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RISK TO LIFE, WARNING SYSTEMS, AND PROTECTIVE CONSTRUCTION AGAINST PAST STORM SURGES IN OSAKA BAY

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ABSTRACT

We here report an investigation of historical changes in the relationships between risk to life and the energy of typhoons which have landed in Japan. Risk to life decreases with the availability of advance information systems as well as with the establishment of protective constructions against typhoons. The effects of warning systems on the risk to life during the three biggest typhoons that have recently hit the islands of Japan are discussed. Based on typhoon information and refuge warnings given during storm surge disasters, soft countermeasures have contributed to a significant reduction in the risk to life.

1. INTRODUCTION

Severe damage was caused by the storm surge that accompanied the Ise Bay Typhoon in 1959, but since that time few large typhoons have landed directly on the islands of Japan. After the 1959 disaster, new constructions to protect against storm surges, in the form of sea wall and lock gates near river mouths, have been built to prevent inundation due to the high tides raised by storm surges. Moreover, advanced information systems and advance typhoon warnings have contributed to a significant reduction in the loss of life, as well as in preventing social disruption and damage to structures and their contents.

Historically, we know that there have been many storm surge disasters in Japan. Disasters have been recorded 188 times in particular zones facing the Pacific Ocean between 701 and 1865 [1], and 100 times more since 1865. It is thus clear that there is a high probability that large storm surges will hit the islands of Japan during typhoon season.

The aggregation of many manufacturing plants and factories on reclaimed lands and the resulting urbanization of the hinterlands was notable during the decade from 1960 to 1970. Great impact on the natural and social environment of the coastal zones has taken place throughout Japan. Now there is a high possibility of a major disaster which would lead to catastrophic enlargement of damaged areas, even if only one accident disrupted the countermeasures taken against storm surges, because man-made anti-storm surge systems are not prepared under the fail-safe concept adopted for atomic power plants and air transportation. Moreover, damage also may be increased indirectly because people tend to forget the lessons learned from previous severe storm surge disasters.

Our objective in this study is to investigate the historical changes in risk to life that accompanied landed typhoons and the energies of these typhoons. Changes in that risk due to countermeasures taken against the recent three biggest storm surges in Osaka Bay are discussed to show how warnings to take refuge have decreased the risk to life.

Note : Discussion open until 1 December, 1982.
KEY WORDS : Life risk, Storm surges, Warning system, Osaka bay, Countermeasures for disasters

2. RISK TO LIFE IN RELATION TO TYPHOON ENERGY

In Japan, the average death toll from typhoons and severe storms has been about 850 over the 64-year period between 1951 and 1978. This figure changes of course with the density of the population and the characteristics of the typhoon or cold front. Life risk was first introduced in a study on reactor safety, the so-called Rasmussen report [2]. This index gives the individual risk as the probability of death per person per year. We here discuss the relationship between risk to life and typhoon energy and the changes in that risk.

2.1 Estimated Typhoon Energy and Risk to Life

The power of a typhoon, E, can be estimated analytically by Takahashi's method [3] as follows: Let W_s be the loss of kinetic energy from the typhoon due to friction between the air and the ground surface and W_a be the loss due to the viscosity of the air. These are

$$W_s = 1.9 \times 10^{16} \Delta P^{3/2} R^2 \text{ (erg/s)} \tag{1}$$
$$W_a = 2.0 \times 10^{16} \Delta P^{3/2} R^2 \text{ (erg/s)} \tag{2}$$

The energy of the typhoon is then given by

$$E = W_s + W_a \tag{3}$$

in which ΔP is the difference between the central pressure of the typhoon and the pressure at the outer edge of its coaxial circles, and R is the dimensionless radius of the typhoon divided by the unit 111 km. In the relationship between the intensity of a typhoon and risk to life, we may use W_s, because this value is more closely related to house destruction due to winds and to the generation of storm surges than W_a. But, in most of the 200 typhoons recorded in the Showa era (from 1925), W_s has been nearly equal to W_a. The historical tendency of typhoon energy probably does not change whichever value is selected. Therefore, E has been used to represent typhoon energy in this paper.

The relationship between risk to life due to the typhoons which hit the islands of Japan between 1934 and 1954 and the energies of these storms are shown in Fig. 1. The total population of Japan was used in the calculations. This figure shows that the approach, as presently employed, gives an approximately linear relationship between risk to life and typhoon energy. This relationship changes, however, when the factors of protective construction against typhoons and information systems are taken into consideration.

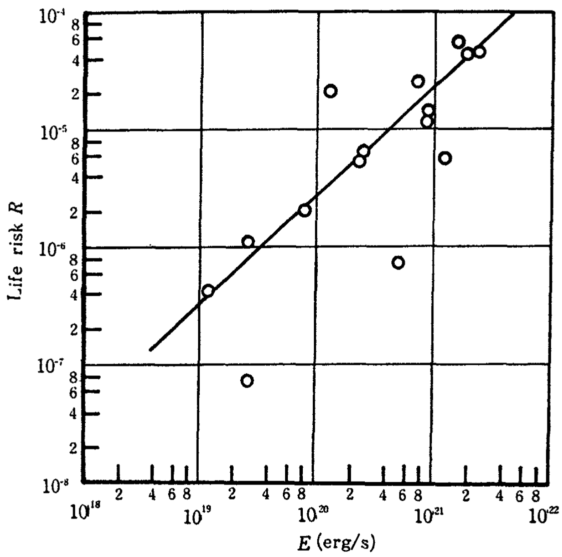

Fig. 1 Relationship between typhoon energy and life risk.

2.2 Historical Changes in Risk to Life

The annual changes in risk to life and the estimated energies of typhoons are given in Fig. 2. The values plotted are averages for three years, except for the number of typhoons generated or landed. Risk to life due to hurricanes in the U.S.A. also is shown for a comparison with the risk in Japan. The average value of E was a nearly constant 10^{21}erg/s before 1965, but after that date it varies in proportion to the decrease in the number of typhoons which landed. The risk to life due to typhoons in Japan is very large when compared with the values found for hurricanes in the U.S.A. The rapid decrease in the risk to life from typhoons after 1960 was brought about by refinements in forcasting and development of network systems of information for refuge warnings, as pointed out by Yanagida [4]. The ratio of R to E, in which R is the risk to life due to typhoons, also confirms the above results. Lately, however, there has been a tendency for this risk to increase. This corresponds with the results reported by Kurashima et al.[5], who characterized this phenomena as being similar to the behavior of a guerrilla under intensive urbanization.

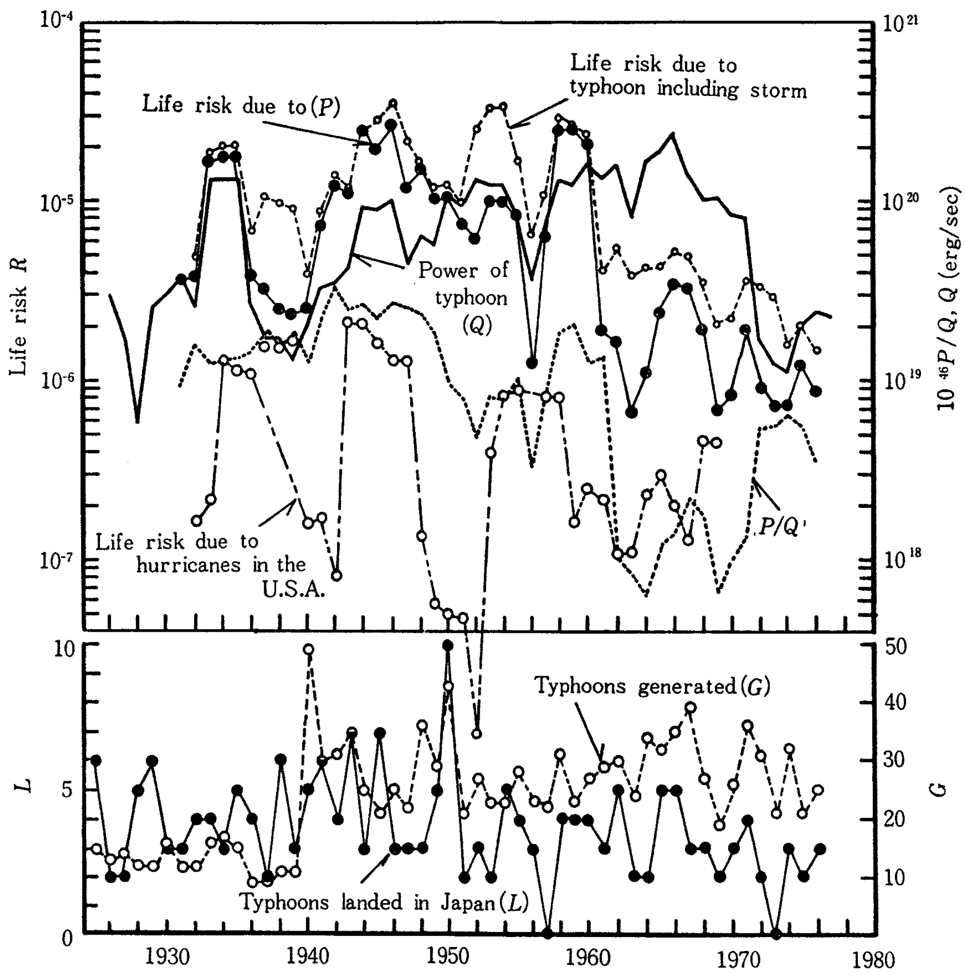

Fig. 2 Changes in life risk and characteristics of typhoons.

