kármán, Director of the Guggenheim Aeronautical Laboratory at the school, under whose direction Dr. Biot is doing the work.
>
> **Seek "Quake-Proof" Building**
>
> By a study of past earthquakes in California and Japan and along the Pacific Coast of Central America, engineers interested in building problems have accumulated a record on which they believe they can calculate the rhythm or characteristic of the earth movement in these particular regions. They have sought to evolve an "earthquake-proof" building on the basis of this data.
>
> As a result of this research, said Dr. von Kármán, there have arisen two schools of thought. One asserts that only the most rigid structures should be built in the earthquake regions and the second, which Dr. von Karman supports, contends that a flexible type of building, which can swing with the earthquake, is better.

Biot's interest in the maxima of the transient response in solids and in fluids preceded, and extended beyond, earthquake engineering. After he formulated the concept of the RSM, he extended it to other vibrational problems such as the analysis of aircraft landing gear. He briefly returned to the subject of earthquake engineering almost 10 years later, presenting response spectral amplitudes of several earthquakes, which he calculated using the torsional pendulum at Columbia University [26]. In 1942 he presented a review of the RSM, discussed the effects of flexible soil on the rocking period of a rigid block [27], and described the spectrum superposition method based on the sum of absolute modal maxima [28]. After 1942, Biot moved on to other subjects, making fundamental contributions to many other fields. He did not write papers on earthquake engineering [29], but followed closely and with interest the work of others [30].

The principal areas of Biot's opus, his exceptional talent, and his technical views have been described by Mindlin [15] and by Tolstoy [31], who wrote: "While Biot's contributions to science owed much to his command of the sophisticated mathematical tools of theoretical mechanics, they were always rooted in concrete problems of engineering and geophysics. His solutions were firmly based on physical insight. He understood the pitfalls of formalism, but at the same time he appreciated the creative role of mathematical elegance upon which he laid much stress. He was one of the twentieth century's true masters of Lagrangian techniques." A complete list of Biot's publications can be found in Trifunac [32], and a list of his patents and awards is contained in the introduction to vol. 14 of the *Journal of Mathematical and Physical Sciences*, published in Madras, India, in 1980, on the occasion of his 70th birthday anniversary.

## 5. Biot's contribution

Biot's Ph.D. Thesis "Transient Oscillations in Elastic Systems" (Thesis No. 259, Aeronautics Department, Caltech, June 1932) dealt with the general theory of transient response. In Chapter II of his thesis, entitled "Vibration of Buildings during Earthquake," he introduced the formulation of what would later become known as the Response Spectrum Method (RSM). He fully developed the concept in Biot [2,3].

In Biot [3], on page 213, he states that "any vibration of an elastic undamped system may always be considered as a superposition of harmonics." Few lines further down, he continues: "…[a] building, like any elastic system, has a certain number of so called *normal modes* of vibration, and to each of them corresponds a certain frequency…we will show that any motion can be calculated when we know these modes of vibration." On the next page (p. 214), Biot defines $F(v)$, which he calls the *frequency distribution* or the *spectral distribution* of ground acceleration—which in our modern terms is the Fourier amplitude spectrum of ground acceleration. Near the bottom of the same page, Biot states:

> …we are not interested in the motion itself of the building, bur merely in its maximum amplitude. This maximum is the sum of the amplitudes of each separate free oscillation. It will not always be reached because it supposes that an instant exists for which all of the free oscillations have their maximum deflection simultaneously. However, this maximum will many times be nearly reached in a short time, and in any case it is the highest possible value.

(Today, when we discuss methods for superposition of modal responses, we refer to this formulation as *Biot's sum of absolute maxima*—e.g., [33]). Finally, on page 215, Biot discusses the properties of the *spectral distribution*, and mentions Suyehiro's observations in Japan. He then concludes: "If we possessed a great number of seismogram spectra we could use their envelope as a standard spectral curve for the evaluation of the probable maximum effect on buildings."

