THE DAWN OF STRUCTURAL EARTHQUAKE ENGINEEIRNG IN JAPAN

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ABSTRACT :

No western scientific and technological information was made available in Japan when the Tokugawa shogun government closed the country from 1639 to 1854. The Meiji Emperor's regime, after the 1968 restoration, made efforts to strengthen military power and to develop industry through promotion of science and technology. The Meiji government invited "young" western and U. S. engineers and researchers to train native students from 1873. Engineering faculty was included in the Imperial University in 1886, and visiting western professors were gradually replaced by Japanese. A huge intra-plate Nohbi Earthquake (M 7.9) hit Nagoya areas in 1891, and Earthquake Investigation Committee was set up in 1892 to promote the study on seismology and earthquake engineering. The 1923 Kanto Earthquake caused significant damage in Tokyo and Yokohama. Seismic design of buildings was introduced in the Urban Building Law in 1924, requiring design seismic forces equal to 10 percent of the floor weight.

KEYWORDS: Seismological Society of Japan, College of Engineering, invited foreign teachers, seismic coefficient, seismic coefficient

1. INTRODUCTION

The Tokugawa shogun government, Japan, closed the country in 1639 to prohibit the propagation of Christianity in the country. The foreign trade was allowed only at a small man-made island in Nagasaki, Kyushu, with Netherlands, China and Korea.

During the isolation period, Japan could enjoy the development of its own culture, such as Kimonos, tea ceremonies, flower arrangements, Kabuki and Noh plays, and Ukiyo-e paintings, but was placed out of reach from western scientific, medical, technical and military developments. Japan re-opened the country in 1854, first to the United States, and then to other western countries.

The Tokugawa shogun government was overturned in 1868, and the ruling by Emperor was restored. An important task of the new regime was to strengthen military power to maintain national independence from invading western imperialistic pressure and also to develop strong industry in the country to support better life of people through the promotion of western science and technology.

2. TECHNOLOGICAL EDUCATION BY INVITED FOREIGN ENGINEERS

The Meiji government established the Ministry of Technology (Kobu-sho) in 1870. First Minister, Hirobumi Itoh (1841-1909) established the College of Engineering (Kogaku-ryo, renamed to Kobu Daigakko in 1877) in 1873 under the ministry for the training of professional engineers, and he consulted Professor William J.M. Rankine (1820-1872) of Glasgow University (present Strathclyde University), Scotland, on education policies and possible candidates for the principal of the college. Upon recommendation, Henry Dyer (1848-1918), as young as 25 years old, took the position and came to Japan with eight British teachers. Dyer outlined the education principle to emphasize practical training. Civil engineering, mechanical engineering, house building (architecture), telegraphy, practical chemistry, mining and metallurgy were taught in six years at the college. Dyer taught civil and mechanical engineering in the college.

Young western and U. S. practicing engineers and researchers, such as John Perry (1850-1920), William E. Ayrton (1847-1908), John Milne (1850-1913), Josiah Conder (1852-1920), James A. Ewing (1855-1935), Thomas C. Mendenhall (1841-1924), Thomas L. Gray (1850-1908) and Cargill G. Knott (1856-1922), were invited to teach motivated native students. Note that most of these invited teachers came to Japan in their mid-twenties. Milne, the pioneering researcher of modern seismology in the world, arrived in 1876 and taught mining and metallurgy, and stayed in Japan until 1895. Conder, a British architect, started architectural education in 1877 and was active in architectural design in Japan until his death. Perry and Ayrton published "On Structures in Earthquake Country" in 1879. Ewing wrote "Treatise on Earthquake Engineering" in 1883. Mendenhall was superintendent of U.S. Coast and Geodetic Survey from 1889 to 1894. Knott wrote "The physics of Earthquake Phenomena" in 1908.

The College of Engineering was placed under the Ministry of Education (Mombu-sho) in 1885 when the Ministry of Technology was terminated.

