Effects of Significant Earthquakes On the Development of Earthquake Engineering

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ABSTRACT: The development of earthquake engineering around the world over the past century has been influenced by several types of causes other than disastrous earthquakes. An earthquake that was large in seismological (e.g. magnitude) or engineering (e.g. destructiveness) measures may have had little effect on engineering tools developed to contend with the earthquake problem. The history of earthquake engineering is not merely a set of events rigidly tied to a chronology of major earthquakes. Nonetheless, some significant earthquakes have been step function events on the graph of long-term progress in earthquake engineering. In this brief historical review, the following seminal earthquakes are discussed: 1906 California, United States; 1908 Reggio-Messina, Italy; 1923 Kanto, Japan; 1931 Mach and 1935 Quetta, India; 1931 Hawke's Bay, New Zealand. Rather than an all-encompassing theory as to why some earthquakes more than others have been influential in the development of earthquake engineering, the author's historical research leads to the conclusion that it is important to examine the unique historical context of each earthquake.

1 INTRODUCTION

The thesis of this paper is that large, damaging earthquakes sometimes but not always have stimulated important developments in the history of earthquake engineering. One such influential earthquake from each of the following countries is discussed in chronological order: the United States, Italy, Japan, India, and New Zealand. Comparisons with the 1931 Hawke's Bay Earthquake are emphasized. For reasons of space, the number of countries discussed is arbitrarily small, though all those included here would deserve to be on a list of countries where earthquake engineering developments have been significant.

2 THE 1906 EARTHQUAKE IN NORTHERN CALIFORNIA

The earthquake of approximately magnitude 8 that was released by the rupture of 500 km of the San Andreas Fault in northern California was to be the largest earthquake in the twentieth century in the United States, outside of Alaska. Estimates of the life loss are in the range from approximately 700, a figure often reported in the older literature such as Freeman (1932, p. 8), to about 3,000, as suggested more recently by Hansen et al. (1989) As in the 1923 Kanto and 1931 Hawke's Bay Earthquakes, fire ignitions, and rapid fire spread due to water system damage, caused great loss.

The centennial of this 1906 earthquake being commemorated this year provides a useful vantage point from which to assess the long-term impacts it had on the development of earthquake engineering. There were some forward-looking engineering responses after the earthquake, such as in San Francisco in 1907 in the seismic design of the Globe Building, with its precocious use of reinforced brick walls made integral with a surrounding steel frame (Tobriner, 1984), but that was exceptional. Overall, few structural engineering or structural dynamics developments followed in the decade after the earthquake in the USA that were comparable to the advanced earthquake engineering being done at the time in Japan and Italy. Rather than adopt the seismic ratio method from abroad, for example, San Francisco and its engineers continued to rely on a surrogate wind load for seismic design purposes (and even that was set as low as 15 psf, or 720 pascal). In terms of research and education, however, there were some very significant long-term effects caused by the 1906 earthquake. See Reitherman, (2006) for further details and complete references concerning the following.

The Lawson Report, (Lawson et al., 1908), named after the chair of the Earthquake Investigation Commission, Andrew Cowper Lawson (1861-1952), was perhaps the most comprehensive report on an earthquake up to that time. Published within that report was the paper by Hugo Fielding Reid (1859-1944) elucidating the elastic rebound theory, which has proven central to ground motion seismic hazard studies to this day. Equally significant but less noted is the fact that the assembling of the team that compiled the document was in effect the recruitment mechanism by which several key individuals devoted themselves to the new field of earthquake studies. A.C. Lawson had a great effect on the initiation of earthquake studies at the University of California at Berkeley. Lawson, like many geology professors of the day, especially in the western USA, was more interested in mining than earthquakes. It was the earthquake of April 18, 1906 that changed his career course.