The above summarizes Biot's formulation of the RSM and of response spectrum superposition concept (written succinctly on three pages). Physically and mathematically it can be argued that it is superior to our modern use of the relative displacement or velocity spectra because it is directly related to the description of ground motion, via the Fourier amplitude spectrum, $F(v)$, of strong-motion acceleration. However, for all practical purposes, the modern procedures are equivalent to Biot's formulation because of (1) close agreement between the amplitudes of $F(v)$ and of the true relative velocity spectra, and (2) because the amplitudes of true velocity spectra and pseudo velocity spectra are also practically the same.

The terminology used in connection with the response spectrum concept has been evolving since 1932. Different scaling functionals were considered and used by those writing the papers on this subject during 1930s (energy spectra, spectral intensity curves, etc.), and others, who worked with the torsional pendulum [34–36] or with the models of buildings on a shaking table (Jacobsen at Stanford), were also doing essentially the same thing—computing the relative displacement response spectra—even when they called it by different names.

Today, Biot is well known to almost everybody working in mechanics, primarily for his contributions to poromechanics [31], the theory of folding, and the second-order theory of elasticity [37]. The year 2005 marked the 100th anniversary of Biot's birth, and papers, special issues of journals, and conferences were organized to celebrate the occasion. An international conference was held in Norman, Oklahoma (May 2005) the *Biot Centennial* [29] and a special issue (vol. 26, no. 6–7) of *Soil Dynamics and Earthquake Engineering* entitled "Biot Centennial—Earthquake Engineering" was published in 2006. While this review is being written, the special issue entitled "Response Spectra" of the *Indian Society of Earthquake Technology Journal* (vol. 44, no. 1, 2007) is in the final stages of printing. This special issue was prepared for the occasion of the 75th anniversary of the RSM and contains 14 papers, which are all devoted to various aspects of response spectra.

Biot did not write journal papers on earthquake engineering after 1942, although he helped and advised committees working on the development of the design codes [38], and he maintained interest and followed the developments in the field. His unpublished discussion [30], written after the publication of the study by Merchant and Hudson [39] and recently discovered by his wife Nady Biot among his papers, is included in the University of Southern California Civil Engineering Department Report, CE 07-01, entitled "Early History of the Response Spectrum Method". It shows his keen interest in and exceptional understanding of the subject.

From mid- to late 1930s, Von Kármán and Biot were writing their book *Mathematical Methods in Engineering* (McGraw-Hill 1940) [40], which had several chapters directly applicable to the structural dynamics problems related to earthquakes [41]. As graduate students Biot, Housner, Hudson, Popov [42], and many others all took courses from Von Kármán, whose style of teaching, with emphasis on the essential physical nature of the problem, left a strong and enduring impression. In EERI [24] Housner recalls, "when I started to work on my Ph.D. thesis on the dynamics of buildings, Prof. Martel asked von Kármán about the differential equation for a vibrating beam."

## 6. Computation of response spectra

Computation of response spectra can begin with the solution of Duhamel's integral [43] and then selection of the maximum response. Prior to the age of digital computers, execution of these tasks was difficult and very time consuming. For example, before the 1940s, direct numerical integration [44] and semi-graphical procedures using Intergraph instruments [45] were used.

The first practical method for computation of spectral amplitudes was based on the torsional pendulum analog [26,36]. In this method, an oscillator is represented by an eccentric mass supported by stretched wire, one end of which is forced to twist through angles proportional to the acceleration amplitude, versus time [26,46,47]. The most time-consuming difficulty associated with the use of such a torsional pendulum was the inconvenience of changing the natural period of torsional response. Gross changes in period were made by using torsional wire of different diameters. Fine adjustments were made by selecting the eccentricity of the mass on the inertia bar. Damping was also difficult to control. At first, it was thought to be zero, but later it was discovered to be in the range of a few percent of critical. The damping in the torsional pendulum came from the internal friction of the torsional spring and from air damping of the inertia bar [47]. With Biot's torsional pendulum at Columbia University, it took about 8 h to construct one spectrum curve consisting of about 30 points [28]. At Caltech, it took about 15 min to construct one spectrum point [47]. Prorating these durations to computation of spectra at 91 period points for five damping values [43] results in a duration of work of about 7000 min (167 h; Fig. 2).