The University of Tokyo was founded in 1877 at Hitotsu-bashi, merging existing several education institutes. The university consisted of four faculties; i.e., medicine, law, science and literature, and was reorganized as the Imperial University in 1886, absorbing the College of Engineering as a faculty. Visiting western professors were gradually replaced by Japanese faculty members in the Imperial University; e.g., Seikei Sekiya (1854-1896), who worked closely with Ewing and Milne, became the first professor of seismology chair at Faculty of Science in 1886. Professor Conder of Department of Architecture, College of Engineering, was replaced by Kingo Tatsuno (1854-1919), one of Conder's first students, in 1884. Professor Tatsuno became Dean of Faculty of Engineering, Imperial University, in 1898.

It should be noted that it took only 15 years for the change in engineering education; from education by invited foreign teachers to that by trained native teachers.

3. SEISMOLOGICAL SOCIETY OF JAPAN

G. F. Verbeck (1830-1898) tried to measure earthquake ground motions in 1872 by a 6-feet long pendulum seismograph. Verbeck, an American, served as principle of a governmental education institute (Kaisei Gakko). Erwin Knipping (1844-1922) also started earthquake observation in 1872. Henry B. Joyner (1839-1884) adopted, in 1875, Palmieri-model seismographs at the Geography Agency (Chiri-kyoku), Ministry of Interior.

A small earthquake (M 5.5) jolted Yokohama on February 22, 1880, causing minor damage to buildings. This earthquake attracted the attention of visiting scholars from Europe and the United States. The Seismological Society of Japan, first world scientific organization on seismology, was established in 1880 under the leadership of John Milne, with the objective to study the earthquake phenomena and volcanoes. Visiting scientists and engineers joined the society, but not many Japanese members. In 1881, the number of members was 117, out of which the number of Japanese members was 37. Note that Seismological Society of Italy was established in 1895, International Seismological Association was founded in Strasbourg in 1901, and Seismological Society of America was established in 1906 after the 1906 San Francisco Earthquake.

Important research findings were published in the transactions of the society in English, dominantly by visiting scholars. For example, Milne introduced the work of Robert Mallet (1810-1881) on observational seismology. Ewing noted the difference between primary and secondary waves in the recorded ground motion. Modern seismographs were developed by Ewing, Gray and Milne, in 1881, to measure three-directional ground movement. This seismograph was formally adopted by Japanese meteorological observatories in 1885; Sekiya contributed to install standard seismographs throughout the country under Geography Agency, and to collect seismic data of uniform quality.

Early earthquake engineers and seismologists knew the importance of acceleration amplitudes of an earthquake motion to estimate inertia forces acting on structures. The seismograph, however, was not capable of measuring ground acceleration. E. S. Holden, Director of the Lick Observatory in California, reported (Holden, 1888) that "The researches of the Japanese seismologists have abundantly shown that the destruction of buildings, etc., is proportional to the acceleration produced by the earthquake shock itself in a mass connected with the earth's surface." He also noted that "The earthquake motion is a wave-motion, and although it is not simple harmonic, it is necessary to assume it to be such to obtain a basis for computation." and that "It would be logical to express I (intensity of ground motion) in fractions of the acceleration due to gravity ..."

Indeed in Japan, efforts were made to estimate the maximum ground acceleration during an earthquake. In 1884, Milne and his student, Sekiya, estimated maximum ground acceleration amplitudes from measured seismograph records by assuming displacement signals to be harmonic. Because the dominant frequencies in displacement and acceleration signals are different, this method tends to underestimate the maximum acceleration.

John Milne introduced the West's equation in 1885 (Milne, 1885), which estimated maximum ground acceleration necessary to overturn a rigid body attached on the ground simply using the equilibrium of moment of lateral force and vertical gravity load about the center of rotation (Figure 1). Charles D. West (1847-1908) succeeded Henry Dyer in 1882 as the principal of the College of Engineering, and taught mechanical engineering and naval architecture. The West's equation was the standard method to estimate the intensity of ground motion in Japan from the dimensions of overturned tomb stones after earthquakes.

