CHAPTER EIGHT

EXTREMAL STATISTICS OF STORM SURGES BY TYPHOON

Yoshito TSUCHIYA, M. ASCE* and Yoshiaki KAWATA, M. ASCE**

ABSTRACT

The objective of this paper is to propose a new approach based on the direction of the typhoon track for determing the probability of occurrence of extremal tides due to storm surges, as well as their return period. The study includes the effects of periods in tidal data and of tidal variation stemming from extensive reclamation along coasts on the fitness of the extremal data to probability density functions. The method is justified by application to an analysis of the probability of occurrence of storm surges in Osaka bay.

INTRODUCTION

Storm surges generated by typhoons have caused extensive damage at estuaries facing the Pacific Ocean in Japan. Historically, we know that there have been many storm surge disasters. There are records of 188 such disasters in certain zones between 701 and 1865, and 100 more have been recorded since 1865. It is, thus, clear that there is a high probability of occurrence of large storm surges in Japan during the typhoon season.

Unfortunately, methods available for the estimation of the return period of an abnormal tide have not as yet been completely established. This is due to not only the limited availability of long-term tidal data (usually more than 100 years are needed for reliable design predictions), but also the inaccuracy of absolute ground elevation measurements coupled with land subsidence in coastal industrial regions. Moreover, the hydrodynamic behavior of storm surges in the estuaries may have changed due to large-scale reclamation along the coast during the last two decades. To overcome these limitations and inaccuracies in the data, much effort has been expended. Generally, the extreme tidal data do not conform to any probability density function. Therefore, the main objective of these investigations is to discover why systematic divergence from the theoretical probability distribution curves appears at extreme tidal values. Führböter(1978) tried to

* Professor, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan

** Associate Professor, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan

explain this discrepancy as the nature of time-dependent tidal data and proposed a hypothetical model for practical use. Graff et al.(1978), Pugh et al.(1978), DeYong et al.(1975) and Tayfun (1979) discussed the joint probability of astronomical tides and storm surges after excluding their trend effects, even those for annual maximum anomaly which is a highly random occurrence relative to the astronomical tide. However, no one has successfully shown significant agreement between the data and any probability density function.

REARRANGEMENT OF DATA AND TRADITIONAL ANALYSIS

[a] Outline of the data

In Osaka and Kobe, tidal observations have been made since 1900 and 1927 respectively. During the Showa Era (since 1925), there have been three large storm surge disasters, in 1934, 1950 and 1961. A map of the region is shown in Fig. 1. Firstly, the characteristics of extreme tidal data in Osaka and Kobe such as the highest tidal level, the maximum anomaly and the lowest tidal level (not very widely used) need to be discussed in detail.

1] Highest tidal level: Fig. 2 shows the annual variation in the highest tidal levels in kobe and Osaka,including those in Tannowa and Kushimoto. The data for Osaka covers the longest period, but the data before 1946 is questionable for two reasons. One is the correction of ground level due to land subsidence. Local benchmarks, which in most cases corresponded to the original Osaka Pile, cannot be completely corrected from records of land subsidence. For Kobe, however, the correction of ground levels was made by the Kobe Marine Observatory. The other reason is the malfunction of an old tidal gage. A few slip between the pulley and the measuring rope connected to the float are needed to be justified, but attempts have as yet been unsuccessful.