In the late 1940s, an analog computer technique was introduced for solving the response of a SDOF system to arbitrary excitation. The significance of the analog computer was that it enabled, for the first time, systematic calculation of response spectra with assigned damping values. It was about 30 times faster than the torsional pendulum analog (Fig. 2). Crede et al. [48] showed how a commercial electronic differential analyzer could be used for determination of response spectra. Then, a special-purpose spectrum analyzer using electronic operation

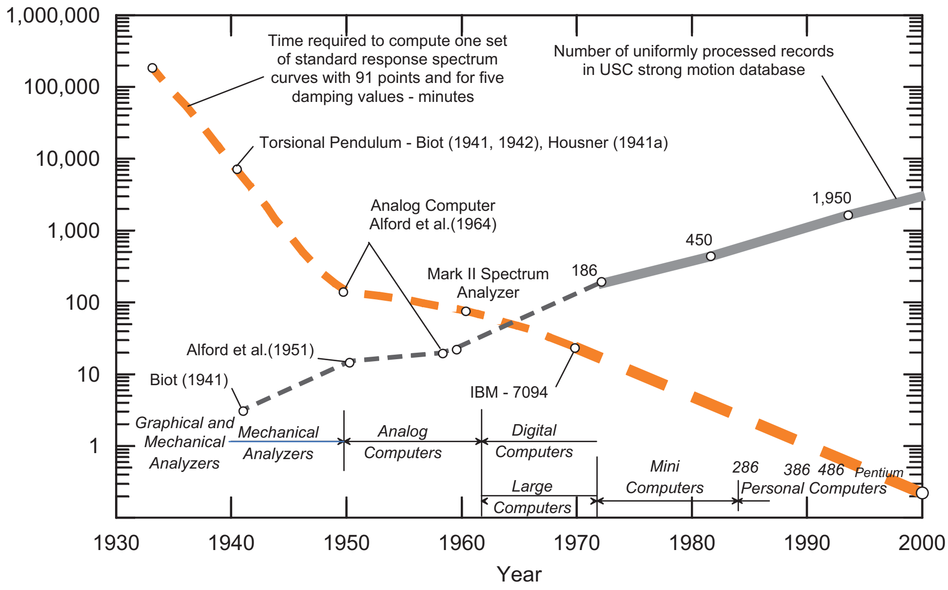


Fig. 2. Time required to compute one set of standard response spectrum curves (in min), and the cumulative number of accelerograms in strong-motion databases (light dashed line for the period prior to 1970) and in the uniformly processed strong-motion databases (wide gray line for the period after 1970) [26,28,46,47].

techniques was described by Morrow and Riesen [49]. Using these ideas, a small special-purpose analog computer system, Mark II, designed for computation of response spectra, was developed in 1954 and tested through the mid-1950s [50]. Using this electric analog, response spectra were calculated for a series of strong-motion earthquakes in the western United States [45].

In the early 1960s the methods for computation of response spectra started to change, following the general availability of digital computers. Digitized accelerograms could be used in Duhamel integral, and integration could be performed numerically. Assuming that acceleration data can be approximated by piece-wise, straight-line segments between equally spaced points in time, the Duhamel integral can be integrated exactly over each time interval, thus reducing numerical integration to a sequential application of $2\times 2$ matrices and two 2-component vectors [51].

Before the digital computer age computation of response spectra of strong-motion accelerograms was difficult and labor intensive, and the results had very uncertain accuracy. This, in combination with a very small number of available recorded accelerograms, made it impossible to carry out empirical studies on the scaling of earthquake spectral amplitudes. Also, it was difficult to explore the governing laws and to link the physical nature of the earthquake source mechanism with the amplitudes and shape of the response spectrum. It was primarily for these reasons that the RSM was confined largely to the realm of academic research for almost 40 years (1932 to ~1972).