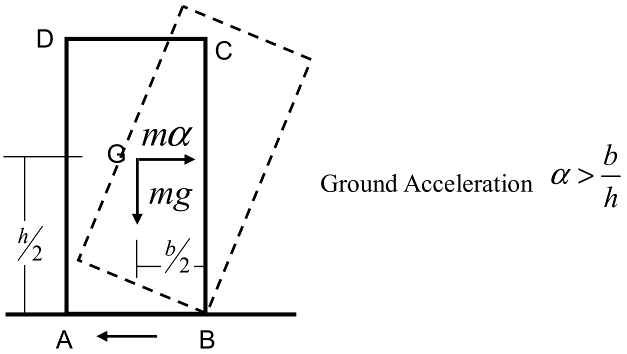

Figure 1 West's Equation to estimate maximum ground acceleration to overturn a rigid body

At the Seismological Society of Japan, main research efforts were made by visiting researchers and engineers at the College of Engineering and the Tokyo University. Main emphasis in seismological investigation under the leadership of Milne was to collect earthquake data through the seismograph observation and dynamic tests of simple structures. Milne was also interested in the effect of earthquake motions on building response.

The Seismological Society of Japan was absorbed by the Earthquake Investigation Committee in 1892, and the role of investigation was given to the hand of Japanese researchers. Another Seismological Society of Japan was established in 1929 under the leadership of Professor Akitsune Imamura (1870-1947), who succeeded Professor Fusakichi Omori (1868-1923) at Tokyo Imperial University.

4. THE 1891 NOHBI EARTHQUAKE

A huge earthquake (Nohbi Earthquake, M 7.9) hit Nagoya areas in 1891. This was a largest-class intra-plate earthquake in Japan. Yertical 6.0 m and horizontal 2.7 m movement was recorded at a surface fault in Neodani.

The earthquake killed more than 7,273 and injured more than 17,000 in sparsely populated areas. 142,177 houses collapsed and 80,184 suffered heavy damage and even then modern brick factories and buildings were severely damaged in Nagoya (Photo 1). Chuta Itoh (1867-1954), then student in department of architecture and later professor of architectural history in Imperial University, attributed the structural damage in brick construction primarily to strong intensity of ground motion, and then to poor materials and work of brick masonry construction. However, brick and masonry construction was badly condemned to be unsafe against earthquakes and prohibited in Japan after the Nohbi earthquake.

John Milne, professor of mining, and W.K. Burton, professor of sanitary engineering, both of Imperial University, reported the disaster assisted by a Japanese photographer, K. Ogawa (Mine and Burton, 1891). Milne noted that "buildings on soft ground, - which is generally the plains, - suffer more than those on the hard ground which may be the hills." He pointed out that "we must construct, not simply to resist vertically applied stresses, but carefully consider effects due to movements applied more or less in horizontal directions." Although he stressed the need of seismic design using lateral forces, no quantitative design forces were proposed for design.