2.3 Risk to Life due to Storm Surges

The average values for risk to life due to storm surges over a three-year period, are shown in Fig. 3. When risk to life was less than 10^{-8}, it was recorded as the minimum value, 10^{-8}. The population used for these calculations was chosen as follows. For storm surges, the population of 16 prefectures were used because surges occurred more than five times in each of these prefectures. In the past 50 years, since death tolls have been counted officially, the

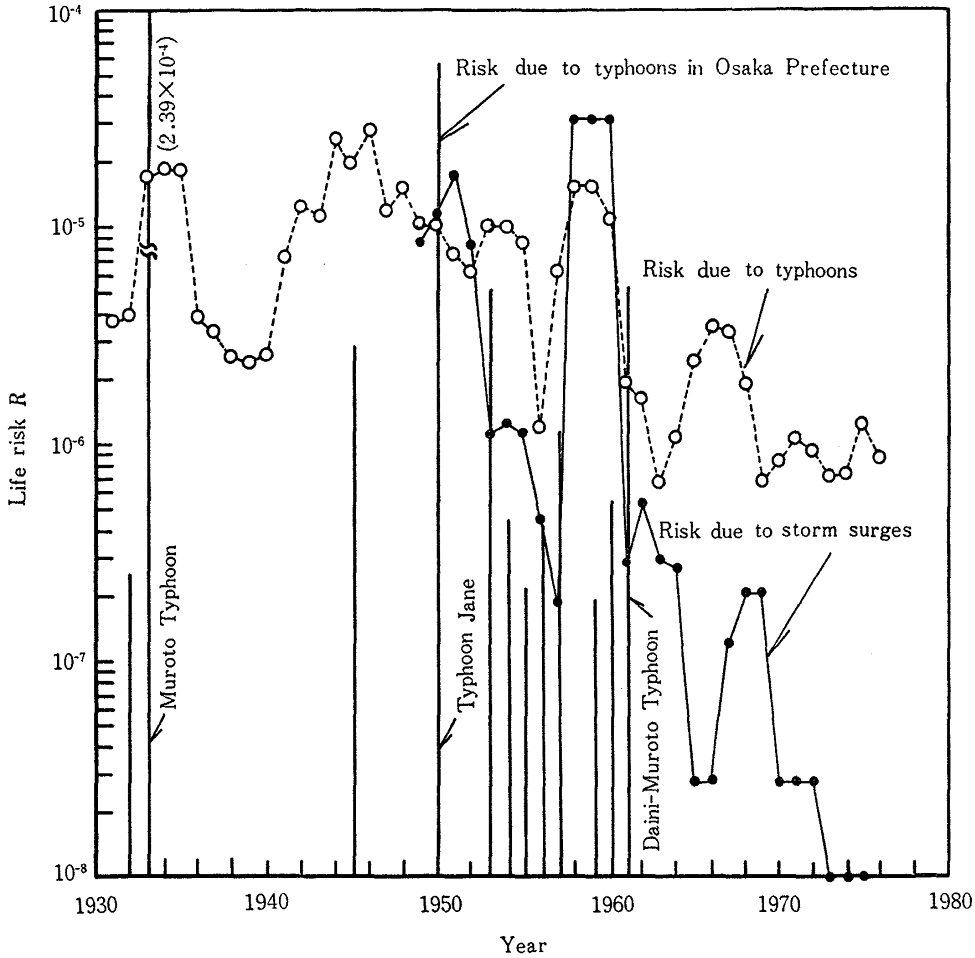

Fig. 3 Changes in life risk due to storm surges.

life risk values for the three biggest storm surges (Typhoon Jane in 1950, Typhoon Ruth in 1951 and the Ise Bay Typhoon in 1959) have been greater than the values for typhoons. The effects of storm surge disasters are restricted to coastal zones and surrounding areas; thus the population which encounters storm surge disasters is inevitably smaller than the population of the entire prefecture. Therefore, life risk increases two fold or more, than the originally calculated values. Thus, the life risk for other years may be comparable to the risk due to typhoons coming after the Daini-Muroto Typhoon in 1961. The effects of storm surge disasters inevitably are smaller than the average life risk values in Japan. By contrast, life risk values for storm surges experienced in Osaka Prefecture are larger than those for the 16 prefectures. We concluded from this historical data on life risk due to typhoons that Osaka and neighboring areas constitute one of the most dangerous storm surge zones in Japan.

3. FREQUENCY OF STORM SURGES IN OSAKA BAY

The mouth of Osaka Bay is elliptical and opens southward the Pacific Ocean through the Kii channel (Fig. 4). Its north coast has been destroyed many times by storm surges. Osaka (once called Naniwa) and Kyoto, located about 40 km northeast of Osaka, were once capitals of Japan; therefore, there are very old and accurate records of storm surge disasters in this area. Unfortunately, the scales used to measure the old storm surges are not clear, but from about 1900, the characteristics of surges have been recorded with measuring apparatus.

3.1 Frequency of Occurrence Since 701

Historical records of storm surge disasters exist for the 1279-year period between 701 and

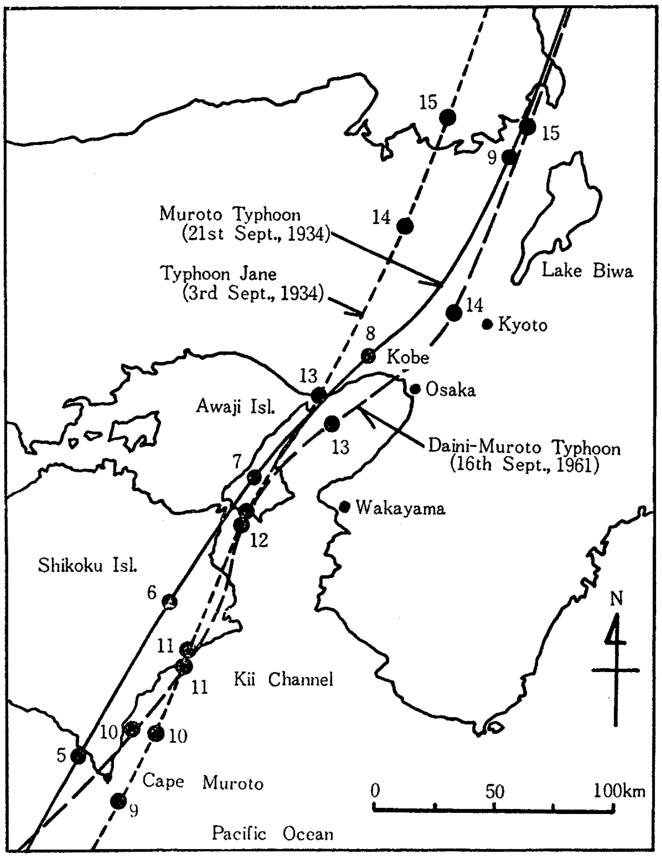

Fig. 4 Paths of Japan's three biggest typhoons.

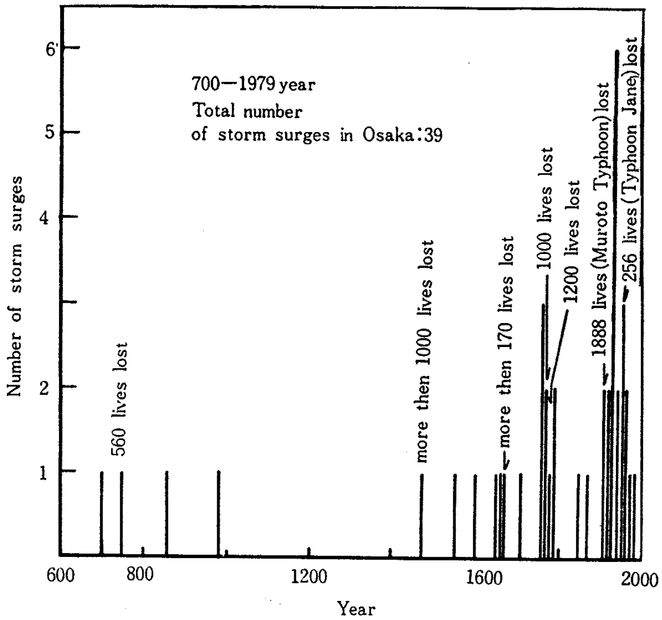

Fig. 5 Frequency of storm surge disasters.

1980. Before discussing the analysis of these data, it should be noted that the characteristics differ for each age, their minuteness or roughness and their accuracy depend on political factors and cultural background.

The number of storm surges that have taken place over the centuries are shown in Fig. 5. Thirty-nine storm surges occurred in Osaka Bay area during this period, four of which could be described as serious in terms of a loss of more than 100 lives. Frequent surges have taken place in both the 18th and 20th centuries. Although no remarkable storm surge disasters were recorded between the 11th and 15th centuries, this probably is not due to lack of storms but to the confusion caused by wars and political machinations.

