HISTORY OF GEOTECHNICAL EARTHQUAKE ENGINEERING IN JAPAN

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ABSTRACT :

Japan is vulnerable to earthquakes and has historically experienced many kinds of seismic damages. The modern earthquake engineering was initiated by introduction of the seismic coefficient method. It was applied to geotechnical engineering as the Mononobe-Okabe dynamic earth pressure theory in 1920s. The 1923 Kanto earthquake supplied a valuable knowledge on the effects of local soil conditions on the damage extent. Liquefaction attracted the first engineering concern after the 1964 Niigata earthquake. Since then, the points of concern have varied from its causative mechanism and assessment of liquefaction risk through preventive measure to consequence of liquefaction and its prediction in the context of performance-based design principle. Moreover, many technologies have developed to mitigate the liquefaction risk. In addition to reinforcing structures as has been conventionally done, the development of lifelines since 1980s resulted in real-time earthquake engineering. Thus, there are many ideas and evolution of geotechnical earthquake engineering in Japan which is frequently attacked by earthquakes and is actually a natural laboratory of earthquake engineering.

KEYWORDS: seismic coefficient, earth pressure, history, geotechnical, liquefaction

1. INTRODUCTION

Located on the boundary between the Pacific Ocean and the Eurasian Continent, Japan has historically experienced many strong earthquakes. The first written record of an earthquake is found in AD 413. In the 7th Century, there are already detailed written records about earthquake damages. Due to repeated experiences, people learnt lessons how to mitigate earthquake damages. A typical example is a flexible structure of pagoda towers in Buddhism temples. Being made of timbers, those towers had the natural period longer than that of brick towers in China and hence avoided resonance with ground motion, resulting in greater chance to survive earthquakes. Ancient documents repeatedly described boiling of water from the ground. Although it is an evidence of liquefaction in today's sense, no special attention was paid to this because there were hardly important structures on liquefiable soils.

Landslides have been other important seismic problems. Fig.1 illustrates the Ohya Landslide which was triggered by the 1707 Hoei gigantic earthquake. This example shows today the problem of long-lasting slope instability that continues even now and requires lots of efforts to prevent debris flow upon heavy rainfall.

Similar to other countries, most earthquake victims in Japan were killed by collapse of traditional houses. In western Japan, particularly, houses are covered by a heavy tile roof as a provision against strong typhoon wind. This heavy roof generates significant seismic inertia force during shaking and destroys easily the soft columns and walls that support the roof (Fig.2). Noteworthy is the resonance of the houses, which have long natural period, and the earthquake shaking on soft alluvium whose predominant period is long as well. This fact is important because most Japanese cities have been traditionally located on soft alluvial planes.

It seems that people in mountain areas empirically learnt to locate their houses in landslide-free places. Fig.3 shows houses in Yamakoshi Village after the 2004 Niigata-Chuetsu earthquake. While many weathered slopes failed due to shaking, houses in the figure were located on flat lands in front of ridges and were not affected. Although this is the case in many places of the village, local trunk roads were totally destroyed by landslides and people had to be evacuated for a long time. In spite of such situations, the understanding of earthquakes and related damages were not scientific in the modern sense. People believed that earthquakes were caused by catfish action and, after damaging quakes, people tried to punish catfish in order to avoid further nightmares (Fig.4).

Figure 1 Ohya landslide

Figure 2 Damaged wooden house (2007 Noto earthquake)

Figure 3 Location of houses and slope failures (2004 Niigata-Chuetsu earthquake)

Figure 4 People punishing catfish after 1855 Ansei earthquake in present Tokyo

Figure 5 Damaged river dike (1891 Nobi earthquake)

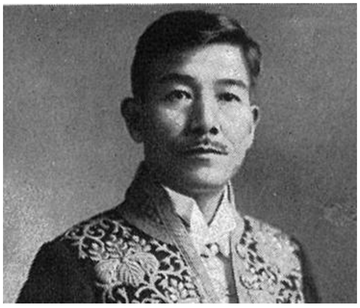

Figure 6 Prof. Toshikata Sano from his memorial book

2. PERIOD OF MODERNIZATION

Modern science and technology began to be introduced into Japan in the second half of the 19th Century. In 1880, three British people, namely J. Milne, J.A. Ewing, and T. Gray, were inspired by strong shaking in Tokyo and established the Seismological Society of Japan. They pointed out the importance of recording the earthquake ground shaking and developed instruments.