One of Lawson's protégés was Harry Oscar Wood (1879-1958), a young geology instructor at Berkeley, who was assigned by Lawson the key task of studying the intensity of shaking in San Francisco. Before the 1906 earthquake, Wood was a mineralogist; ever after he was a seismologist. Wood subsequently launched the seismographic program in Southern California of the Carnegie Institution, a foundation set up by the richest man in the world, Andrew Carnegie. At the time, the national government provided almost no funding for earthquake studies. Thus the support of the Carnegie Institution was so important. The Carnegie Institution's program begun by Wood was to be handed off in 1927 to the California Institute of Technology. This was the origin of what was to become that university's major presence in that field. By 1923, Wood had invented with astronomer John Anderson the Wood-Anderson seismograph and had begun to deploy it in a functional Southern California seismographic array. This was prior to when Caltech added a geology department in 1926, and prior to when Charles Richter (1900-1985) was hired by Caltech in 1927. The Wood-Anderson seismograph produced so many accurate and standardized seismograms that Richter was led to invent the magnitude scale to make sense of that data. The title of his historic paper, "An *Instrumental* Magnitude Scale," (Richter, 1935, emphasis added) refers to the instrument Wood had the lead role in inventing. In addition to Harry Wood, John Buwalda (1886-1954) was another former Berkeley faculty member who migrated to southern California, establishing the Geology Division at Caltech, bringing with him a motivation that came from his seismic research that originated in 1906 at Berkeley.

Meanwhile, at the other university in Northern California, Stanford University, the head of the geology department, John Casper Branner (1850-1922), was also proselytized by the 1906 earthquake to enter the earthquake field with a passion. J.C. Branner was pulled away from his first love, the geology and other aspects of one of the most non-seismic regions on Earth, Brazil. Because of the 1906 earthquake, J.C. Branner became a leading advocate of earthquake research in California and is at the root of the family tree of earthquake research and education at Stanford University, as well as later serving as its president. Branner was also the one who encouraged fellow faculty member F. J. Rogers to build a shake table to conduct dynamic soil studies after the earthquake. In addition, Branner recruited Bailey "Earthquake" Willis (1857-1949) to take over the leadership of geology at Stanford, and also to assume Branner's role as president of the Seismological Society of America. Willis in turn was instrumental in the hiring of mechanical engineer Lydik Jacobsen (1897-1976) to the faculty. Jacobsen, who became the first president of the Earthquake Engineering Research Institute when it was constituted in 1948 and began to function in 1949, established a vibration laboratory at Stanford and was the advisor of John Blume (1909-2002). Blume was to begin his influential career in earthquake engineering in the 1930s and for many years thereafter be an important figure in the new field. Today, there are many engineers whose primary vocation is earthquake engineering, but it was a rare career path in the 1930s.

The Seismological Society of America was established in San Francisco directly as a result of the 1906 earthquake, and it was operational by the end of that year. Even with the impetus of the dramatic disaster, SSA struggled financially for many years, and without the earthquake, it is likely no such organization would have been established until probably after the 1933 Long Beach Earthquake. A reading of the issues of the *Bulletin of the Seismological Society of America* in those pre-1933 years indicates what a loss to the field that delay in its establishment would have been.

In my research, I was surprised to find out that Arthur Ruge (1905-2000), the co-inventor of the modern electric resistance strain gauge, had his "Eureka!" moment while conducting shake table experimentation in 1937 and 1938 at MIT. That research was funded by the insurance industry's concern over fire losses caused by the 1906 earthquake, a direct causal link connecting that disaster with one of the most important inventions in engineering instrumentation of the twentieth century. It is puzzling why such a momentous connection with the 1906 earthquake and earthquake engineering in general has not been previously recognized.

The now well-established series of World Conferences on Earthquake Engineering all began in 1956 with the first in that series. It was no accident that 1956 was exactly 50 years after the California earthquake of 1906. George Housner, President of EERI at the time, in his Preface in the proceedings (Housner, 1956), listed the first purpose of the event as "Observing by an appropriate technical meeting the fiftieth anniversary year of the destructive San Francisco Earthquake of 1906."

More broadly, the 1906 earthquake established the credibility of the study of earthquakes in the United States, making it a worthy subject for a small but productive cadre of scientists and engineers to devote their careers to, first in academia and later in practice. At least one such major earthquake has generally had to occur in a country before earthquake engineering has taken root there and grown. In the USA, that earthquake was the 1906 earthquake in Northern California.