3.2 Return Period of Storm Surges

The highest tidal levels and maximum anomalies observed for Osaka and Kobe are available from tide gauge records kept continuously since the early part of this century. For each port there is a similar period of data available; for Osaka the periods 1929–1944 and 1950–1980, and for Kobe the period 1926–1980. The first half of the data for Osaka is not as accurate as the data for Kobe. The return periods of finite tidal levels and anomalies for Kobe and Osaka have been computed by Miyazaki [6] and Nachi [7]. Their results for Osaka are shown in Table 1, along with data for two other stations, Tokyo and Nagoya. Clearly, Osaka is the most dangerous of the three ports in terms of storm surges. Since 1900, destructive storm surges in which the maximum anomaly was more than 2m have occurred 10 times in Japan, and five of these have been at Osaka. The historical evidence confirms the dangerousness of Osaka's position.

Table 1 Return period of storm surges at three stations[6].

Station \ Anomaly	0.5 m	1.0 m	1.5 m	2.0 m
Tokyo	1.0 years	8 years	23 years	35 years
Nagoya	0.6	3	8	15
Osaka	0.7	3	7	10

The approach of the return period as analysed, by Gumbel's and other methods, did not produce the simple representation of an approximately linear relationship between extreme storm surges and their corresponding frequencies. The reasons why they did not fit this relationship may be due to the shortness of the sampling period for tidal records and to differences in the characteristics of storm surges due to the relative paths taken by the typhoons to the harbour or station in question. The classification of storm surges by cause and the relative paths of the typhoons are shown in Fig. 6. The highest annual tidal levels observed were reduced to the standard reference sea level of Tokyo Peil (T. P.). The storm surges could be divided into three groups. Large surges occurred when a typhoon passed to the west of Kobe; whereas, small scale surges occured when a typhoon passed to the east. There also

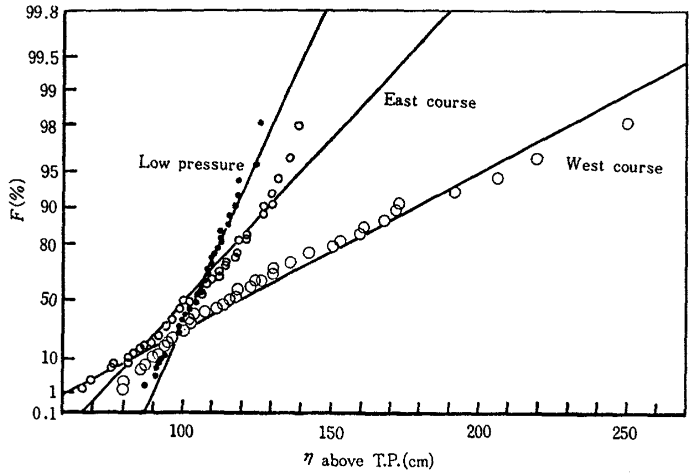

Fig. 6 Probability of the highest tidel level in Kobe.

seems to be a limit to the scale of the storm surges. Therefore, it was necessary to reexamine the return period of the storm surges based on particular probability density functions, as shown in Fig. 6. Our results show that Osaka is the most dangerous place for storm surges in Japan.

4. THE THREE LARGEST STORM SURGES AND THE DAMAGE PRODUCED

In 1934, there was a storm surge in Osaka Bay caused by the Muroto Typhoon. This was a remarkable surge on account of its rapid development and the considerable increase in the water level associated with it. After the Second World War, two large storm surges took place; with Typhoon Jane in 1950 and with the Daini-Muroto Typhoon in 1961. All these typhoons passed west of Osaka Bay (Fig. 4) and their storm surges have been called "the three largest storm surges" in this area. Table 2 gives an outline of their characteristics.

Table 2 Characteristics of typhoons and storm surgse in Osaka.

Items	Muroto Typhoon	Typhoon Jane	Daini-Muroto Typhoon
Date	9th Sepf., 1934	3rd Sept., 1950	16th Sept., 1961
Lowest atmospheric pressure (mb)	954. 3	970. 3	937. 3
Moving velocity of typhoon (km/hr)	60	58	50
Maximum mean wind velocity for ten minutes (m/s)	42. 0	28. 1	33. 3
Instantaneous maximum wind velocity (m/s)	more than 60	44. 7	50. 6
Highest tidal level above O.P. (m)	4. 2	3. 85	4. 12
Total precipitation (mm)	22. 3	62. 2	44. 2
Maximum anomaly (m)	2. 92	2. 37	2. 45

4. 1 Tracks of Typhoons and Their Scales

4. 1. 1 *Muroto Typhoon*

An extra-large storm, called the Muroto Typhoon, landed at the point of Cape Muroto in Kochi Prefecture at 05 : 10 on the 21st of September, 1934 then passed near Kobe. The barometric pressure, which was almost 997 mb at sea level at 06 : 00 on the 16th of September, fell rapidly and reached a minimum of 911. 9 mb just before the typhoon landed, but it recovered quickly and reached 973 mb at 18 : 00 near Miyako city in Miyagi Prefecture. Because of the close spacing of the isobars, the pressure of the resulting winds was severe. At the point of Cape Muroto, the instantaneous maximum wind velocity exceeded 60 m/s and the mean velocity for ten minutes was 45 m/s westerly. The time diagram in Fig. 7 includes wind conditions at Osaka. The mean wind velocity increased rapidly to more than 10 m/s east-southeasterly by 07 : 00 then to 29. 8 m/s southerly at 08 : 05, by then having veered southwesterly to west-southwesterly. The lowest atomospheric pressure was 954 mb at 07 : 55 recorded at Osaka.

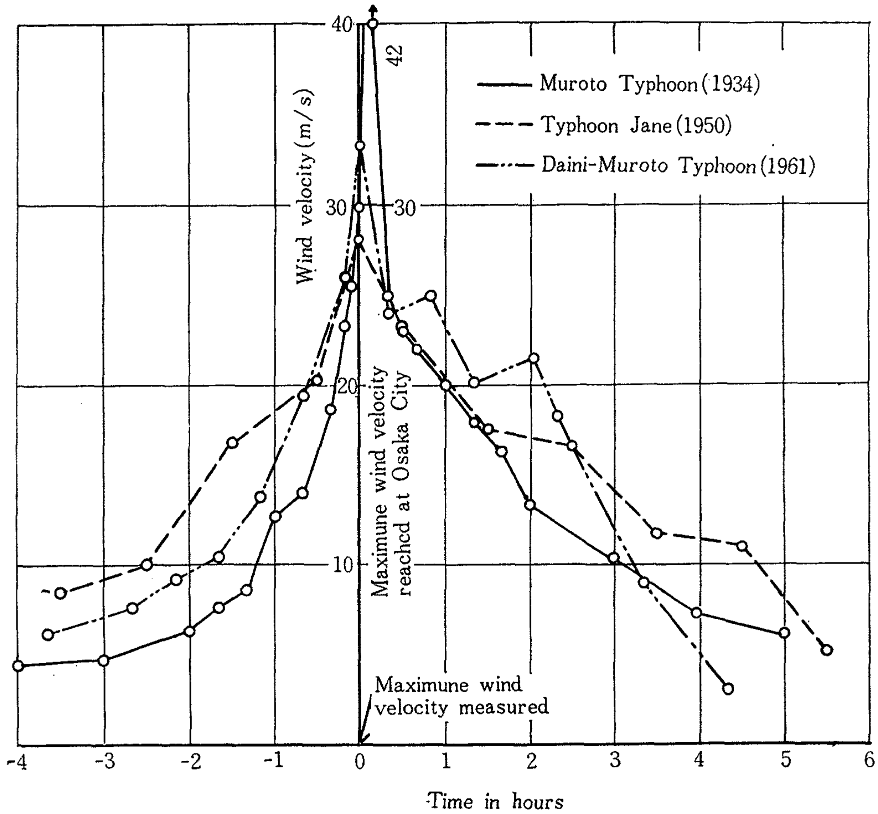

Fig. 7 Variations in maximum wind velocity.

4. 1. 2 *Typhoon Jane*

This storm attacked the Kansai district at the beginning of September, 1950 and took a course similar to that of the Muroto Typhoon. It approached Cape Muroto in the early morning of the 3 rd of September, and landed along the southeast part of the cape at 08 : 45. The characteristics recorded at the nearest representative weather station (Muroto) follow. The lowest atmospheric pressure was 965 mb. The instantaneous maximum wind velocity was 59. 1 m/s easterly and the mean velocity was 43. 1 m/s westerly. After sweeping over the southeast edge of Awaji island at 11 : 00, it landed on the west side of Kobe at noon, then passed over Maizuru City shortly after 13 : 00 without notable attenuation of its intensity. The maximum and mean wind velocities at Osaka were 44. 7 m/s and 28. 1 m/s, both in the southerly direction (Fig. 7). The lowest atmospheric pressure was 970 mb, making this typhoon as large as the Muroto Typhoon.

4. 1. 3 *Daini-Muroto Typhoon*

In Japanese, Daini means 'the second', and the characteristics of this typhoon resemble those of the first Muruto Typhoon. Its lowest atmospheric pressure (885 mb) was recorded near 19. 5 N, 131. 1 E at 15 : 00 on the 13th of September, 1964. Its maximum wind velocity was more than 75 m/s. At 09 : 30 on the 16th of September, it landed at the point of Cape

Table 3 Lowest atomospheric pressure (mb) for the Muroto and Daini-Muroto Typhoons[8].