## 7. Response spectrum in design

In his 1934 paper, Biot stated that if a large enough number of seismogram spectra were available it would be possible to use their envelope as a standard spectral curve for evaluating the probable maximum effect on structures. In Biot [26], he continued: "These standard curves…could be made to depend on the nature and magnitude of the damping and on the location. Although the previously analyzed data do not lead to final results, we…conclude that the spectrum will generally be a function decreasing with the period for values of the latter greater than about 0.2 s. A standard curve for earthquakes of the Helena and Ferndale…for values $T>0.2$ s, could very well be the simple hyperbola $A=\frac{0.2g}{T}$, and for $T<0.2$ s, $A=g(4T+0.2)$, where $T$ is the period in seconds and $g$ the acceleration of gravity. Whether this function would fit other earthquakes can only be decided by further investigations."

Eighteen years later, Housner averaged and smoothed the response spectra of three strong-motion records from California (El Centro, 1934, $M=6.5$; El Centro, 1940, $M=6.7$; and Tehachapi, 1952, $M=7.7$) and one from Washington (Olympia, 1949, $M=7.1$). He advocated the use of this average spectrum shape in earthquake engineering design [52,53].

Newmark and co-workers [54,55] found that the shape of response spectra can be determined approximately by specifying peak acceleration, peak velocity, and peak displacement of strong ground motion. Spectrum shape was further studied by Mohraz et al. [56] using 14 strong-motion records and by Blume et al. [57], who analyzed 33 records. The joint recommendations of the Newmark and Blume studies of the shape of the response spectra [58] were later adopted by the US Atomic Energy Commission (now the US Nuclear Regulatory Commission) (USAEC) [59] for use in the design of nuclear power plants (Fig. 3).

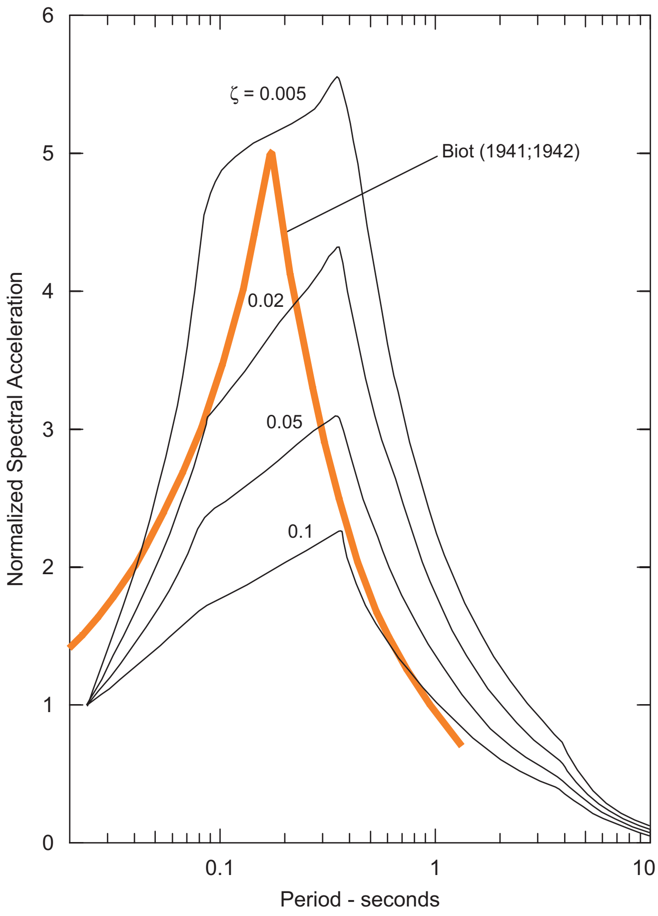


Fig. 3. Comparison of Biot [26,28] "standard spectrum" (heavy line) with the regulatory guide 1.60 spectrum [59] (four light lines for damping values $\varsigma = 0.005$, 0.02, 0.05, and 0.10).