The 1991 Nobi earthquake was of the magnitude of 8 and destroyed many structures in Nagoya and surrounding areas. This earthquake is famous for creation of a fault cliff. Moreover, Fig.5 shows longitudinal cracks along the Nagara River dike. They were probably caused by subsoil liquefaction and the consequent lateral expansion of the dike. After this devastating earthquake, the government decided to establish the Earthquake Disaster Prevention Investigation Council in 1892 and initiated both scientific studies on earthquakes and development of engineering for damage mitigation.

One of the most significant developments in modern earthquake engineering was achieved by Prof. Toshikata Sano who visited San Francisco after the 1906 earthquake and got the idea of using seismic inertia force as the design earthquake action. Sano (1907 and 1916) stated that the seismic force is given by the ground acceleration multiplied by the mass of a structure and then recommended the acceleration to be 10 to 30% of that of gravity. This proposal was adopted in building design codes in 1920s and drastically reduced the number of earthquake victims afterwards. The idea of seismic inertia force as a static design force was immediately applied to the design of retaining walls by Mononobe and Okabe (Figs.7 and 8); Mononobe (1924), Mononobe and Matsuo (1929), and Okabe (1924 and 1926). It is noteworthy that the Mononobe-Okabe theory is an extension of Coulomb active earth pressure theory and hence does not address the earth pressure that does occur during shaking.


Figure 7 Prof. N.Mononobe around 1930


Figure 8 Dr. S.Okabe in 1926

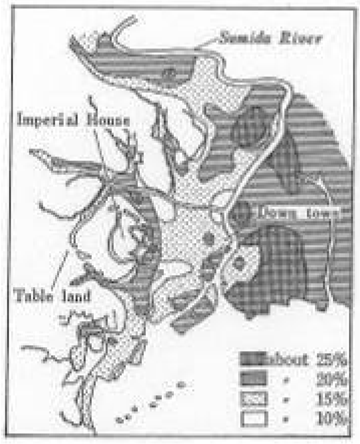

Figure 9 Damage distribution of wooden houses in Tokyo during 1923 Kanto earthquake (Okamoto, 1973)

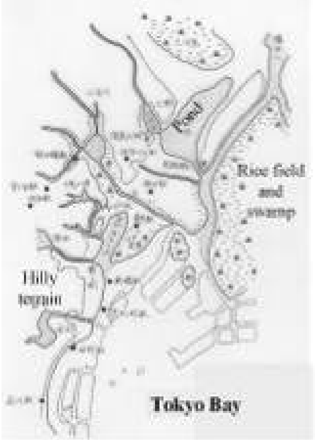

Figure 10 Original topography of Tokyo before AD 1600 (after Murai, 1994)

The 1923 Kanto earthquake totally destroyed Tokyo and Yokohama. Fig.9 shows the distribution of damage rate of wooden houses in Tokyo. Apparently, greater rate of damage occurred in the east part of Tokyo where a big river eroded the original ground during the era of low sea level in the Pleistocene period and that valley was filled with soft soils later in the Holocene period. It should be noted, furthermore, that there is another area of high damage rate near the Imperial House. To understand this situation, the original topography around AD 1600 when urbanization of Tokyo started is illustrated in Fig.10. It is seen therein that the eastern part of Tokyo used to be a rice field and swamps owing to the very soft subsoil. It is important that there is a small inlet to the east of the Imperial House, suggesting that there is likely soft soil deposit therein as well. Moreover, a big pond in the upper half of Fig.10 corresponds to another area of high damage rate in Fig.9. Thus, the experience in 1923 (Fig.9) implies the amplification of earthquake motion due to soft subsoil in the present sense.