Meteorological station / Typhoon	Cape Muroto	Hiwasa	Toku-shima	Sumoto	Wakayama	Osaka	Kobe
Muroto Typhoon	911. 9	—	942. 4	941. 7	959. 1	954. 4	954. 6
Daini-Muroto Typhoon	930. 7	928. 7	935. 4	934. 7	939. 3	937. 3	946. 5

Muroto with a low pressure of 930 mb. The local changes in the lowest atmospheric pressure are shown in Table 3. After landing at Cape Muroto the attenuation of the intensity of the Daini-Muroto Typhoon was smaller than that of the Muroto Typhoon. The most important difference between these typhoons is that in Osaka Bay the Daini-Muroto Typhoon passed 10 to 15km east of the path of the Muroto Typhoon. Therefore, the strong wind zones shifted eastward against the major axis of the ellipse that is Osaka Bay, which greatly effected the characteristics of the storm surges described below.

4.2 Oceanographical Aspects of Storm Surges

The three large typhoons described above caused storm surges all along Osaka Bay with accompanying high waves that produced disastrous flooding in low-lying areas along the coast. During the Muroto Typhoon, the sea level was too high to record with tide gauges. A survey of water traces left on the walls of some houses and buildings near Osaka Harbour, indicated that the highest tidal level and the maximum anomaly in Osaka were 4.2 m above O.P. and 2.92 m at 08:20 on the 21st of September, 1934. Moreover, a maximum anomaly of more than 2 m was estimated from Kobe to Kishiwada along the northeast coast of Osaka Bay. Tidal curves for Osaka during the Muroto Typhoon are given in Fig. 8. The drastic changes in sea level associated with the forerunning storm surge and resurgence can be seen from this figure.

Typhoon Jane also had an accompanying storm surge at 13:00 on the 3rd of September, 1950 (Fig. 8). The scale of the storm surge was smaller than of that which accompanied the Muroto Typhoon, but damage remaining from World War II and subsidence caused by the pumping off of groundwater in this area accelerated functional disorders in the countermeasures taken against the storm surge. Due to these unfavorable factors, disastrous flooding in low-lying areas of Osaka City lasted for some weeks. The highest tidal level and maximum anomaly in Osaka were 3.85 m above O.P. and 2.37 m, but these values were

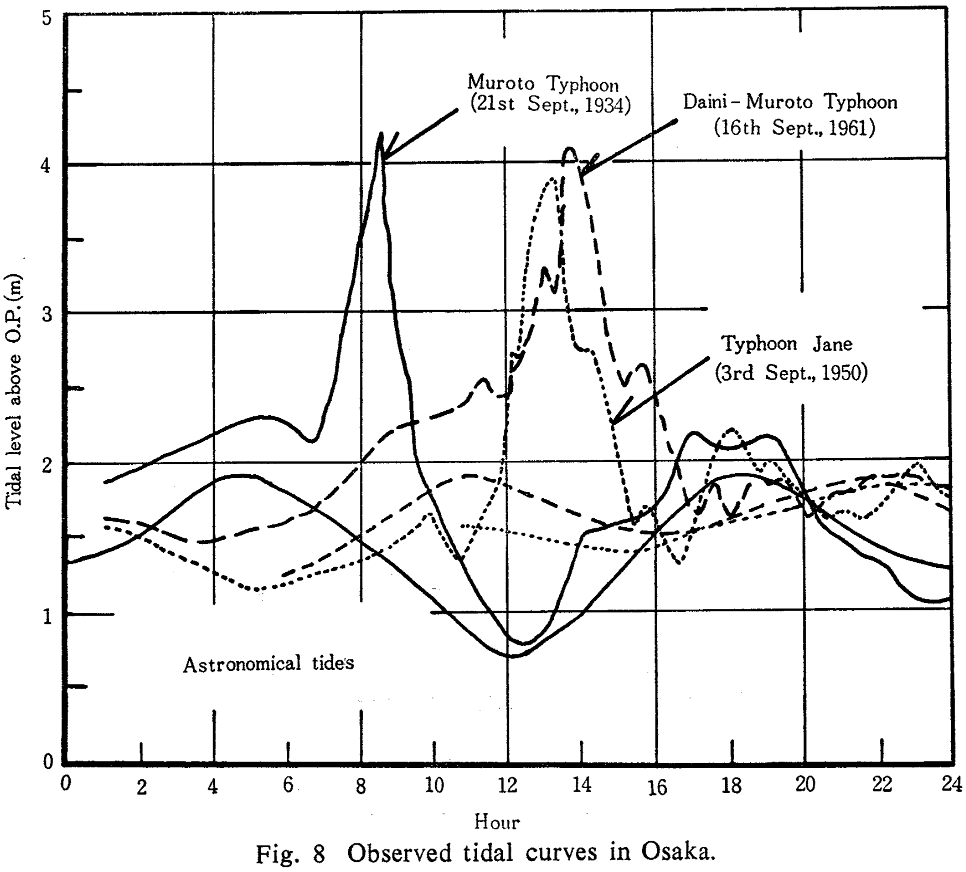

Fig. 8 Observed tidal curves in Osaka.

not obtained by direct measurement with tide gauges. They were scaled out for about 1 hour after 12:40.

The Daini-Muroto Typhoon caused the largest storm surge ever recorded in Osaka Bay. The highest tidal level was 4.12 m above O. P. at 13:53 on the 16th of September, 1961; the maximum anomaly was 2.41 m. Although the scales were very large, a significant reduction in the loss of life was realized because of the development of 'software' and 'hardware' against storm surge disasters.

4.3 Submersion of Hinterlands and Damage to Protective Construciton

4.3.1 *Submersion of hinterlands*

The northwest coastal zones and their hinterlands were all flcoded due to the three large storm surges described above. Severe damage caused by submersion took place in Osaka City. Therefore, our description of submersion focuses on this damage.

The low-lying land facing Osaka Port, located on the flood plain between the mouths of the Yodo and Yamato River, has been reclaimed by drainage over the past five hundred years. Since the 1920s the area has developed into industrial and commercial districts which depend chiefly on shipbuilding and on domestic and foreign trade. Enlargement of industrial activity accompanied by increases in the usage of water has resulted in severe ground subsidence due to the removal of ground water. The accumulated rates of ground subsidence over the forty-year period from 1935 to 1976 is shown in Fig. 9. The values for ground subsidence are plotted within coaxial circles which center on a point located near the mouth of the Yodo River. The ground level of the city area is below the mean sea level. Recently, however, subsidence has been reduced to less than a centimeter per year for most of the city area. This is due to regulations on the use of ground water and the installation of an

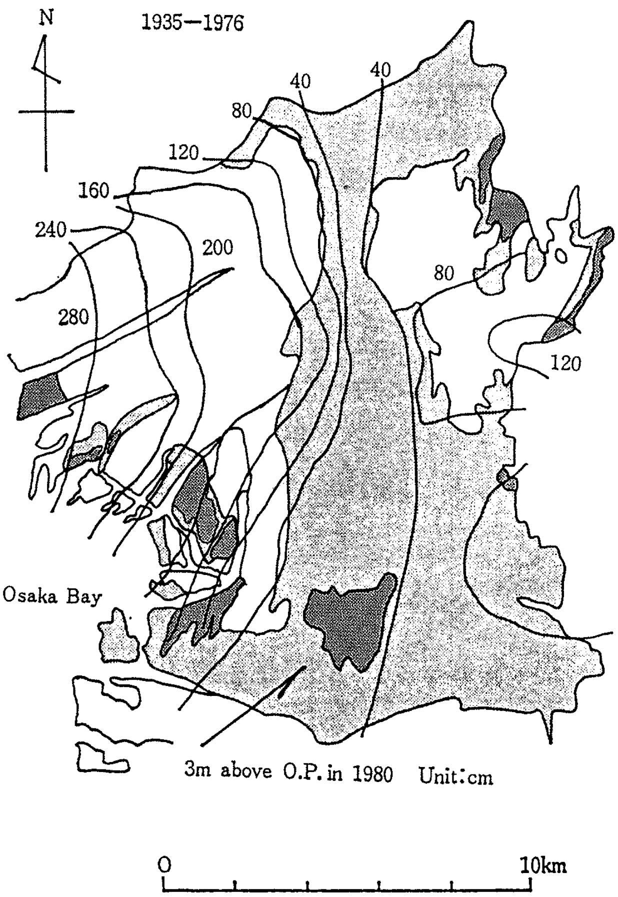

Fig. 9 Accumulated values for sudsidence.