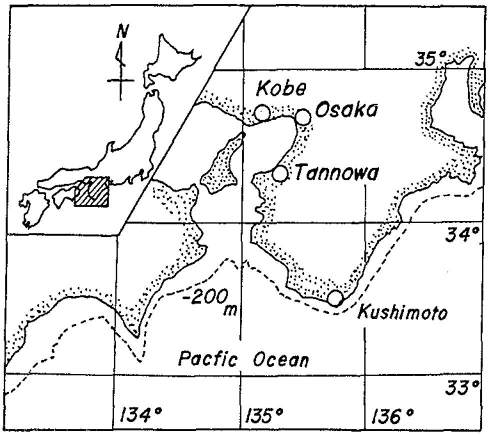


Fig. 1 Location map of study area

Fig. 2 reveals that the highest tidal level has exceeded 2 m T.P. [Tokyo Pile] four times since 1925. The highest tidal levels in Osaka and Kobe were recorded in 1934 (Muroto typhoon) and the second highest, in 1961 (Daini-Muroto typhoon). Third and fourth highest were recorded in 1950 (Jane typhoon) and for Typhoon 6420. There seems to be a periodic variation of three to five years and to be characterized by the group occurrence of storm surges between the end of World War II and 1970. This period will be studied by time series analysis in a later section. The data from Tannowa show the locality of storm surge generation and the influence of the typhoon path as in 1964 the rise of the sea level due to the typhoon was not marked in comparison with those in Osaka and Kobe. In Kushimoto, meteorological tides due to storm surges on the open coast affected the records. Therefore, it is valuable to have a boundary condition when the numerical simulation of a storm surge is attempted.

2] Maximum anomaly: Data for the annual maximum anomaly generated by typhoons and cyclones (low pressure) have been recorded since 1928 in Osaka and since 1931 in Kobe. Both have a few gaps, but from the historical reports of storm surges during these gaps, it has been determined that no large storm surges could have hit the area then. An annual maximum anomaly of over 2m was recorded four times in Osaka due to the large typhoons mentioned, but in Kobe there was only one recorded incidence, in 1934. This is proof that the probability of a storm surge disaster occurring in Osaka is much higher than in Kobe.

3] Lowest tidal level: The period covered by the time series data for the lowest tidal level is the same as for the highest tidal level. There are no extreme peak values, as for the highest tidal level and

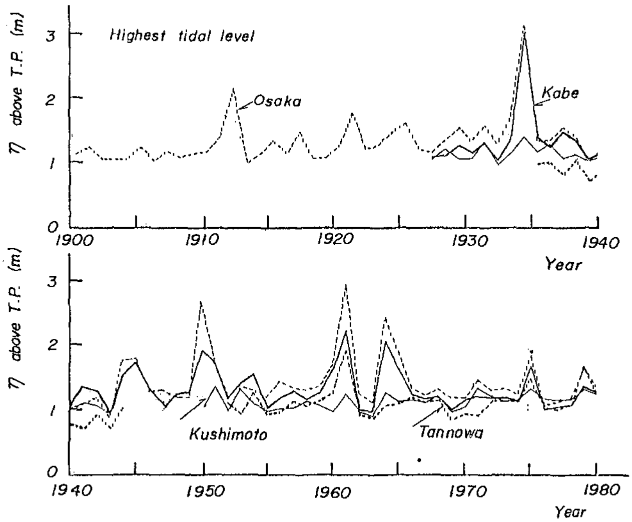


Fig. 2 Annual variation in the highest tidal levels in Kobe and Osaka

maximum anomaly. The occurrence of extremely low tides depends on the northwesterly monsoons in December or January. The low tidal levels due to the resurgence of a storm surge are not significant in comparison with those in monsoon season.

[b] Extremal statistics by traditional methods

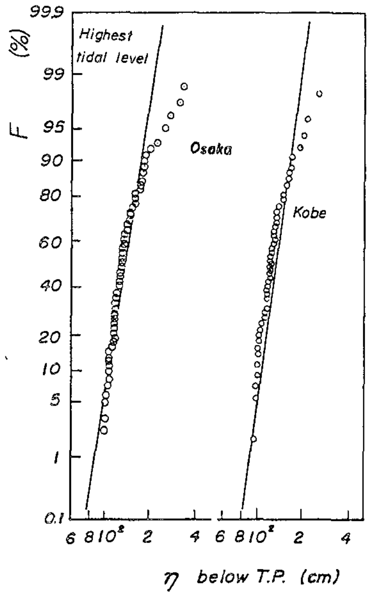
To obtain the return period of occurrence of a storm surge, traditional methods of extremal statistics are usually applied to data such as the highest tidal level and the maximum anomaly. Originally, these methods were applied for the analysis of the statistical characteristics of other hydrological events, such as precipitation and river discharge. It has always been held that the fitness of data to any probability density function depends chiefly on the sampling size. For the application of extremal statistics, the period of the tidal records must usually be much shorter than the return periods. For practical use, however, the design tidal level or the maximum anomaly has to be determined in order to take countermeasures against storm surges. In any analysis, some risks are inevitable, so that slight overestimates are preferable for engineering application.