In 1930s, interest in mechanical properties of soils started. Ishimoto and Iida (1936 and 1937) developed both a theory and a device for resonant column tests on soils, in which loading frequency of cyclic loading was varied and the frequency at the maximum response was employed to determine the elastic properties of soils. Since no confining mechanism was available for soil specimens in those days, only specimens with fines or moisture, which were able to maintain their shapes, were tested. Later, Iida (1938) introduced cellophane sheets to maintain the shape of dry sandy specimens. Because still no effective stress was applied to specimens, low S-wave velocity of 50 to 200 m/sec was obtained. Resonant column tests developed significantly in 1960s.

Important knowledge on faults and tectonic actions were obtained in the first half of the 20th Century. The first example is the appearance of a strike-slip fault that appeared in an ongoing tunneling project (Fig.11) at the time of the 1930 Kita Izu earthquake. Since the tunnel was not damaged by this significant fault effect, people came to believe that tunnel is safe during earthquakes. Although this idea was correct in hard rocks, the 1995 Kobe earthquake and the 2004 Niigata-Chuetsu earthquake showed that tunnels in soft soils and rocks are not very safe.

The second knowledge was obtained during the 1944 Tohnankai earthquake of 7.9 in magnitude. Mogi (1985) reported unexpected variation of geodetic survey results before and after this quake. Even more remarkable is the fact that the experienced leveling engineers could not adjust their instruments when the earthquake was going to start. This implies that some ground movement had started before the onset of the main shock. More substantial tectonic movement was observed after the 1946 Nankai earthquake of 8.0 in magnitude. Fig.12 illustrates the sea submergence of Suzaki Town due to tectonic action. According to ancient documents, similar events occurred at least four more times in AD 684, 1099, 1707, and 1854 with possibly more unrecorded ones. Note that the site in Fig.12 is above the sea level now because of the uplifting of land that occurred slowly after the earthquake.

Figure 11 Fault plane that appeared in ongoing Tanna Tunnel project (Atami Construction Office, 1933)

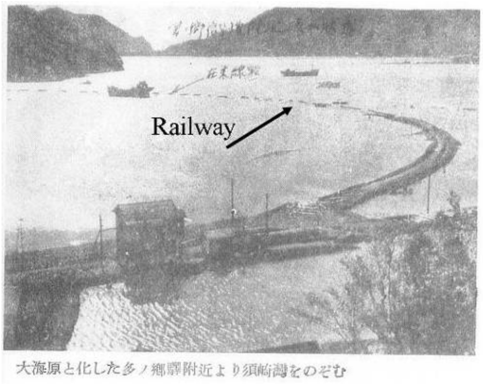

Figure 12 Submergence of Suzaki Town due to tectonic action during 1946 Nankai earthquake (Kohchi Prefectural Government)

3. DEVELOPMENTS IN SECOND HALF OF 20TH CENTURY

In the second half of the 20th Century after the World War II, the political structure totally changed and people's life style and types of infrastructures became drastically different from previous ones. Hence, new kinds of earthquake damages became important and also many types of mitigations emerged. To begin with, a remark is made of a tsunami attack in 1960 in the north east part of Japan. The tsunami was triggered by a gigantic earthquake of Mw=9.5 in magnitude off Chile of South America. The generated tsunami traveled across the Pacific Ocean and, 22 hours later, reached Japan to kill 142 people. Since a big sea wall helped some local community, the importance of wall construction was widely recognized. It is well known, moreover, that the international tsunami warning system was established after this earthquake.

3.1. Influence of 1964 Niigata earthquake

The 1964 Niigata earthquake was characterized by subsoil liquefaction. Although it had been known in former earthquakes, liquefaction came to be recognized as one of the earthquake-induced disasters after this quake. The reason for this is that urban development and human activities extended to a liquefaction-prone geology in 1964. For example, Fig.13 shows there used to be a big cove on the left bank of the Shinano River in Niigata City. This water area was filled with dune sand in middle 20th Century by transporting abundantly available dune sand in the coastal area. Since no compaction effort was required in those days, a young and water-saturated loose deposit was formed by clean fine sand. This area was named Kawagishi-Cho, which meant a town beside a river, and, upon the 1964 earthquake, liquefaction occurred significantly, causing tilting of apartment buildings (Fig.14). Other striking events were falling of brand-new Showa Bridge (Fig.15) and subsidence of new Niigata Airport Terminal Building.