3 THE 1908 EARTHQUAKE IN REGGIO AND MESSINA, ITALY

This earthquake, located in the strait between the mainland of Italy (the city of Reggio) and Sicily (Messina), caused 120,000 fatalities. Earlier earthquakes in Italy had also caused massive losses, and some had inspired embryonic attempts to fashion improved construction methods to resist earthquakes, such as the 1783 Calabria Earthquake (Tobriner, 1984) But it was the 1908 earthquake which, in the opinion of an authority such as John Freeman (1855-1932), had such a historic effect on earthquake engineering. "The beginning of scientific study of the mechanics of earthquake-resisting construction followed immediately after more than 100,000 people had been killed in the Messina-Reggio earthquake of December 28, 1908. It began with the appointment of a remarkable committee, comprising nine practicing engineers of large experience and five eminent college professors of engineering." (Freeman, 1932, p. 565) In post-1906 research in California, the earth scientists had a higher profile than the engineers; in the post-1908 work in Italy, the engineers stepped forward.

Luigi Sorrentino of the "La Sapienza" University of Rome has recently examined a number of contemporary reports and regulations that were produced by that committee. Led by Modesto Panetti (1875-1957), the engineers produced a calculation method on the basis of rational engineering theory using the seismic ratio concept and simplified it into a workable equivalent static lateral force design method. Newton's quantification of inertial force, $F = m\ a$, had long been available, and it was easy for engineers to compute the mass, but the acceleration term in this seemingly simple equation would not lend itself to calculations. The first strong ground motion accelerogram of modern form was only obtained in 1933, and useful records were only slowly to build up after that. Even with a single or composite reliable ground motion record, the seismic ratio method faced great challenges because of the rapidly changing sequence of accelerations interacting with a structure's response. The method, which in modern form is still the most common means of calculating seismic design loads, in effect must reduce a complex series of varying forces down to one representative design force at a given level in the building. Structural data on periods of vibration, damping levels, modal effects, and ductility were non-existent or sketchy one hundred years ago. Faced with these challenges, the Italian engineers selected a few buildings that performed well under strong shaking in the earthquake. They back-calculated an estimate for the static lateral force that the buildings were capable of resisting. They used this to help calibrate a design lateral force ratio, for typical kinds of construction. This results today in the familiar base shear calculation, namely the product of building weight (mass) and the seismic ratio applied to various stories. They increased the seismic ratio up the height of the building, realizing that a multi-story building did not displace as one rigid box, and that upper levels experienced greater accelerations than lower ones. They specified a design lateral force of 1/12 of the mass of the building's ground story, 1/8 for the story above. The "raporto sismico" in Italy, or the "shindo" in Japan where we shall see it was independently developed by Toshikata Sano, later became "seismic coefficient" or "seismic ratio" in English. An engineer who was influential though not on the committee was Arturo Danusso (1880-1968), whom Sorrentino credits with an early response spectrum method for one- and two-degree-of-freedom structures responding to harmonic loading.

This productivity in earthquake engineering, far from being an evolutionary deadend, is recognizably part of the seismic genealogy that has resulted in earthquake engineering as we know it today. According to Giuseppe Grandori however (Grandori, 2005), that activity was followed by decades of relative silence in the earthquake engineering field in Italy, until engineers of his generation began university research and education in the subject in the 1960s. The large earthquake in Italy that occurred relatively soon after the 1908 event, in 1915 in Avezzano, was when the country was preoccupied with World War I. After that, there were other damaging earthquakes and some follow-on code or engineering developments, such as after the July 23, 1930 earthquake near Irpino, but some of the engineers involved in the 1908 earthquake studies had become absorbed in other areas, such as aircraft design or the development of a reinforced concrete construction industry for a growing infrastructure, and some had passed away.

4 THE 1923 KANTO EARTHQUAKE IN JAPAN

The September 1, 1923 earthquake that struck the Kanto region, including the large cities of Yokohama and Tokyo, had a fatality toll estimated at 140,000. Although the Hawke's Bay Earthquake of 1931 was to strike a region of lesser urbanization, earthquake-caused fire in conjunction with water system disruption was a factor common to both earthquakes.