A statistical analysis of storm surges in Osaka has already been carried out by Nachi (1972). Now, about ten years of new data can be added to the old ones and improvement in the fitness due to this increment in the amount of data is studied in this section. A Gumbel distribution and a log-normal distribution have already been found to give a relatively reasonable description of the tendencies of the data. They are used here for the analysis of the new data set with a χ-square test of fitness.

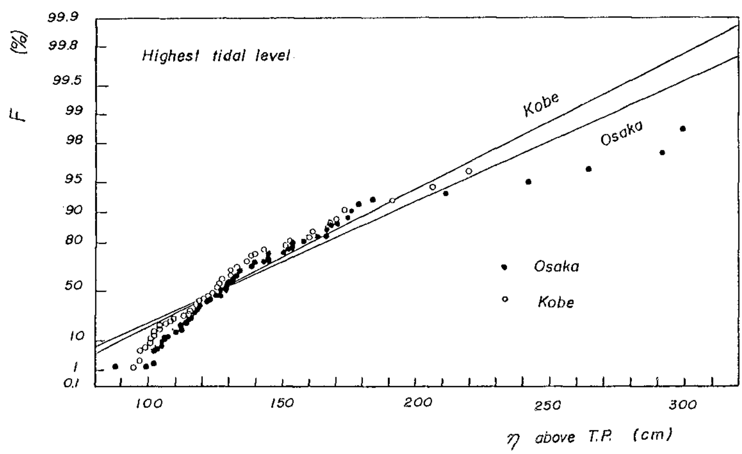
1] Highest tidal level: Figs.3(a) and(b) show the occurrence of highest tidal level in Osaka and Kobe on the probability papers of a Gumbel distribution and a log-normal distribution with Thomas plot. No distribution could follow the tendency of the data exactly because, especially for very large tidal levels, the discrepancy is remarkable. The statistical characteristics of the data from Osaka are very similar to those from Kobe. Comparison of these results with Nachi's fails to show any improvement in the degree of fitness. It is, therefore, concluded that the degree of fitness of the data to a probability density function does not necessarily depend only on the period of the data recorded.

For further improvement, Führböter proposed a new method of treatment for tidal data which had been recorded for over 120 years in West Germany. In the method, he has not described any physical background for selecting the annual highest tidal levels every two or three years. It was, however, shown that the estimated tidal levels corresponding to the 100 year return period approach a constant value with the increment in sampling years. Fig. 4 shows the results in Kobe by applying this method. The same characteristics are recognizable in Osaka. The method includes the smoothing of annual variations in the highest tidal level, so that the clearly small sample size leads to a rough prediction of the return period of storm surges.

2] Lowest tidal level: Fig. 5 shows the probability distribution for the occurrence of lowest tidal levels in Osaka and Kobe. The data fit well into a Gumbel distribution. This agreement has never been found in any other extremal statistics for tidal data except for the lowest tidal level. Annually, the lowest tidal levels occur in January or in December. During these months, the northwesterly monsoon blows continuously for one or two days after reaching a stable distribution of atmospheric pressure (in this situation, an anticyclone stagnates in western Siberia and a developing cyclone slowly moves eastward in the central part of the Japan Sea) causing extraordinarily low tide. Under these circumstances, the lowest tidal level can be treated as statistically independent variables. This will be discussed later with the time series for the lowest tidal level. The effect of sampling interval on the return period is not evident as has already been shown in Fig. 4.