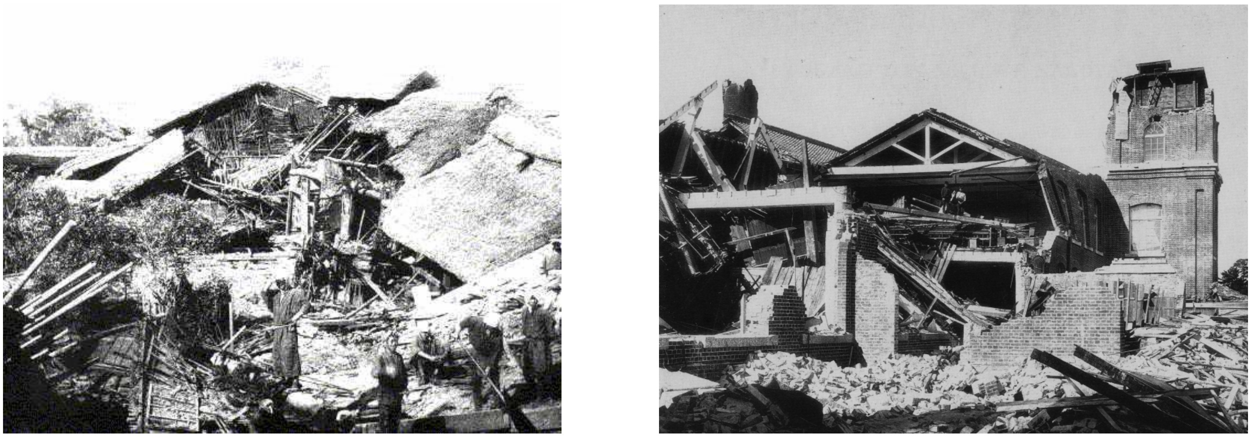

Photo 1: Damage of timber houses and new brick factory (the 1891 Nohbi Earthquake)

Upon strong recommendation in the Diet by Dairoku Kikuchi (1855-1917), Dean of Science Faculty, Imperial University, the government established the Earthquake (Disaster Prevention) Investigation Committee in 1892 to promote the study on seismology (especially earthquake prediction) and earthquake engineering, to investigate earthquake resistant construction and earthquake disaster mitigation methods, and to implement research findings in practice. The chairman of the committee, Hiroyuki Kato (1836-1916), President of Imperial University, was appointed by the Emperor, and its members by the Cabinet upon recommendation by Minister of Education. The committee, consisting of all Japanese, studied seismology, tsunami, volcanic eruption, characteristics of earthquake motions, terrestrial magnetism, earth gravity, history of earthquakes, building materials and earthquake resistant structures. The committee published research finding in "Report of Earthquake Investigation Committee" in Japanese and also "Publication of the Earthquake Investigation Committee in Foreign Languages."

The emphasis of investigation, carried out by Japanese, gradually shifted from the earthquake prediction to the development and implementation of earthquake resistant building construction. Graduates of department of architecture were heavily involved in the committee activity on earthquake resistant construction. "Principle of Construction of Earthquake Resistant Timber Houses" was published in 1895, in which the use of diagonal braces and rigid foundation was recommended. Kingo Tatsuno, Dean of Faculty of Engineering and professor of architecture, became the chairman of the Earthquake Investigation Committee in 1901.

It is important to note that the Meiji-Sanriku Earthquake (M7.6 to 8.2) occurred off east coast of Sanriku under the Pacific Ocean, in June 1896. The ground shaking was not so severe on land, but huge tsunami killed 26,360 and washed away 9,879 houses in the Northeast coast of Japan. Causes of an earthquake disaster are not limited to ground shaking.

5. EDUCATION OF ARCHITECTURE AND EARTHQUAKE RESISTANCE

Josiah Conder, a British architect, was invited to teach house building engineering (architecture) at the College of Engineering. Conder studied architecture at the Royal Institute of British Architects in London and joined the office of William Burgess (1827-1881) who specialized design of Victorian style architectures. Conder participated in a design competition hosted by Royal Institute of British Architect and won the Soane Prize in 1876. He came to Japan in 1877. His contract at the college was 5 years from 1877, and the contract was extended for another two years.

The first four students, admitted in 1873 to the department of architecture, had already finished preparatory and professional study for four years, and were about to start their two-year professional training. However, no invited foreign teachers in the college could guide practical training in architecture until Conder arrived. The four students successfully graduated the college in 1879.

Kingo Tatsuno (1854-1919), one of his first students at the college, succeeded Conder as professor of architecture in 1884. The College of Engineering was merged to the Imperial University in 1886. Conder became a part time instructor in the department in 1886 and then retired from the Imperial University in 1888.

He opened his own architect office in 1891.

It should be noted that architectural education in Japan started in a college specializing engineering rather than art. The construction of modern western buildings, especially brick and masonry construction, was so different from Japanese traditional timber construction, and was thought to be an engineering issue. The profession of carpenters were established in Japan, capable of building large castles, palace buildings, shrines and temples in addition to residential houses; these were all timber construction. Carpenter's art (technology) was handed down from a master to apprentices at the construction site, and there was no systematic nor structured education for this profession. The brick and masonry construction was so different from timber construction that the students in the department of architecture had to study the materials, construction methods and structure in addition to architectural design.