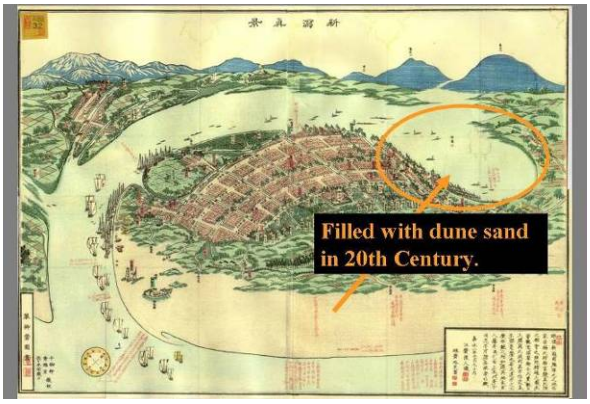

Figure 13 Former topography of Niigata in 1849

Figure 14 Tilting of Kawagishi-Cho Apartment buildings

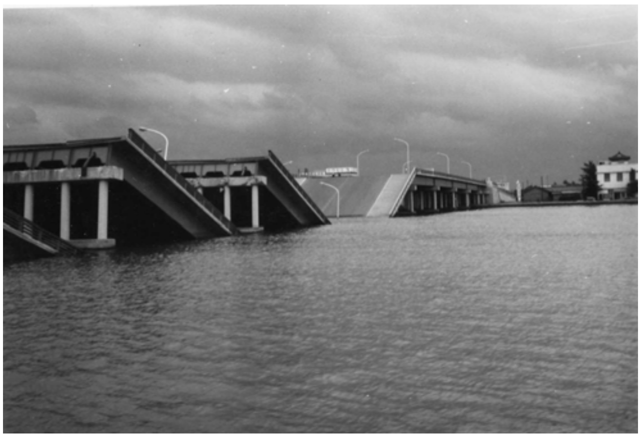

Figure 15 Liquefaction-induced collapse of Showa Bridge

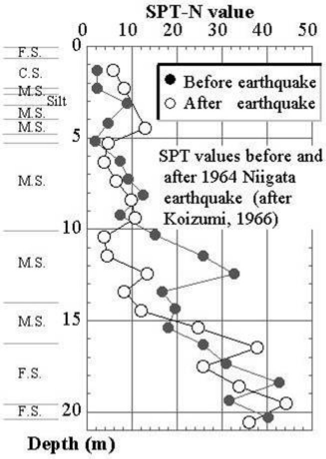

Figure 16 Variation of SPT-N due to liquefaction (Koizumi, 1966)

After this earthquake, intensive efforts were initiated to understand the mechanism of liquefaction, to assess the liquefaction potential of given subsoil conditions, and to mitigate the risk. It is important to say that those efforts were based on case history studies, field investigations, and laboratory soil tests as well as shaking model tests. This point is significantly different from the way of studies in previous times in which theoretical and analytical studies had been considered important; see Mononobe-Okabe earth pressure studies. Fig.16 is an example in which the variation of *SPT* blow counts due to shaking is plotted. It is therein seen that the blow counts increased at the depth of 3-5 meters, implying densification of sand due to liquefaction. In contrast, the blow counts at 10-15 meter depth decreased, probably because sand was loosened by strong shaking. It was thus concluded that there is a critical *SPT*-N value that borders liquefiable and unliquefiable sands. This idea of critical N value led to early design codes for assessment of liquefaction risk.

Studies on the causative mechanism of liquefaction was initiated by shaking model tests; for example, see Yoshimi (1967). However, cyclic triaxial tests soon became very popular due to the influence from USA where the importance of liquefaction studies was similarly recognized after the 1964 Alaska earthquake. While shaking model tests can clearly demonstrate the general feature of liquefaction, laboratory shear tests can observe stress-strain behavior of sand in the course of liquefaction, and clearly measure the resistance of sand against liquefaction. This feature of cyclic triaxial device made it possible to study experimentally the effects of such many soil parameters on liquefaction resistance of soils as density, gradation, stress history, and fines content among others.