(a) Log-normal distribution



(b) Gumbel distribution

Fig. 3 Probability of occurrence of the highest tidal level by traditional methods

3] Maximum anomaly: Fig. 6 shows the probability distribution for the occurrence of the maximum anomaly. The discrepancies between the data and theoretical curves are marked, as for as the highest tidal level. The scattering of the data in Osaka resembles that in Kobe, so that on the basis of the physical background of storm surges, the occurrence of the maximum anomaly may be analyzed.

[c] Effect of tidal observation period on degree of fitness

The tides have been recorded for more than ten years since the last study done by Nachi(1972). However, in spite of this increase in the available sample size, the degree of fitness of the data to the probability distribution did not improve as was hoped. Thus, the sample size is not the dominant factor determing the degree of fitness. Even if the maximum anomaly can be regarded as a statistically independent variable, the "accidental" data do not agree with the theoretical curves. From Figs. 3 and 6, it is evident that the fitness of the maximum anomaly to a Gumbel distribution is worse than in the case of the highest tidal level. The influence of the period of the data is, of

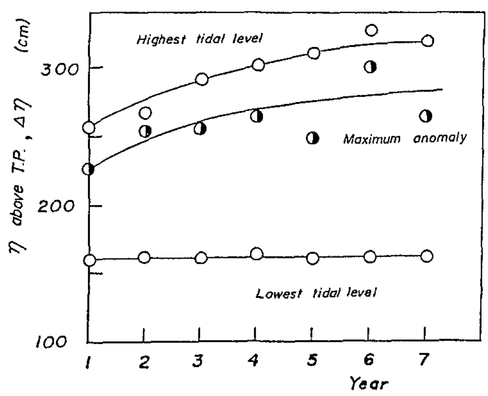


Fig. 4 Changes in estimated tidal values in Kobe with sampling years corresponding to 100 year return period analyzed by Führböter's method

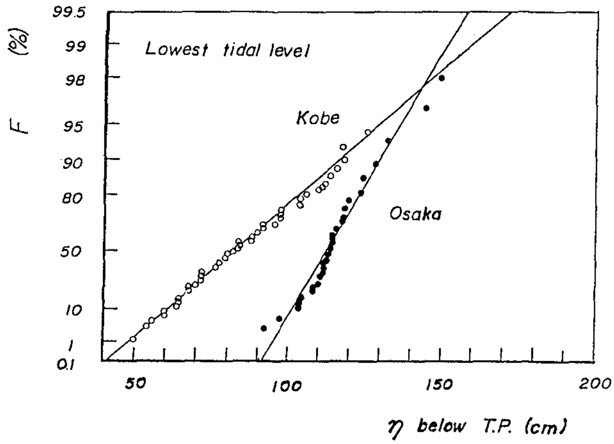


Fig. 5 Gumbel distribution for the lowest tidal level

course, part of this difference in fitness.

One of the probable explanations for this discrepancy is the effect of marked reclamation along the coast in Osaka Bay. Reclamation was rapid in the 1960's and since Osaka is located at the northeast end of the bay, as shown in Fig. 1, the effect is easily amplified. If the characteristics of the data have statistically changed due to this reclamation, it is necessary to divide them into two groups, for example, into the annual extremal values before and after reclamation. At the same time, the statistical independency of the data has to be justified. For example, if periodicity is to be found in the number of typhoons and cyclones which hit or move alongshore, the tide will consequently include their influences to some degree and careful editing should show the periodicity.

Attention must also be paid to changes in tidal characteristics due to differences in the wind fields along the tracks of typhoons. When a typhoon passes the west side of the bay, it results in a large storm surge by strong winds blowing over the sea counterclockwise. Therefore, the effect of wind drift on sea water accumulating in the semicircle is more remarkable than that in a western one. In this process, the influences of solid boundaries, such as the geographic shape of reclaimed areas and the general direction of coastlines, are also significant.

INFLUENCE OF RECLAMATION ON TIDE AND ITS TREND

[a] Influence of reclamation

Fig. 7 shows the cumulative curve for reclamation on Osaka Bay.