In the department of architecture, College of Engineering, strength of materials, building materials, building and residential construction were taught to provide students with structural engineering background. The engineering and science subjects were more encouraged to students when the College of Engineering became Faculty of Engineering, Imperial University. Lectures on seismology were given by Seikei Sekiya in 1887, and many students from the department of architecture attended the lecture.

After the 1891 Nohbi earthquake, many graduates of architecture visited the affected areas, observed the damage of buildings, and discussed the cause of heavy damage. The safety of houses and buildings from earthquakes was convinced to be an important issue in Japan. Josiah Conder observed the severe damage in buildings and pointed out in a speech at a meeting of the Institute of Japanese Architects (present Architectural Institute of Japan), founded in 1886 under strong guidance of Conder, that an architect in the seismic prone country must be a scientist before an artist.

Lectures on iron construction was given in the department of architecture, Tokyo Imperial University, by Lecturer Tamisuke Yokogawa (1864-1945) from 1903. Lecturer Toshikata (or Riki) Sano (1880-1956), a pioneer researcher in earthquake engineering in Japan, replaced Yokogawa in 1905 and lectured calculation of building construction (structural analysis) and iron construction. The Imperial University was renamed to the Tokyo Imperial University in 1897 when the Kyoto Imperial University was founded.

Associate Professor Sano visited San Francisco after the 1906 San Francisco Earthquake. He reported his findings in Journal of Japanese Architecture (present Journal of Architecture and Building Science); (1) the number of casualties was deliberately reported small by the local government, (2) the fire disaster was extensive, (3) the damage of buildings was severer in the reclaimed land than on the hills, (4) the intensity of ground shaking was estimated to be 0.1 G on the hills and 0.25 G in the reclaimed land, (5) the performance of steel structures was generally good under shaking, (6) the performance of the two reinforced concrete buildings was good, (7) the failure of brick and masonry construction was attributed to poor material quality and workmanship (Sano, 1906 and 1907). The West's equation was used to estimate the intensity of ground motion in San Francisco.

It is interesting to note that reinforced concrete, one of the most advanced building materials in the world, was prohibited to use in walls in San Francisco because bricklayers were afraid to lose their employment opportunities and threatened the government for action. However, Sano found a reinforced concrete building, called the Park Panorama Building in Golden Gate Park, built before the ban, and observed its good behavior. He was convinced that reinforced concrete construction should be good for earthquake resistance and recommended its construction in urban areas in Japan.

6. SEISMIC DESIGN FORCES FOR BUILDINGS

The December 1908 Messina Earthquake in Sicily killed approximately 83,000. The Royal Government of Italy established Geological Committee and Engineering Committee in early 1909 to study the disaster and recommend the earthquake disaster mitigation measures. The Engineering Committee reported (Oliveto, 2004) the damage in the affected areas; (a) the masonry construction in the affected area had poor structures made of irregular fluvial stones and poor mortar, (b) the barrack houses, recommended after the 1783 Calabria earthquake, performed well, and (c) reinforced concrete frames of good materials and connections performed well.

The Engineering Committee, after studying the lateral load resistance of buildings which survived the earthquake motion, recommended that the seismic ratio (seismic acceleration divided by the gravity acceleration) equal to 1/12 for the first floor and 1/8 for the floors above should be used in seismic design of buildings. The Committee proposed equivalent vertical forces much larger than the horizontal forces because vertical motion acted as impacts. This was the first quantitative recommendation of design seismic forces in the history. Design examples were included in an appendix of the report. It should be noted that the design lateral force was determined on the base of estimated lateral resistance of surviving buildings.

The recommendation was adopted in Royal Decree No. 573 of April 29, 1915. The height of the buildings was limited to two stories, and the first story should be designed for a horizontal force equal to 1/8 the second floor weight and the second story for 1/6 of the roof weight.

Toshikata Sano, associate professor of architecture, Tokyo Imperial University, wrote a doctoral thesis, entitled "Earthquake Resistance of Buildings," in 1915, in which he proposed the use of equivalent static horizontal loads in seismic design of buildings. He also pointed out the importance of strength, ductility and stiffness of structural members (Sano, 1916 and 1917).