One could also cite other earthquakes in Japan that were very significant in the history of earthquake engineering. The 1880 Yokohama Earthquake caused the formation of the Seismological Society of Japan, the world's first such association. The 1891 Mino-Owari Earthquake led to the formation of the Imperial Investigation Committee. (By chance, that committee's series of reports and studies, some of which consisted of more than one book-length part, reached Volume 100 on the occasion of the 1923 earthquake.) Also in 1891, Bunjiro Koto (1856-1935) accurately realized that the faulting he observed was the cause of the ground shaking, not the effect--a key breakthrough. John Milne (1850-1913) and Fusakichi Omori (1868-1923) were influential in the development of earthquake engineering by the 1880s. Along with Milne, there were other key British faculty at the University of Tokyo (called here by its modern name, though in those years much of the work was accomplished at the branch called the Imperial College of Engineering): James Ewing (1855-1935), Cargill Gilston Knott (1856-1922), Thomas Corwin Mendenhall (1821-1924), John Perry (1850-1920), T. Gray (1850-1908), William Ayrton (1847-1908). Exactly twenty years prior to the 1906 earthquake in California, Kiyokage Sekiya (1855-1896) was appointed to a full-time chair of seismology at the University of Tokyo. (Otani, 2004, p. 4)

Nonetheless, the 1923 Kanto Earthquake can be singled out for its effect on the field of earthquake engineering. The Earthquake Research Institute was established at the University of Tokyo after the earthquake, assuming the role of the Imperial Earthquake Investigation Committee, and to this day it has been a major research and education force in the field. The earthquake caused the establishment of the first seismic regulations in a building code in the world to affect a concentration of large engineered structures—the 1924 Building Code Enforcement Regulations. (Otani, 2004, p. 6) Building code regulations had been passed after the 1908 earthquake in Italy and in earlier Italian earthquakes, but the 1924 legislation is historic for its application to Tokyo and other intensively developed urban areas that had large structures. The seismic ratio ("shindo") method in that code, using a 10% force level, was based on the work of Toshikata Sano of the University of Tokyo and his student, Tachu Naito (1886-1970), who became the head of structural engineering at Waseda University. Prior to that 1924 mandatory code, Naito had incorporated such thinking and carried out the necessary seismic calculations and detailing in his design of several large structures that performed well in 1923, such as the Kabuki Theater and Industrial Bank of Japan.

This was a historic first in earthquake engineering: A structural engineer employed seismic analysis computations, carefully designed the structure to resist those seismic loads, detailed the construction to implement new construction practices, and then saw the resulting building tested by a major earthquake. Naito's buildings performed very well in contrast to the standard non-seismic designs of an American firm doing work in Tokyo at the same time, the George Fuller Company. They also did well as compared to the significantly damaged Imperial Hotel of Frank Lloyd Wright (1867-1959). (Reitherman, 1980) Wright's admittedly brilliant architectural skills, as well as his knack for self-promotion, gave him a reputation as a heroic seismic designer in the popular press, but the engineering world was impressed by Naito. Naito's theories of seismic design conveniently had the warm-up test of the smaller Uragasuido Earthquake in 1922. Naito had recommended that the Marunouchi Building should incorporate seismic features of the steel-reinforced-concrete type, a steel frame encapsulated with reinforced concrete, but his advice was not followed and it was badly damaged in that moderate test in 1922. As if the 1923 Kanto Earthquake had been waiting impatiently to provide a confirmation that modern earthquake engineering was on the right path, the earthquake occurred only six months after Naito's treatise on earthquake engineering was published. (Naito, 1923) The hypothesis had been stated; the experiment was conducted; the hypothesis was verified.

One of the few American engineers of the time heavily involved in the young field of earthquake engineering, Harold Engle, noted that "the three buildings in Tokyo specifically designed by Dr. Naito to be earthquake-resistant actually fulfilled their function in 1923, while many other large structures designed more along customary American lines were subject to very serious damage in many cases in the shock of 1923." (Engle, 1929, p. 89) Engle also stated that Naito "after 1923 made available to engineers in this country the details and design of some of those buildings that he designed before 1923 and which survived the shock so successfully." (Engle, 1956, p. 39-5) While the single American earthquake selected here for discussion is the 1906 event, the first widespread seismic regulations in building codes in the United States date from the 1933 Long Beach Earthquake. The engineering content of those regulations, the Field Act and Riley Act, evolved from earlier Japanese engineering work, especially as it became more well known after 1923, and was not a result of the 1906 earthquake as one might tend to assume.