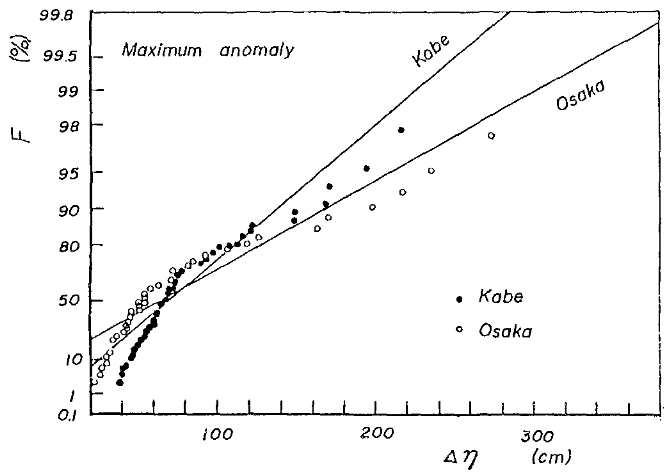


Fig. 6 Gumbel distribution for maximam anomaly

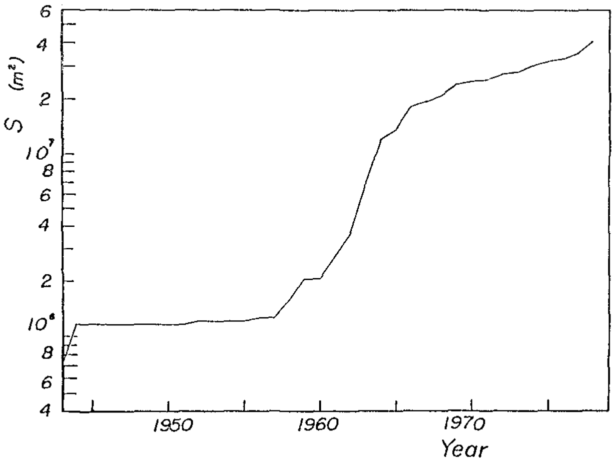


Fig. 7 Cumulative curve of reclamation area around Osaka Bay

The survey covers the coast between Akashi and Tannowa, a distance of about 90km. The acceleration in reclamation in the 1960's was a result of the rapid economic growth in Japan. According to an environmental white paper, natural beach, such as Nishikinohama and Suma beaches, occupies less than two percent of the length of the coastline. In general, the coast can be divided into rectangular areas of reclamation having sides less than several hundred meters in length continuously located along the coast. In small strips, behavior of storm surges may be amplified. In Kobe, man-made Port Island and Rokko Island are relatively large in comparison with the reclamated areas in Osaka, so that the former unevenness in shape is not remarkable enough to make small rectangular strips of reclaimed areas.

It is very difficult to estimate quantitatively the effects of the reclamation on the tide because changes in astronomical tides are a slowly varying phenomenon. However, every tidal observations are carried out close to coast, and so the geographical boundary conditions must surely affect the tidal measurements. For this reason, changes in tidal constituents are first discussed on the basis of a comparison of predicted and observed tides, and secondly, the annual variation in high water level in the spring tide during typhoon season (July to September) is studied.

Fig. 8 shows the annual changes in the amplitude and phase angle of the tidal constituent M2 in tidal predictions. In Kobe, the changes are trivial, but in Osaka, an annual increase in the amplitude and a decrease in the phase angle can be seen. Other tidal constituents such as S2, K1 and O1 have also been found to have similar clear trends in Osaka. In order to confirm this phenomenon, further investigation is required, but at present, it can be surmised that the cumulative influences due to wide reclamation near Osaka have changed the behavior of the tide.

Fig. 9 shows the annual variation in the high water level of the spring tide during the typhoon season since 1950. A period of three to four years is evident in Osaka and Kobe with no phase lag between the two places. This phenomenon has also been detected at other tidal observation points around Osaka Bay, but the variations in amplitude are smaller than those in Osaka and Kobe. Probable factors which generate these variations, that is, the influence of typhoons and the meandering of the Kuroshio along the southwest coast of Japan have been investigated with field data; however, it appears that they do not contribute to this periodic variation in the high water level.