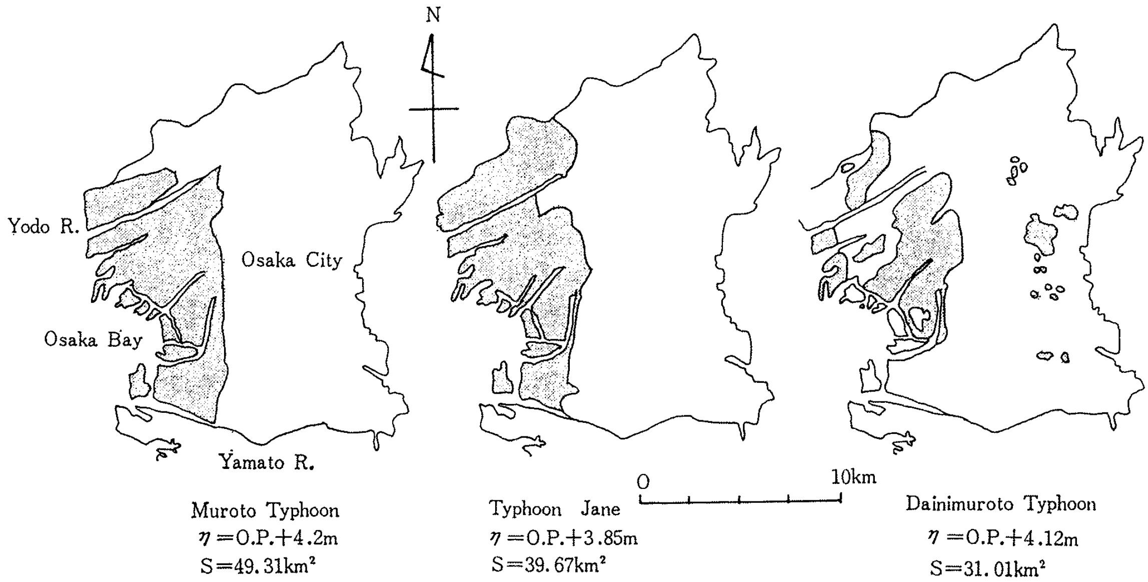

Fig. 10 Areas of submersion due to flooding.

industrial water supply system in 1959 which have had good effects on retarding subsidence.

The submerged areas produced by the three biggest storm surges are shown in Fig. 10. The average depth of submersion and its rate in relation to the total land area of each administrative district is shown in Table 4. A comparison of the two shows that

(1) The storm surge caused by the Muroto Typhoon resulted in the most severe submersion not only because of the large scale of the storm surge but because of the poor countermeasures taken against it.

(2) The greatest depth of submersion was recorded for Typhoon Jane, because ground subsidence had developed rapidly in coastal areas. Unfortunately, these areas had experienced many air-raids toward the end of World War II and most of the countermeasures against typhoons had been destroyed.

Table 4 Rate of submersion of land areas (Muroto/ Jane/ Daini-Muroto).

Administrative district	Area submerged in km²	Rate of submersion %	Mean depth of submersion in m
Higashiyodogawa-ku	0.11/ 3.60/0.92	1/14/ 3.5	——/1.1/——
Nishiyodogawa-ku*	6.92/11.98/7.74	41/78/ 29.7	1.4/2.5/0.66
Fukushima-ku*	0/ 2.60/4.68	0/57/100	0/1.3/0.65
Konohana-ku*	11.25/ 8.96/4.18	100/82/ 40	1.7/2.6/0.93
Niski-ku	0.84/ 4.80/5.27	20/96/100	0.6/1.4/0.45
Minato-ku*	9.38/ 7.00/6.23	100/90/ 76	1.6/2.9/0.95
Taisho-ku*	9.11/ 7.56/1.28	100/83/ 14	1.7/1.9/——
Naniwa-ku	5.42/ 1.12/0.23	14/22/ 0.06	1.0/0.8/——
Nishinari-ku	2.25/ 2.30/0.23	32/31/ 3	1.0/0.9/——
Sumiyoshi-ku*	8.89/ 7.60/——	2/35/——	1.6/0.8/——

* coastal district

(3) In spite of the second biggest storm surges taking place during the Daini-Muroto Typhoon, the depth of submersion and the area it covered were relatively small. The lessening of damage caused by storm surges chiefly was due to the operation of drainage equipment, the partial completion of seawalls and dikes, and the building of embankments in low-lying areas along the coast after Typhoon Jane.

4.3.2 *Damage to Protective Construction*

1) Muroto Typhoon: There had been no big storm surges during the two decades before 1934 and, in every quarter, banks built of soil and wood had been through by roads and passages for harbour loading and unloading. Because of these conditions, the city area was easily inundated by storm surges. Moreover, many ships coming to anchor in Osaka Port had been driven out from the quays and river mouths during storms and had made innumerable breaks in the banks. The number of ocean-going ships and coastal vessels sunk or destroyed was 36 and that of steam-and-sail boats and barges 1067. This damage to vessels was due to the sudden arrival of the Muroto Typhoon and its violent winds.

2) Typhoon Jane: After the Muroto Typhoon, planning for countermeasures against storm surge disasters was promoted by the national and local governments. It was organized scientifically but restricted financially. At that time, the river dike was not continuous, and its height was less than 3.5 m above O.P. Ground subsidence had advanced at an annual rate of about ten to nineteen centimeters in the coastal zones within Osaka City. As a result, two storm surges, in which the highest tidal levels were 2.8 m in 1944 and 3.2 m in 1945 above O.P., caused severe damage due to submersion. After World War II, the national and local governments had decided to construct dikes that would be 3.5 m above O.P., but soil and coal cinder mainly were used in their construction. Therefore, these dikes were easily destroyed by an overflow of sea water or when waves overtopped them. The broken dikes numbered forty-five; a total length of about 40 km.

3) Daini-Muroto Typhoon: The first countermeasure against storm surges in Osaka Bay was started in 1950. Dikes along the rivers and canals were built as the first step in the project. The total length constructed was about 124 km and the height varies from 3.5 m to 5 m above O.P. At that time, the annual ground subsidence rate was at the worst stage, and the heights of these dikes were not sufficient protection against the storm surges. During construction, the second biggest storm surges caused by the Daini-Muroto Typhoon again came. But this time, the continuous concrete dikes prevented a vast inflow of sea water except where they overtopped. Only one dike was broken. Incidentally, during the second step of the countermeasure, three lock gates of arch type and dikes 5.2 m above O.P. were the principal constructions.

4.4 Loss of Human Life and Houses Destroyed

The number of fatalities from the typhoons Muroto, Jane and Daini-Muroto were 3066, 519 and 202, respectively. The statistics listed in Table 5 provide evidence of the loss of human life and houses destroyed in each administrative district in Osaka City. The loss of human life here includes both the numbers of dead and missing. These numbers reflect the population density of the areas listed. Therefore, the life risk, R, the number of human lives lost per unit of population was calculated and is listed in the table. The life risk in Osaka City is shown in Fig. 11; the values represented by the white and black circles were calculated from the population of the city and submerged areas, respectively. Only seven deaths from the Daini-Muroto Typhoon, were attributed to causes other than storm surge. Clearly the risk to life rapidly decreased with time in spite of the large scale storm surge.

The characteristics of the houses destroyed by storm surges and typhoons are important because they are an indication of the strength of the external force. An outline of the destruction caused to houses by the three typhoons is given in Fig. 12. The following characteristics emerge

Table 5 Statistics on the loss of human life and houses destroyed.

a. Muroto Typhoon (1934)

Administrative district	Population	Number of house-holds	Number of dead and missing	Persons injured	Life risk in thousands $R\times 10^3$	Number of houses ruined and swept away	Rate of houses destroyed to households in thousands $N_r\times 10^3$
Nishinari-ku	196, 399	44, 755	81	321	0. 412	232	5. 22
Kita-ku	243, 630	51, 809	3	61	0. 012	18	0. 35
Konohana-ku	207, 441	45, 909	256	867	1. 230	490	10. 60
Higashi-ku	170, 257	29, 346	18	71	0. 105	32	1. 09
Nishi-ku	130, 436	23, 908	2	31	0. 015	6	0. 25
Minato-ku	264, 416	71, 987	69	1, 064	0. 260	110	1. 52
Taisho-ku	125, 390	28, 169	111	578	0. 885	204	7. 24
Tennoji-ku	122, 909	26, 234	19	107	0. 154	2	0. 08
Minami-ku	119, 233	2, 218	1	35	0. 008	3	0. 14
Naniwa-ku	149, 852	3, 173	2	39	0. 013	23	0. 72
Nishiyodogawa-ku	181, 040	41, 042	243	748	1. 340	220	2. 86
Higashinari-ku	289, 149	66, 369	106	375	0. 366	252	3. 80
Asahi-ku	116, 295	35, 940	63	217	0. 541	140	3. 85
Higashiyodogawa-ku	216, 947	49, 269	32	187	0. 148	205	4. 16
Sumiyoshi-ku	265, 358	61, 582	47	348	0. 177	295	4. 79

(1) The number of houses inundated by the overflow is proportional to the scale of the storm surge, inundation under the floor being greatest durlng the Daini-Muroto Typhoon. This damage mainly was due to severe ground subsidence in the east of Osaka City as well as in the coastal areas.
(2) Flooding from Typhoon Jane resulted in the most severe damage to houses. As the population of Osaka City in 1950 was about 1. 96 million and in 1934 and 1961 about 3 million, this result was somewhat curious. This damage mainly was due to poor living conditions and lack of housing after World War II. This is well documented because the number of houses destroyed is nearly equal to the number inundated by overflow.
(3) The value for the number of houses ruined or swept away during the Daini-Muroto Typhoon is several orders smaller than the value for houses inundated. This is because flooding was not caused by the breakdown of dikes but by overflows on dikes along the rivers.