In engineering design work, the fixed shapes of Housner and Newmark spectra, normalized to unit peak acceleration, were scaled by selecting the "design" peak acceleration. This procedure, which was first systematically used in the design of nuclear power plants, emerged as the "standard" scaling procedure for determination of design spectra in the late 1960s and early 1970s.

The rapid increase in the number of recorded strong-motion accelerograms, which started with San Fernando earthquake, in California, in 1971, made possible advanced and more complete empirical scaling of the response spectral amplitudes. Detailed review of this subject is beyond the scope of this paper, but the reader can find a detailed review in Lee [7].

The development of current seismic building code provisions started in the 1950s. A Joint Committee of the San Francisco Section of the ASCE and the Structural Engineers Association of Northern California prepared a "model lateral force provision" based on a dynamic analysis approach and response spectra [60]. The Proposed Design Curve, $C = K/T$, was based on a compromise between a standard acceleration spectrum by Biot [26,28] and an El Centro analysis by E.C. Robison. The Biot curve for peak ground acceleration (PGA) of $0.2g$ has a peak spectral acceleration of $1.0g$ at a period of 0.2 s. The curve then descends in proportion to $1/T$. If the peak spectral acceleration is limited to 2.5 times the PGA, the Biot spectrum is very close to the 1997 UBC design spectrum for a PGA of $0.2g$. The proposed design lateral force coefficient was $C = 0.015/T$, with a maximum of 0.06 and a minimum of 0.02. These values were considered consistent with the current practice, and the weight of the building included a percentage of live load [22].

## 8. Contemporary role of the RSM

As the purpose of this writing is to focus on the early history in the development of the RSM, a review of its modern developments and uses is well beyond the present scope. Nevertheless, for completeness of this presentation, we will mention a few central topics and cite several sources that can help by providing some linkage of this work with the contemporary uses of the method.

An important development that preceded the widespread use of RSM in engineering design was carried out by N. Newmark and his co-workers and students. It introduced a simple, practical procedure, based on the comparative analysis of linear and nonlinear SDOF systems excited by the same strong ground motion record, which enabled simple approximate estimation of the nonlinear response spectral amplitudes for use in design. Implementation of this approach starts with the linear response spectrum amplitudes, which are then multiplied by the reduction factors to yield the nonlinear design spectra. A recent review of this work and of its validity near earthquake faults can be found in the papers by Jalali et al. [61], and Jalali and Trifunac [62,63].

Since mid-1970s, numerous studies of the empirical scaling methods of spectral amplitudes have been developed. This work has typically occurred in cycles, which followed significant increases in the strong-motion database after major earthquakes. The first successful scaling equations were developed in mid-1970s with less than 200 strong-motion records, but by the mid-1990s there were about 2000 records [7].

Biot viewed the formulation of the standard design spectra as an enveloping process that depended upon the availability of many accelerograms recorded under different earthquake and site conditions (see [3]). This approach was used extensively in numerous projects requiring site-specific design criteria, and it has also been responsible for influencing the spectral shapes used in design codes [22]. After the mid-1970s, with the accumulation of the recorded and processed strong-motion accelerograms (Fig. 2), and following the development of the concept of uniform hazard spectrum in 1977 [64], Biot's concept of searching for envelopes evolved into a process of finding the distribution functions of site-specific spectral amplitudes. After the detailed distribution functions of spectral amplitudes were developed [7], it became possible to use the uniform hazard spectrum in both site-specific work and in seismic microzonation [64].

Other developments contributed to (1) better understanding of and refinement in the selection of the peaks of the relative response of structures (studies using order statistics for estimation of the largest peaks—e.g., [65], (2) proposals on how to use the RSM in the presence of soil–structure interaction [66], and (3) the generalization of the RSM for long structures, which are sensitive to differential amplitudes of strong ground motion (e.g., [61,67]).

As already noted, a special issue (vol. 44, no. 1, 2007) of the *Indian Society of Earthquake Technology* (*ISET*) *Journal* was devoted to the RSM. It contains 14 papers on various aspects of the use and development of the RSM and can serve as a valuable source for many contemporary references.

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