Not much later after the Niigata earthquake, soil improvement to mitigate the liquefaction risk became possible. Typical examples are densification and gravel drains. While the former is reliable after densification without maintenance, heavy ground vibration and noise are the problems. The installation of gravel drains to accelerate the dissipation of excess pore water pressure solved these problems. Note, however, that the capability to reduce the liquefaction risk was much greater for densification.

It was later found that liquefaction in Niigata City induced lateral displacement of ground and consequent breaching of embedded lifelines as well as bending failure of pile foundations. Although these events attract much engineering concern today, they were not focused on immediately after the earthquake.

3.2. Situations in 1970s

The period of 1970s was a time to develop modern geotechnical earthquake engineering after the experience in 1960s. The 1971 San Fernando earthquake in California also promoted this situation. It appears that major developments occurred in four particular fields. First, technologies in laboratory shear tests on sand achieved significant developments, and hence much knowledge was obtained on behavior of soils under cyclic loading. Examples are the stress-strain behavior and the resistance against liquefaction. The author collected and assembled those achievements in one book (Towhata, 2008).

Second, the aforementioned knowledge helped constitutive models of soils and numerical dynamic analyses to be improved. Most dynamic analyses that are in use today originated in 1970s or at least employ constitutive models that were developed in those days. One problem is that those models do not address large residual deformation or permanent deformation of liquefied ground because those topics were not interested in in 1970s. Hence, care should be taken today not to overestimate the value of residual deformation that is predicted by those constitutive models.

The third development occurred in field investigation technologies. Data was collected from insitu tests as well as undisturbed soil samples to make it possible that dynamic analyses and assessment of liquefaction potential are carried out in more reliable manners.

The fourth development occurred in soil improvement. Both densification and gravel drains became widely employed in order to reduce the liquefaction risk. Most densification technologies in 1970s had such problems as heavy vibration, noise, and soil displacement, and therefore they were not easily practiced in urban areas. In this regard, quieter grouting came into practice.

3.3. Lateral displacement of liquefied ground during Nihonkai-Chubu earthquake in 1983

The traditional idea on mitigation of liquefaction was actually prevention that did not allow high excess pore water pressure to develop. This idea had to be modified upon the 1983 Nihonkai-Chubu earthquake. Fig.17 shows a gentle dune slope in Noshiro City where liquefaction induced significant lateral displacement in a slope of 2% gradient. As illustrated in Fig.18, this displacement destroyed a local trunk pipeline for urban gas supply (Hamada et al., 1986). This damage was taken seriously by gas and other lifeline industries because lateral displacement of several meters due to liquefaction in such a gentle slope and its remarkable effects to embedded pipelines had not been known. Leakage of gas could have caused fatal problems to local communities.

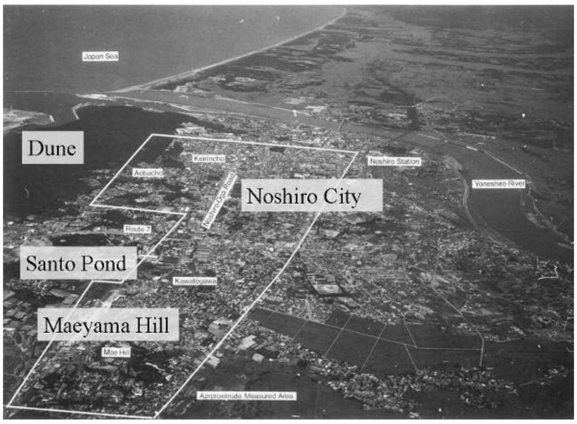

Figure 17 Gentle slope around Maeyama Hill that liquefied and moved laterally (after ADEP)