Sano assumed a building to be rigid and directly connected to the ground surface. He defined a seismic coefficient (Shindo) to be the maximum ground acceleration normalized to gravity acceleration G. Although he noted that the lateral deformation of a structure might cause lateral response acceleration larger than the ground acceleration, he ignored the effect and assumed the lateral response acceleration of a structure was equal to the ground acceleration. He estimated the maximum ground acceleration to be 0.30 G and above in Honjo and Fukagawa areas in Tokyo on alluvial soft soil on the basis of the damage to houses in the 1855 Ansei-Edo (Tokyo) Earthquake, and 0.15 G in the Yamanote area on diluvial hard soil. He estimated the maximum ground acceleration in Osaka to be 0.35 G and above, and that in Nagoya to be no less than 0.30 G. He assumed that vertical ground acceleration to be approximately one-half to one-third of the horizontal acceleration.

Sano also discussed in his doctoral thesis earthquake damage to brick masonry, steel, reinforced concrete and timber buildings and proposed methods to improve the earthquake resistance of such structures.

The author considers that the concept of Sano's seismic coefficient is the same as the horizontal acceleration considered in the West's formula (Figure 1), in which the horizontal acceleration acting on a rigid body was the same as the horizontal ground acceleration. Sano, indeed, used the West's formula to evaluate the intensity of ground motion in the 1904 Taiwan Earthquake and also in the 1906 San Francisco Earthquake. The originality of Sano may be his use of ground acceleration in structural design while the West's formula was intended to estimate the intensity of ground motion. The fundamental difference from the Italian definition of design lateral force is that Sano's Shindo was based on the intensity of ground motion while the Italian Committee after the 1908 Messina Earthquake determined the design lateral force based on the estimated lateral resistance of surviving structures.

7. THE 1923 KANTO EARTHQUAKE AND SEISMID DESIGN REGULATIONS

The 1923 Kanto Earthquake (M 7.8/7.9, Ms 8.2) occurred along the Sagami Trough, approximately 100 km to the south of Tokyo. Approximately 105,000 were killed dominantly by fire, 103,700 injured, and 109,000 houses collapsed, 212,000 houses burnt. Major damage occurred in Tokyo and Yokohama. The disaster became worse by fire of timber houses because the earthquake occurred just before noon. Fire engines could not be used due to the breakage of water pipes.

The Naigai building collapsed, which was nearly completed at the time of the earthquake using U.S. construction method (Photo 2). The seven-story Industrial Bank of Japan building survived the earthquake with little damage. The structural engineer of the bank building was Tanaka (or Tachu) Naito (1886-1970), professor of architecture in Waseda University, who used a seismic coefficient of 1/15 in the seismic design of the bank building and also provided many reinforced concrete structural walls to resist earthquake forces. A twelve-story Ryoun-kaku Tower in Asakusa collapsed; brick construction to 10th floor, and timber construction in the eleventh and twelfth floor.

The statistics of damage on reinforced concrete buildings in Tokyo revealed that only 22 out of 553 R/C buildings suffered heavy damage (Table 1); more than seventy-five percent of reinforced concrete buildings survived with no damage. The statistics is amazing if one notes that the buildings were not designed for earthquakes at the time. The intensity of ground motion might not be so large in Tokyo, although the fire worsened the disaster.

Photo 2: The Naigai Building near completion collapsed

Table 1: Damage of reinforced concrete buildings in Tokyo (Earthquake Investigation Committee, 1926)

Damage level	No. of buildings
Collapse	7
Severe damage	11
Major damage	4
Minor damage	69
Light damage	462
Total	553

The reinforced concrete construction was proven to be earthquake and fire resistant by this earthquake. The damage was observed in buildings with (a) brick partition walls, (b) little shear walls, (c) poor reinforcement detailing, (d) short lap splice length of reinforcing bars, (e) poor beam-column connections, (f) poor construction, (g) irregular configuration, and (h) poor foundation.