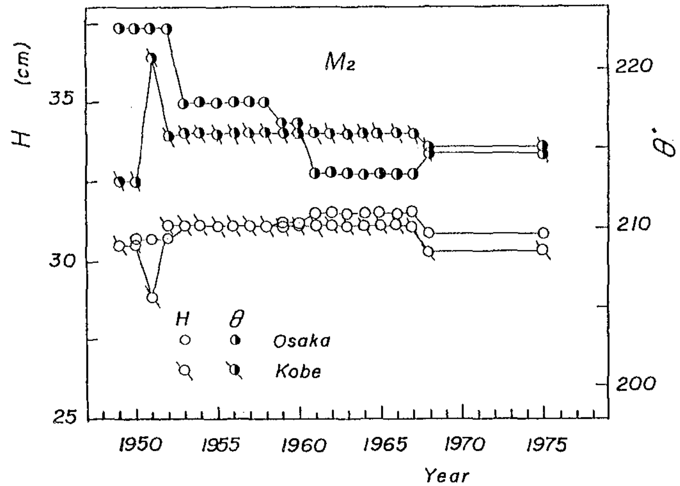


Fig. 8 Annual changes in amplitude and phase angle of tidal constituent M2

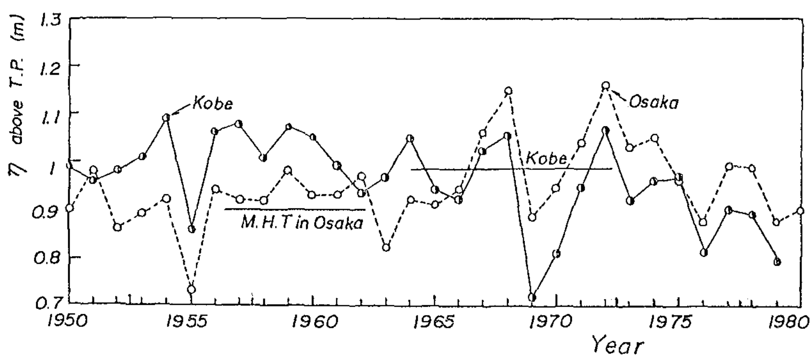


Fig. 9 Annual changes in high water level of spring tide in typhoon season

Next, hourly changes of the tide are studied to see if the reclamation could be causing the unusually high water levels. Fig. 10 shows the hourly changes in the tide in Osaka for four days around the spring tide of August 14 and 27, 1965. The discrepancies between the predicted and observed tides are clearly greater just before and after the spring tide. Such systematic discrepancies are usually observed during the rising stage of a tide. Moreover, flattening of the high tidal level peaks in the spring tide has been pointed out by the Kobe Marine Observatory since 1970, which almost coincides with the construction of Port Island in Kobe. Therefore, the tide may be under the influence of the reclamation

The above investigation gives the quantitative effects of the reclamation on the tide and shows that the tidal level tends to be amplified by a rapid increment in reclaimed areas.

[b] Time series of tide and its trend

Trends may be included in the time series for extremal values, such as the highest tidal level and the maximum anomaly. Such trends are due to long-term natural changes or to artificial impacts, such as rise of sea level or reclamation along the coast, land subsidence, etc.

The trend index is given with the rank correlation by

$$IT = \sqrt{18}\left[2\sum_{i=1}^{N-1} n_i - N(N-1)/2\right] / \sqrt{N(N-1)(2N+5)} \tag{1}$$

in which N is the number of samples, n_i the number of events larger than x_i after the occurrence of x_i. If $IT > 1$, the time series includes an increasing trend. On the contrary, if $IT < -1$, there is a decreasing trend. In the case of the highest tidal level, IT is 2.08 in Osaka and -0.78 in Kobe. The same tendency can be detected in the lowest tidal level, but there is no trend in the maximum anomaly for either place.