The greatest loss of human life during storm surge disasters takes place when houses are ruined or swept away. Therefore, there may be a relationship between the loss of human life and the characteristics of houses destroyed in storm surge disasters.

b. Typhoon Jane (1934)

Administrative district	Pouulation	Number of house-holds	Number of dead and missing	Persons injured	Life risk in thousands $R\times10^3$	Number of houses ruined and swept away	Rate of houses destroyed to households in thousands $N_r\times10^3$
Kita-ku	66, 918	16, 298	1	87	0. 015	82	5. 03
Miyakojima-ku	50, 196	11, 506	3	40	0. 060	226	19. 60
Fukushima-ku	79, 475	19, 261	2	296	0. 025	161	8. 36
Konohana-ku	43, 878	10, 843	33	1, 638	0. 752	492	45. 30
Higashi-ku	37, 976	8, 857	3	27	0. 079	69	7. 80
Nishi-ku	44, 545	11, 259	3	1, 428	0. 067	587	52. 10
Minato-ku	41, 508	10, 398	63	12, 099	1. 510	1, 326	12. 80
Taisho-ku	59, 784	15, 176	13	1, 276	0. 217	531	35. 00
Tennoji-ku	50, 970	12, 248	2	3	0. 039	168	13. 70
Minami-ku	52, 713	12, 346	3	15	0. 057	20	1. 60
Naniwa-ku	43, 505	10, 617	2	358	0. 046	475	44. 70
Oyodo-ku	42, 987	10, 612	0	0	0	163	15. 40
Nishiyodogawa-ku	76, 519	18, 438	58	1, 107	0. 757	341	18. 50
Higashinari-ku	116, 129	27, 301	1	20	0. 009	51	1. 87
Ikuno-ku	176, 200	41, 417	1	30	0. 006	25	0. 60
Asahi-ku	99, 121	24, 119	0	52	0	53	2. 19
Jyoto-ku	124, 650	29, 303	0	52	0	89	3. 04
Nishinari-ku	151, 509	37, 668	4	104	0. 026	134	3. 55
Abeno-ku	133, 253	32, 776	3	24	0. 022	36	1. 10
Higashiyodogawa-ku	163, 125	38, 696	4	11	0. 025	431	11. 00
Sumiyoshi-ku	143, 505	34, 997	22	124	0. 513	329	9. 40
Higashisumiyoshi-ku	157, 670	37, 072	0	3	0	62	1. 67

c. Daini-Muroto Typhoon (1961)

Administrative district	Population	Number of households	Number of dead and missing	Persons injured	Life risk in thousand $R \times 10^3$	Number of houses ruined and swept away	Rate of houses destroyed to households in thousand $N_r \times 10^3$
Nishinari-ku	215,154	57,519	1	4	0.005	24	0.42
Kita-ku	79,361	18,937	—	4	—	23	1.21
Miyakojima-ku	111,677	28,116	—	4	—	58	2.06
Fukushima-ku	94,674	22,029	—	78	—	260	11.80
Konohana-ku	83,503	20,985	1	226	0.012	359	17.10
Higashi-ku	59,370	11,455	—	5	—	10	0.87
Nishi-ku	73,946	16,648	—	2	—	58	3.48
Minato-ku	104,797	26,107	1	92	0.009	1,502	57.50
Taisho-ku	94,533	22,985	—	2	0.013	28	1.22
Tennoji-ku	77,877	18,904	1	12	—	23	1.21
Minami-ku	73,479	16,703	—	1	—	1	0.06
Naniwa-ku	83,741	20,609	—	13	—	26	1.26
Oyodo-ku	61,750	14,775	—	3	—	16	1.08
Nishiyodogawa-ku	119,796	28,627	—	9	—	500	17.50
Higashinari-ku	138,446	30,771	—	3	—	32	1.04
Ikuno-ku	238,653	53,502	—	7	—	142	2.65
Asahi-ku	143,617	36,251	—	1	—	1	0.03
Jyoto-ku	226,151	52,100	1	16	0.004	316	6.07
Abeno-ku	162,783	41,839	—	18	—	30	0.72
Higashiyodogawa-ku	269,511	72,895	—	5	—	52	0.71
Sumiyoshi-ku	252,300	60,874	2	19	0.008	212	3.48
Higashisumiyoshi-ku (Hirano)	270,049	62,894	—	77	—	1,612	25.60

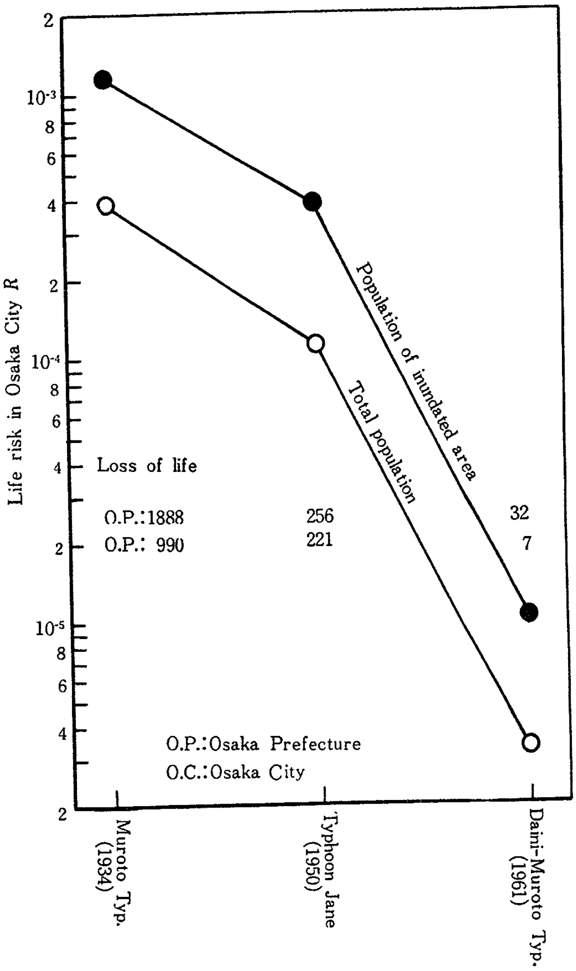

Fig. 11 Life risk in Osaka.

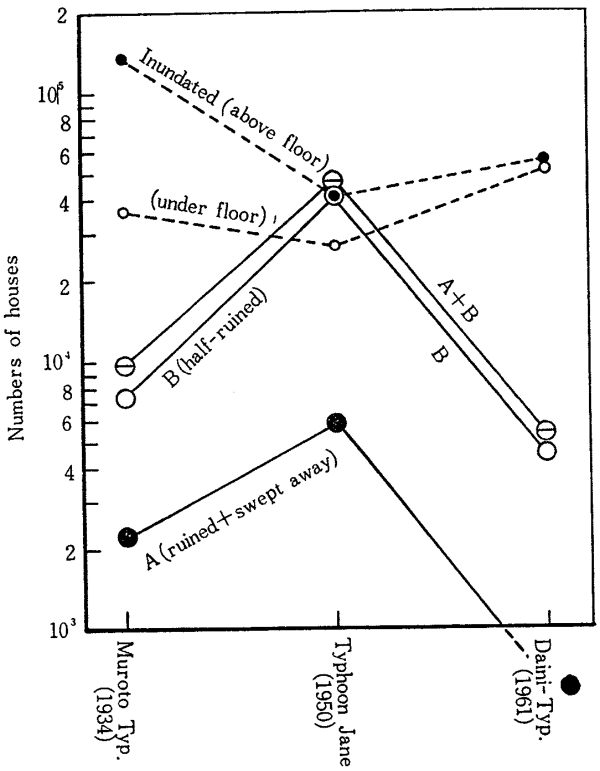

Fig. 12 Damage to houses in Osaka.

5. RISK TO LIFE AND COUNTERMEASURES

5. 1 Backpround of Warning System

More advanced storm surge disaster warnings used as a kind of soft countermeasure should lead to a significant reduction in the loss of life as well as in property. It is evident from historical records that there were no systematic warnings given before the Muroto Typhoon (1934). The Central Meteorological Agency was responsible for preparing official forecasts and issuing public warnings of typhoons in all areas of Japan. But its typhoon forecasting system was very weak because there were no field observations from airplanes nor radar detection. In addition, there was no established transmission service between meteorological observatories and organizations with receiving equipment. The warning systems used were as follows.

1) Muroto Typhoon: The issues associated with the forecast and warning system used during the Muroto Typhoon may be summed up in two points: (1) technical problems relating to a timely and accurate cssessment and the prediction of typhoons and storm surges, and (2) systematic guidelines for the dissemination of typhoon information; warnings, evacuation, and care of refuges. During the Muroto Typhoon, both were insufficient, so that this big typhoon with high storm surges hit the Osaka district unexpectedly on the morning of the 21st of September, 1934. The Muroto Meteorological Observatory recorded the typhoon landed at 04:00 in the morning at the point of Cape Muroto and tried to transmit information about its strength to the Osaka Meteorological Observatory by telephone and telegraph, but this

was impossible because electric current had been cut off and antennae had collapsed. Therefore, the storm surge information received was insufficient and very inaccurate. First, at 02:00 on the 21st, NHK (the Japan Broadcasting Corporation) broadcast that a storm surge of about 90 cm might be expected at 04:55 in the morning during high tide. For only five minutes on the hour, it broadcast old typhoon information using an independent electric power plant. By 07:00, twenty-five percent of the households had lost electric power and the ratio of the spread of radio warnings was estimated as about 40 percent. Almost none of the warnings and information reached the public directly. As proof, many students and workers were hit by the storm on their way to school or to the office.