5 THE 1931 MACH AND 1935 QUETTA EARTHQUAKES IN INDIA

Here I give myself a waiver from my self-imposed limit of one key earthquake per country. The 1931 Mach and 1935 Quetta Earthquakes form a closely related pair that tells the story of an interesting development in the history of earthquake engineering in India. The earthquakes of August 1931 in Mach in Baluchistan, the largest of which was over magnitude 7, occurred in what was then part of the British colony of India and is now part of Pakistan. Of interest here is the fact that the most highly engineered construction in the region, the railroad system, had significant damage, and that S. L. Kumar, a young engineer working for the railroad, was tasked with designing new earthquake-resistant dwellings for displaced railroad employees. That episode in the history of earthquake engineering as well as other details discussed here are drawn from Jain (2002). In 1933, Kumar published his "Theory of Earthquake Resisting Design With A Note on Earthquake Resisting Construction in Baluchistan," which included a seismic zonation map of India and a variation in seismic ratio from 5% to 15%, depending on both the seismic zone and the importance of the structure. (Kumar, 1933) (Seismic ratios in different codes such as are mentioned here should not be compared without considering how live loads are included and what the allowable stresses were, which space does not allow.) Kumar was aware of the earlier work in Japan on the seismic ratio method, illustrating again how influential that work was elsewhere. Reminiscent of Naito's preference for steel-reinforced-concrete was Kumar's advocacy of a steel frame embedded in concrete, or in masonry to reduce cost. Actually, his first designs incorporated iron rather than steel frames, because he used the iron rails that were available within the railroad system at a time when steel rails were being phased in. Kumar devised connection details to use the rails for columns, beams, and roof truss members. Two other aspects of this account of early Indian earthquake engineering are similar to the story of Tachu Naito and the 1923 Kanto Earthquake: Not only did Kumar design buildings with a particular seismic design method and lay out the theory of his approach and publish it prior to the earthquake, in addition Kumar's buildings were soon tested by a major earthquake. In the magnitude 8 Quetta Earthquake on May 30, 1935, a disaster that killed 20,000, Kumar's buildings did very well, while the others in the vicinity were badly damaged or collapsed. As Jain (2002, p. 320) notes, "For the first time in India, the effectiveness of earthquake-resistant construction was tested during a severe earthquake." In India, the 1935 Quetta Earthquake marks the start of the first seismic regulations in the building code, an effect comparable to that of the Hawke's Bay Earthquake on construction standards in New Zealand.

6 THE 1931 HAWKE'S BAY EARTHQUAKE IN NEW ZEALAND

From an earth sciences perspective, the large magnitude, 7.9, of the February 3, 1931 Hawke's Bay Earthquake immediately made it noteworthy. For example, in the classic textbook by John Milne, as updated by Lee (Milne and Lee, 1939), the seismogram recorded at the Kew Observatory in London of this New Zealand earthquake is singled out for its instructiveness with respect to reflection and refraction of waves through the earth. The aftershocks were also well studied. Surface faulting was noted. What are usually called ground failures occurred in abundance. Liquefaction and seismic compaction caused water pipeline damage, contributing to the great fire loss in Napier and Hastings. Landslides cut off roads. In addition, the term "ground failure" seems inadequate to describe the effect of the earthquake on the scale of the overall landscape of the greater Napier region: 1500 sq km of what had been marshes or part of the sea suddenly became dry land due to uplift. Docks and boats were left high and dry. When one flies to Napier today, the airplane lands where fish previously swam. The permanent displacement of the ground proved to be a significant effect in other earthquakes in coastal areas, notably the 1964 Alaska Earthquake. All in all, the 1931 earthquake provided a rather comprehensive catalog of earthquake phenomena.