The first Japanese building code, Urban Building Law, was promulgated in April 1919, to regulate buildings in six major cities (Tokyo, Yokohama, Nagoya, Kyoto, Osaka, and Kobe). The construction of large buildings was permitted only when the government approved the application. The Urban Building Law Enforcement Order limited the building height to 100 feet (30.3 m). Building Law Enforcement Regulations, issued in November 1920, specified structural design for timber, masonry, brick, reinforced concrete and steel constructions on the basis of allowable stress design methods. Quality of materials, connections, reinforcement detailing, dead and live loads, and method of calculating stresses in section were prescribed in the regulations. Design against earthquake and high wind forces was not specified in 1920.

The Urban Building Law Enforcement Regulations were revised in June 1924 to introduce the use of seismic coefficient of 0.10 in structural design. The maximum ground acceleration of 0.3 G was estimated in downtown Tokyo during the Kanto Earthquake. The safety factor of 3 was used to determine the allowable stress level relative to the material strength. No dynamic amplification in structural response was considered as Toshikata Sano assumed in his doctoral thesis. In case of rare events such as a strong earthquake, it was judged acceptable to rely on the full material strength to resist disturbances. Therefore, the design seismic coefficient was determined by dividing the estimated maximum ground acceleration of 0.3 G by the safety factor of 3.0 to yield 0.10. The regulations further specified minimum lap splice length for reinforcing bars, use of top and bottom reinforcement in girders, and minimum dimensions and reinforcement of columns.

Although seismic forces were specified in the regulations, no practical methods of stress analysis were available to structural engineers in the 1920s. Building structures are highly statically indeterminate. Actions and stresses in a building must be calculated before seismic forces can be utilized in design. Naito (1924) analyzed a series of rectangular frames under horizontal forces to study the lateral stiffness of columns and the height of inflection points, and he proposed lateral force distribution ratios (D-value) for interior (1.0) and exterior (0.5) columns, and for flexible frames (1.0) and shear walls (8 to 20).

The Naito's D-value method was further extended and improved by Professor Kiyoshi Muto (1903-1989), Tokyo Imperial University, and adopted in "Standard for Structural Calculation of Reinforced Concrete Structures" of Architectural Institute of Japan in 1933. Lateral stiffness of columns was theoretically evaluated taking into account (a) flexural stiffness of the column, (b) stiffness of adjacent girders immediately above and below the column, and (c) support conditions at the column base. Story shear was distributed to columns in the story proportional to their lateral stiffness. The moment distribution of the column was determined by the column shear and the height of inflection point, which was evaluated taking into account (a) the relative location of story, (b) the stiffness of adjacent girders immediately above and below the column, (c) changes in the stiffness of the adjacent girders, and (d) the difference in inter-story height immediately above and below the column. The sum of column end moments at a joint was distributed to girder ends in proportion to the girder stiffness. Various factors were prepared in table format for practical use.

The importance of structural engineering was convinced at the Architectural Institute of Japan (AIJ). Tamisuke Yokogawa became AIJ President in 1925, first from structural engineering field. It became an unwritten rule at AIJ, after Yokogawa, to select its presidents alternately from architectural design and planning field and structural engineering field.

SUMMARY

Modern scientific and technical education in Japan was initiated by invited young foreign teachers in 1970s at the College of Engineering. These foreign teachers and engineers founded the Seismological Society of Japan in 1880, and carried out extensive research on experimental seismology with John Milne as the leader. Japanese researchers educated by the invited foreign teachers gradually took over faculty positions at the Imperial University from 1886. The 1891 Nohbi Earthquake made a turning point in seismological research in Japan; i.e., research was carried out by Japanese staff, and the earthquake disaster mitigation became the main objective of research. Unlike European and American tradition, the education of architecture started in engineering environment in Japan, education, The 1923 Kanto Earthquake caused significant damage in Tokyo and Yokohama. Seismic design of buildings was introduced in the Urban Building Law in 1924, requiring design seismic forces equal to 10 percent of the floor weight. The seismic design became possible by the development of simple and practical structural analysis methods.

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