2) Typhoon Jane: Fortunately, meteorological observations of typhoons with airplanes began in 1940, and thereafter the U. S. Army also made continuous meteorological observations by airplane in the central area of the Pacific Ocean. With the new observation system, accurate typhoon information greatly reduced the number of deaths and property damage from typhoon disasters. The characteristics of Typhoon Jane could be forecast some days before it landed. The Osaka Meteorological Observatory had issued information about the typhoon through the telegraph and radio on the 30th of August. On Friday morning (at 10:00 on the 2nd of September), it stated that the typhoon might pass through the Kinki district on the 3rd. This information was transmitted unofficially to municipal offices by telephone because the 3rd was a Sunday, but public officers could give no explicit instructions on the appropriate action to be taken. After this transmission, seven weather advisories and warnings were announced by the Osaka Meteorological Observatory up to the afternoon of the 3rd. These were broadcast twenty-four times (Table 6). The warnings of the storm and the storm surges were issued at 07:00 and at 10:35, respectively. The detailed storm surge warning given at 11:45 started that the most critical period of the expected storm surge would coincide with the high tides at 00:50 at Osaka Port. Though the warnings were

Table 6 Announcement of various warnings from the Osaka Meteorological Observatory during Typhoon Jane.

Classification	Time of issue	Time of cancellation
Typhoon information No. 1	15:00, 2 Sept.	
Wind and rain warning	05:00, 3 Sept.	Change to storm warning
Storm warning	07:00, 3 Sept.	
Typhoon information No. 2	10:15, 3 Sept.	
No. 3	10:35, 3 Sept.	
No. 4	11:15, 3 Sept.	
Storm surge warning	11:45, 3 Sept.	
Typhoon information No. 5	12:15, 3 Sept.	
No. 6	12:35, 3 Sept.	
Flood warning	13:00, 3 Sept.	00:00, 4 Sept.
Typhoon information No. 7	13:15, 3 Sept.	
No. 8	14:00, 3 Sept.	
No. 9	15:00, 3 Sept.	15:30, 3 Sept.
No. 10	20:00, 3 Sept.	

Table 7 Announcement of various warnings from the Osaka Meteorological Observatory during the Daini-Muroto Typhoon.

Classification	Time of issue	Time of cancellation
Typhoon information No. 1	09: 00, 15 Sept.	
Wind and rain warning	11: 50, 15 Sept.	Change to storm warning
Typhoon information No. 2	11: 50, 15 Sept.	
No. 3	14: 40, 15 Sept.	
No. 4	15: 45, 15 Sept.	
No. 5	21: 00, 15 Sept.	
No. 6	23: 30, 15 Sept.	
No. 7	02: 30, 16 Sept.	
No. 8	06: 00, 16 Sept.	
Storm warning	07: 45, 16 Sept.	17: 00, 16 Sept.
Storm surge warning	07: 45, 16 Sept.	
Storm warning	09: 30, 16 Sept.	
Storm surge warning	09: 30, 16 Sept.	17: 00, 16 Sept.
Typhoon information No. 9	10: 00, 16 Sept.	
No. 10	11: 00, 16 Sept.	
No. 11	11: 30, 16 Sept.	
No. 12	12: 00, 16 Sept.	
No. 13	13: 00, 16 Sept.	
No. 14	14: 15, 16 Sept.	
No. 15	14; 45, 16 Sept.	
No. 16	15: 35, 16 Sept.	
No. 17	17: 00, 16 Sept.	

accurate, neither the scale of the storm surge nor an evacuation procedure were given. Therefore, many people inhabiting dangerous zones stayed at home during the worst of the typhoon.

3) Daini-Muroto Typhoon: Table 7 lists various warnings given by the Osaka Meteorological Observatory during the Daini-Muroto Typhoon. The storm-surge warning given at 09:30 on the 16th of September stated that along the north coast of Osaka Bay the highest tidal level might be more than 4.5 m above O. P., a value corresponding to that reached in the Muroto Typhoon. The warning was very useful for refuge-taking.

Earlier, before the storm had reached disaster proportions, the Director of Operations in Osaka City had begun to receive reports of the typhoon and its storm surges from various stations along the coast of Shikoku Island and had set in motion the emergency plan for disasters at 11:00 on the 15th. As information reached the Office of Emergency Operations, alerts were transmitted to all the agencies responsible for rescue and evacuation. Emergency

Table 8 Warnings to take refuge during the Daini-Muroto Typhoon.

Administrative district	Time of issue	Name of region concerned
Kita-ku	13 : 45, 19 Sept.	Dojima, Nakanoshima
Fukushima-ku*	13 : 30, 16 Sept. 14 : 20, 16 Sept.	Noda, Tamagawa, Shinya All regions
Nishi-ku	11 : 00, 16 Sept. 13 : 10, 16 Sept.	Old persons and children All regions
Konohana-ku*	11 : 00, 16 Sept. 13 : 00, 16 Sept.	All regions (preparations for evacuation) All regions
Minato-ku*	10 : 30, 16 Sept.	All regions
Taisho-ku*	09 : 30, 16 Sept. 12 : 00, 16 Sept.	Kitaokajima Sangenya, Naniwajima, Izuo Minamiokajima
Nishiyodogawa-ku*	12 : 00, 16 Sept.	Ono, Hiyakujima, Nakajima, Nishijima
Sumiyoshi-ku*	10 : 00, 16 Sept.	Minamikagaya, Nanko Kitajimashikitsuura, Shibatani, Kagaya
Nishinari-ku	14 : 20, 16 Sept.	Tsumori
Higashiyodogawa-ku	12 : 00, 16 Sept.	All regions

* Coastal administrative district

crews were dispersed to pre-arranged quadrants of the city during repeated radio transmission of evacuation instructions. Faced by the great amount of information on disaster which had been broadcast over radio and television, many inhabitants were motivated to seek refuge and try to avert a disaster. Eventually, more than 100,000 people got away from perilous areas and gathered in shelters such as concrete school buildings and city halls. Table 8 lists the warning communications given and the refuge taken in each administrative district. Refuge from disaster was effectively completed for inhabitants in dangerous areas.

5.2 Effects of the Warning System on Risk to Life

The relationship between life risk (R) and the ratio of the number of ruined or swept-away houses to the total number of households in the submerged area (N_r) has been investigated on the basis of the warning system used.

The relationship for each administrative coastal or inland district during the Muroto Typhoon and Typhoon Jane is presented in Fig. 18. This figure shows that although the maximum value of N_r^{-1} during Typhoon Jane is about ten fold the value during the Muroto Typhoon, the life risk in the former was one tenth that of the latter typhoon; inhabitants in submerged areas in 1934 were in a more perilous situation then those in the typhoon of 1950. This is due mainly to the qualitative difference in the warnings given during the storm surge disasters. In addition, during the Typhoon Jane the relationship between R and N_r for the administrative coastal districts differs from that for the inland districts. As stated, insufficient dikes had been constructed against the storm surges from Typhoon Jane. They might have prevented districts from being inundated during moderated storm surges but when overflow or wave overtopping took place because of a rise in sea level, the dikes immediately were broken at forty-five points.

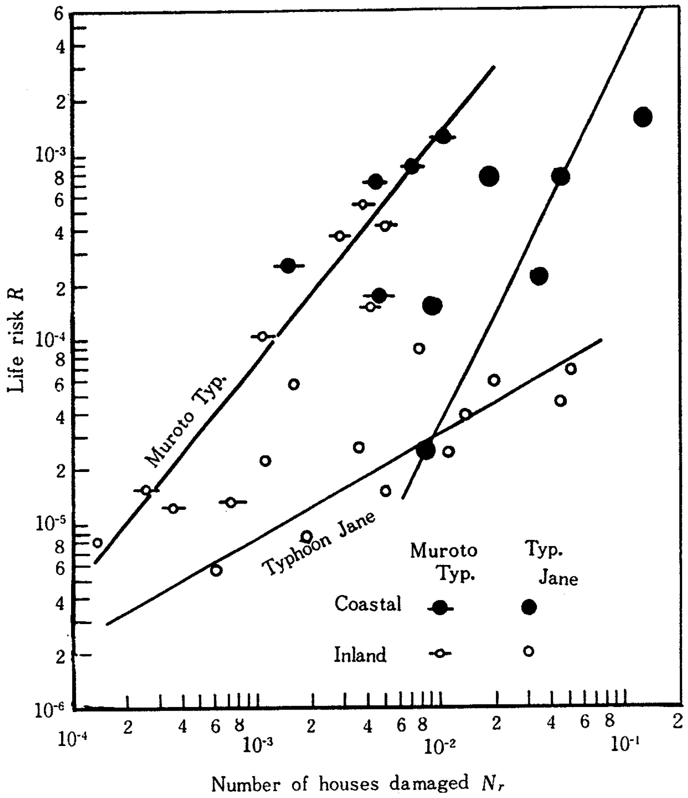

Fig. 13 Relationship between the ratio of houses ruined or swept away and life risk.