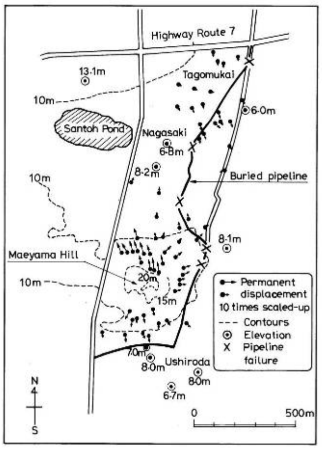

Figure 18 Permanent lateral displacement around Maeyama Hill due to subsoil liquefaction (after Hamada et al., 1986)

Figure 19 Damage of Tokachi River dike during 1993 Kushiro-Oki earthquake (Ministry of Construction)

Figure 20 Damage of Yodo River dike during 1995 Kobe earthquake (Fudo Construction)

Figure 21 Liquefaction in Kobe Port Island

Figure 22 Collapse of fill on former valley topography (2004 Niigata Chuetsu earthquake)

Although subsoil liquefaction is thus a significant threat to lifeline industries, it is difficult for those industries to improve soil and prevent liquefaction. This is partly because of financial restrictions but also because the industries do not own the land. Accordingly, the industries had to seek for technologies that allow liquefaction and large ground displacement but avoid fatal damage to the business and local communities.

3.4. Damage in River Dikes during Earthquakes in 1990s

The conventional idea against liquefaction was modified due to damages in river dikes. Figs.19 and 20 demonstrate subsidence during the 1993 Kushiro-Oki and 1995 Kobe earthquakes, respectively. Because of the remarkable length of existing dikes on potentially liquefiable subsoil, complete prevention of liquefaction is financially impossible. On the other hand, the function of river dikes is still achieved even if the height is reduced to a certain extent. Hence, measures that allow subsoil liquefaction but avoid extreme subsidence came into reality. This idea is in line with performance-based earthquake-resistant design.

3.5. Lessons from 1995 Kobe earthquakes

The 1995 Kobe earthquake is characterized by the strong acceleration records and the devastating damage that affected local economy. Fig.21 shows liquefaction in Kobe Harbor. Due to this, the operation of the harbor stopped for two years and many clients left this harbor. Thus, design of seismic resistance of important infrastructures should take into account the economic aspects. The strong acceleration destroyed many structures such as buildings and a subway station. On the other hand, this extent of shaking was considered extremely rare, and increasing the intensity of design earthquake was considered uneconomical.

In this regard, design earthquakes were divided into two categories. Level 1 earthquake is the one that may occur once in the life period of a concerned structure. Basically no damage is allowed under this earthquake. The other is called Level 2 earthquake that occurs once every hundreds of years or longer. Under this action, limited damage is allowed but fatal damage or collapse should not occur. This approach is called performance-based design and is going to be adopted worldwide.

Urban gas industries have achieved a remarkable progress after the Kobe earthquake. Many earthquake monitoring instruments were deployed over the service area and ground motion data is transmitted to the head quarter immediately after an earthquake. By interpreting the data, possibility of fatal damage to pipelines is judged and, if necessary, gas supply to the damaged area is stopped (Shimizu et al., 2006). This approach is called real-time earthquake engineering and is expected to make further development.

3.6. 2004 Niigata-Chuetsu earthquake

Recent geotechnical problems occur in hilly and mountainous areas where many fills and embankments rest on unstable surface soil or valley deposits. Fig.22 is an example during the 2004 Niigata-Chuetsu earthquake. Earth fill in valley topography collects ground water and becomes heavy. Moreover, it is often the case that soft valley deposits are not removed prior to earth filling. These situations reduce the seismic stability of a fill. On the contrary, sufficient budget is not always available for good seismic resistance of structures in mountainous areas. Once collapse occurs, road transportation stops and emergency rescue becomes very difficult. This situation occurred during the 2008 Wenchuan earthquake of China as well. No definite solution is available yet to this problem.

4. CONCLUSION

Review was made of the development of geotechnical earthquake engineering in Japan. Because of repeated earthquakes in the past, many technologies and their validation were made for mitigation of earthquake damages. The recent developments may be characterized by verification of ideas and theories by using experimental and field information. This tradition increases the reliability of engineering both in the past and in future.

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