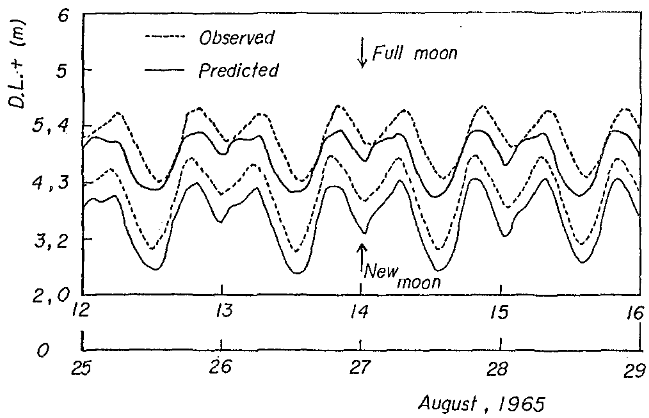


Fig. 10 Hourly changes in tide in Osaka

When the trend is detected, it is usual to eliminate it from the data by applying a polynomial expression. However, it is also evident that in the future, the situations affecting the tidal level will inevitably change. Reclamation, as mentioned affects the characteristics of the tide, but the trend that results will change again with more reclamation. Moreover, the rising trend of the highest tidal level in Osaka is due to a group occurrence of storm surges after World War II. In this paper, therefore, the trend due to natural factors are also included in the analysis.

Fig. 11 shows the auto- and serial-correlation coefficients of time series of the extreme tidal data in Kobe. From this figure, it is recognized that the maximum anomaly changes in periods of four, twelve and fourteen years. This situation is almost the same in Osaka. The reason this clear periodicity exists is mainly due to the characteristics of typhoons as the external force causing storm surges. Fig. 12 shows the auto-correlation coefficients of the number of typhoons generated and the number of typhoons which struck. The observation period of the data is the same as in Fig. 11. A periodicity of four, twelve and sixteen years can be found in the number of typhoons which struck. This result has also been confirmed by analysis with a periodogram. It is clear that the occurrence of the maximum anomaly strongly depends on characteristics of typhoons approaching Japan.

Another problem is revealed by this analysis. When the maximum anomaly is not made up of statistically independent variables, as shown in Fig. 12, it is, in a strict sense, impossible to apply the theory of extremal statistics, but as Gumbel (1957) said, it is reasonable that the probabilistic distribution of statistically dependent variables has some of asymptotic characteristics found in independent variables. Therefore, practically speaking, extremal statistics is also applicable to the maximum anomaly.

EXTREMAL STATISTICS OF STORM SURGES

[a] Changes of tide with typhoon track

As already pointed out, acceptable fitness of the highest tidal level and the maximum anomaly to a Gumbel distribution is not obtainable by traditional methods. The investigation shows that the shortness of the observation period is not always the main reason for the discrepancy between the observed data and theoretical distribution curves. On the contrary, for the lowest tidal level, the fitness of the data to a Gumbel distirbution or a log-normal distribution is good.

For improvement in the degree of fitness, the process of the occurrence of an extremal tide should be studied. Most extremal data, except those in recent years, are due to typhoons. In the east area of the typhoon track, in which the moving speed of a typhoon is superposed on the gradient wind, strong wind are blown. Therefore, storm surges in the east semicircle are generally larger than those in the west one. Thus, the extremal data can be divided into two groups according to the directional characteristics of the typhoon tracks. Weather charts can be used to clarify the position of typhoons.