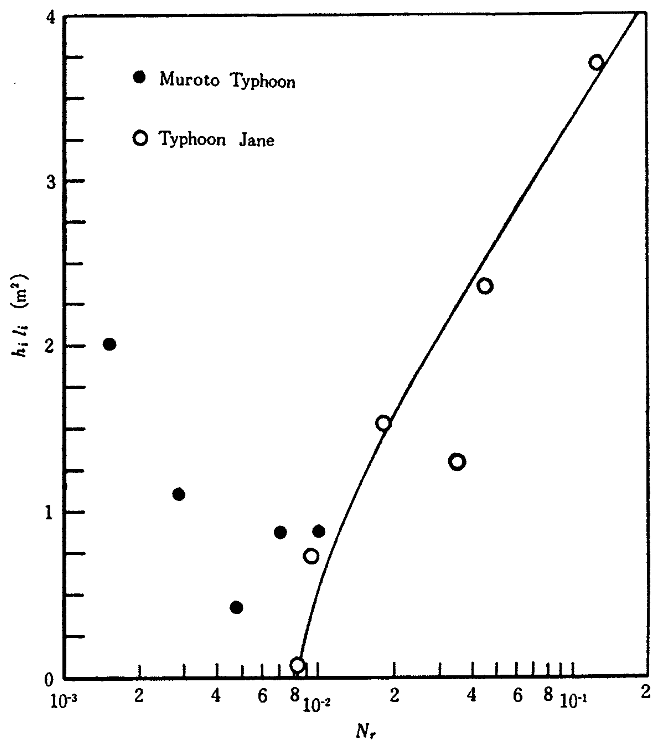

Fig. 14 Relationship between $h_i l_i$ and life risk.

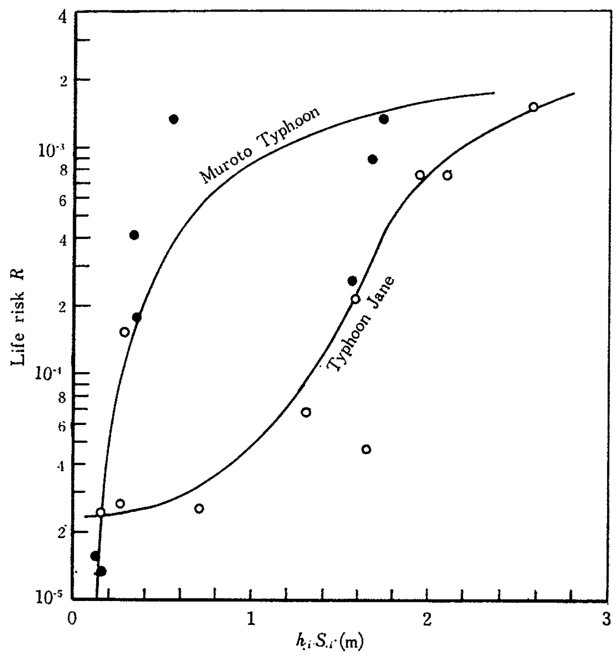

Fig. 15 Relationship between the ratio of houses ruined of swept away and h_iS_i.

Rapid and vast flooding of sea water into administrative coastal districts could result in a catastrophic death toll from storm surge. In verification of this, the relationship between N_r and the characteristics of dikes broken at each administrative seaside district is shown in Fig. 14, in which l_i is the total length of dikes broken and h_i is the mean depth of submersion. It is evident that there is a relationship between them for Typhoon Jane, but not for the Muroto Typhoon.

The relationship between life risk and the characteristics of submersion is shown in Fig. 15, in which S_i is the ratio of the area submerged to the total area. Values on the abscissa, h_iS_i, correspond to the volume of flooding. Although in storm surge disasters the loss of human life depends on the extent of submersion, another factor, the soft countermeasures taken against storm surge disasters is very important. Their effects on life risk are shown at the stage when there was a small volume of flooding. The discrepancy in the relationships during the Muroto Typhoon and Typhoon Jane improves with the increment of h_iS_i because in the latter typhoon many inhabitants who did hear the warnings had insufficient time to take safe refuge, or paid little attention to them.

Fortunately, no deaths were attributed to the storm surges that accompanied the Daini-Muroto Typhoon because of early warnings and the resulting evacuation of about 100,000 people. Therefore, no estimation of life risk could be made. Thus a new life risk, which includes persons seriously and slightly injured, is newly defined by R_p. For that reason, houses half ruined were included with houses destroyed and estimated as N_d. Fig. 16 shows the relation between N_d and R_p in the three biggest storm surges. The following facts emerge.

Life risk R_p during the Muroto Typhoon was very large; the R_p in coastal districts is larger than that for inland districts for the same value of N_d. This is of course due to the sudden attack of the storm surge without warning and partly to violent winds of more than 60 m/s. The numbers of dead and injured caused by damage to houses and wooden schools in Osaka City were 257 and 1,076. The total value is twenty-seven percent of the entire death toll in the city.

The relation between N_d and R_p also may be applied to the Daini-Muroto Typhoon. But, in Typhoon Jane, warnings were insufficient quantitatively and qualitatively as compared with those for the latter typhoon; thus, life risk R_p was very large in the coastal

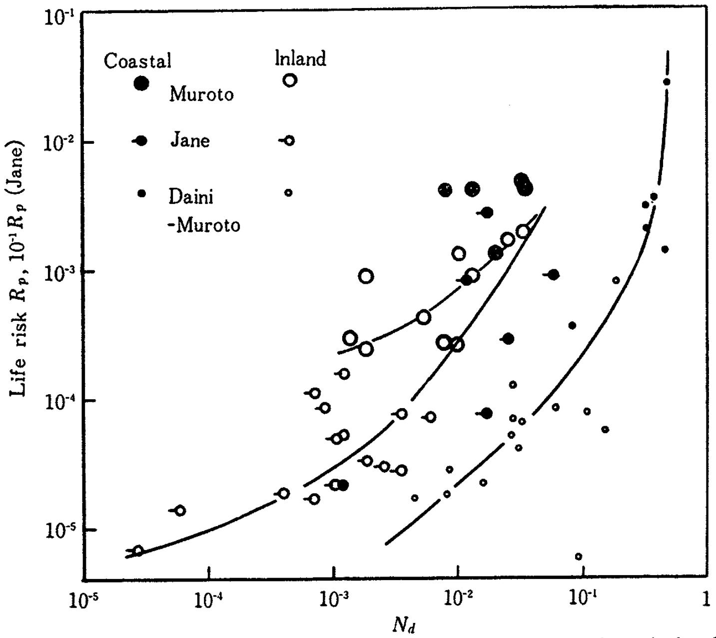

Fig. 16 Relationship between the ratio of houses damaged and the life risk that includes injured persons.

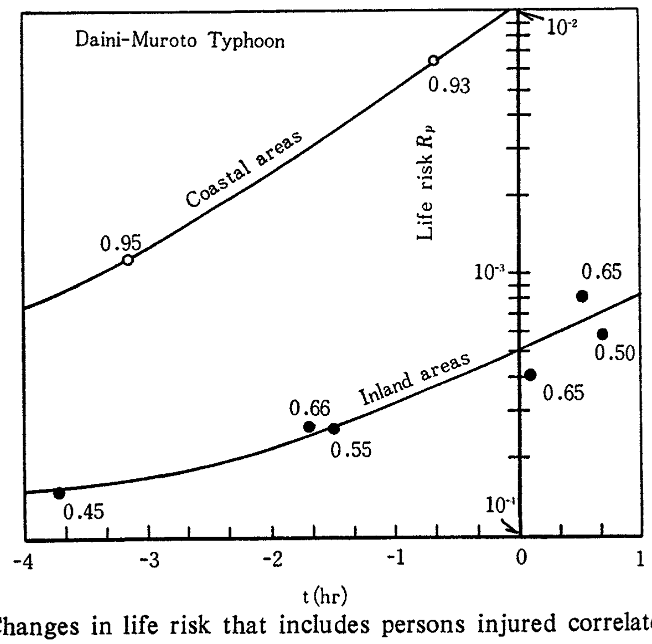

Fig. 17 Changes in life risk that includes persons injured correlated with the time when refuge was taken.

districts. In this relation, the so-called hard countermeasures also had some effect. The mean depth of submersion especially has a significant effect on the minimizing of life risk. The relationship between R_p and the time of taking refuge during the Daini-Muroto Typhoon is shown in Fig. 17. The numbers in the figure indicate the mean depth of submersion for each administrative district. The earlier the evacuation was initiated, the smaller the life risk.

6. CONCLUSION

The so-called three biggest typhoons; the Muroto in 1934, Jane in 1950 and the Daini-Muroto in 1961 were accompanied by storm surges which caused severe damage in Osaka and neighboring areas. The aspects of these storm surge disasters differed because the soft and hard countermeasures taken against storm surges have developed with the industrial growth and the resulting urbanization of inland areas. When there was limited financial support for the construciton of hard countermeasures and highly disastrous circumstances, the soft countermeasures taken and their effects on life risk were investigated. The following conclusions are made.

(1) The average value for the energy of typhoons landing on the islands of Japan was a nearly constant 10^{21} erg/s before 1965, but after that date it decrease with the numbers of typhoon experienced. Life risk due to typhoons is in the order of magnitude of 10^{-6}, more than ten times the value found for hurricanes in the U. S. A. We also confirmed that the reduction in life risk due to typhoons after 1960 was due to forecasts made by typhoon and network systems of information for taking refuge.

(2) The relationship between the characteristics of houses destroyed by storm surges and typhoons and life risk were compared with the effectiveness of soft countermeasures. We concluded that adequate typhoon information and warnings to take refuge are exceedingly useful in reducing life risk, even when the process of dike breakdown differed and the resulting submersion was enlarged by severe ground subsidence.

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