It is primarily the effects of the earthquake on engineering and construction that are of most relevance here, though earthquake engineering has progressed hand-in-hand with its sister discipline of seismology. On the city planning scale, Napier today has a low-rise, Art Deco characteristic that makes it unique in New Zealand. After the damage to Lisbon from ground shaking, fire, and tsunami in the 1755 earthquake, the Baixa central business district was rebuilt along then-modern lines, with a grid street system. Another example of city-scale impact on a city's post-earthquake construction is the re-building of Noto in Sicily in the Baroque style of the day after that medieval town was so badly damaged in the 1693 Sicilian Earthquake. (Tobriner, 1983) In Napier, the architectural impact of the earthquake and the reconstruction is well chronicled by McGregor (1999, 2002, 2003). Earthquake engineering considerations as well as the architectural style of the day imported from Europe were significant in determining how the city would re-build. In Napier, "the masonry buildings were severely damaged in almost all cases, although the new concrete ones generally survived." (McGregor, 2002, p. 19) Steel was a relatively expensive and hard to obtain material, especially in those days of the depression. At that time, when George William Forbes was Premier, the country like the rest of the developed world had already been in a depression since 1929, but it hit New Zealand especially hard. By 1933, the national debt was one of the largest in the world on a per capita basis, and paying the interest on that debt accounted for 40% of the government's expenditures. (Sinclair, 2000, p. 264) For reasons of both economy and structural engineering, reinforced concrete was thus the logical choice for the new Napier. If forced to name only one of the primary structural materials that New Zealand earthquake engineering has concentrated on, it would probably be reinforced concrete and its family members precast and prestressed concrete. The development of earthquake engineering research on concrete buildings began in the 1960s by the generation of people such as Robert Park (1933-2004) and Thomas Paulay who had no direct connection to the Hawke's Bay Earthquake. However, that best known of New Zealand earthquakes had some effect in boosting the trend toward reinforced concrete construction, just as the 1923 Kanto Earthquake did in Japan. Also noted by engineers of the time was the benefit of including a complete structural frame in a building, even if load-bearing walls were also present.

The development of earthquake engineering is not merely a chronology of the evolution of a country's building regulations, but it is almost always true that in the absence of such regulations, earthquake engineering is a subject of little interest. The Hawke's Bay Earthquake led to the inclusion of seismic regulations in the New Zealand Standard Code of Building By-Laws (Murphy, 1956, p. 21-1). The original regulations were of the seismic ratio type used in Japan, without explicit factors accounting for dynamic effects, but once a code was in place, there was a framework that could be improved upon over the years. As time went on, the basic seismic ratio method, developed originally in Italy and Japan as discussed above, was modified in the New Zealand code to pattern itself after contemporary American practice, such as the "Lateral Forces of Earthquake and Wind" produced by a joint committee of the American Society of Civil Engineers and the Structural Engineers Association of Northern California, cited as being influential by Murphy (1956).

In the 1960s the era begins when New Zealand earthquake engineering rapidly progressed and set its own course. Innovative seismic design thinking by practitioners such as J.P. Hollings and Lyall Holmes, encouragement of improvements to building standards by government officials such as Otto Glogau, and university research by professors such as Bob Park, Tom Paulay, and Nigel Priestley, are all part of the era that extends to today. That subject of the present lies beyond this paper's scope, except to point out that the 1931 Hawke's Bay Earthquake was more influential than any other in preparing the way for the current era of progress in earthquake engineering in New Zealand.

7 CONCLUSIONS

The thesis of this paper is that disastrous earthquakes sometimes but not always have stimulated important developments in the history of earthquake engineering. A corollary is that leading nations in the field of earthquake engineering typically experienced at least one earthquake of disastrous impact within relatively modern times before a high priority was placed on earthquake engineering. The earthquakes discussed here, culminating with the 1931 Hawke's Bay Earthquake, whose 75th anniversary is being commemorated this year, all stop short of the current era of earthquake engineering, because the scope here is focused on the origins of that era rather than its present state. Predicting what effect a future significant earthquake in New Zealand might have on earthquake engineering is even further beyond the scope of this paper as well as the capabilities of the author. However, I will speculate that some or even all of the following ten characteristics of New Zealand earthquake engineering that have been evident in the past (Park and Paulay, 2006) will exert their influence when that future major earthquake occurs.

1. Framing of research agendas around the needs of engineering practice;
2. Efficient communication of developments in New Zealand to other countries;
3. Placing at least as much importance on experimental discovery and verification concerning the "capacity side of the equation" as on software development and analysis on the "demand side of the equation";
4. Lack of liability and litigation barriers to implementation of needed innovations;
5. Absence of a heavy bureaucratic burden imposed by government agencies and regulations;
6. Recognition of seismic risk as a nationwide problem;
7. Capitalizing on the small size of the nation to facilitate communication and dissemination of new ideas;
8. Close collaboration among universities, practicing engineers, the construction industry, and government;
9. Evolution along its own earthquake engineering path because of geographic remoteness;
10. Influences on earthquake engineering exerted through the traits of the New Zealand people in general, especially the pioneering tradition of self-reliance.

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