Fig. 13 shows the auto correlation coefficients of the highest tidal level in Kobe when the typhoon tracks are considered. The characteristics of variation of the auto-correlation coefficients differ from those shown in Fig. 12 where the directional characteristics of the typhoons are not considered. This situation is the same in Osaka. Furthermore, comparison of the auto-correlation coefficients for west-

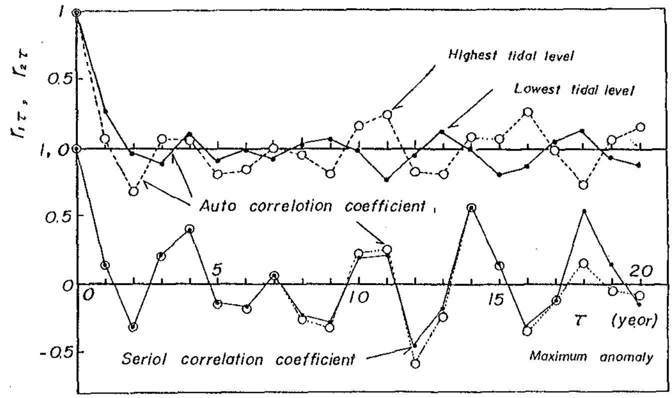


Fig. 11 Auto- and serial-correlation coefficients of time series for extreme tidal values in Kobe

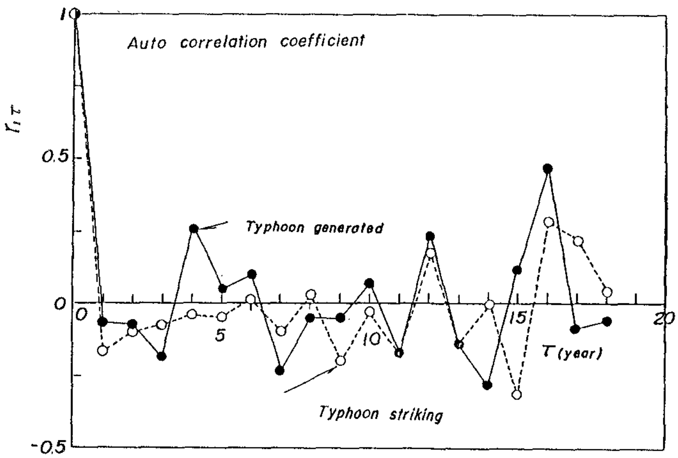


Fig. 12 Auto-correlation coefficients of numbers of typhoons generated and of typhoons striking Japan

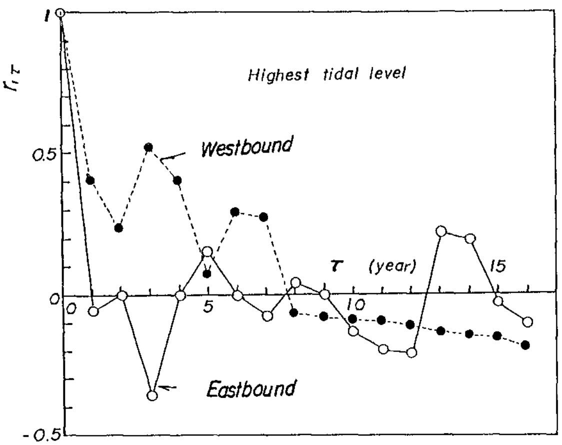


Fig. 13 Auto-correlation coefficients of the highest tidal level in Kobe, considering direction of typhoon track

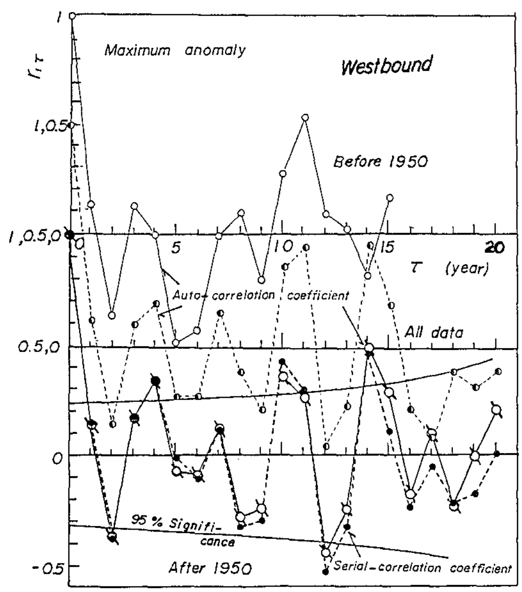
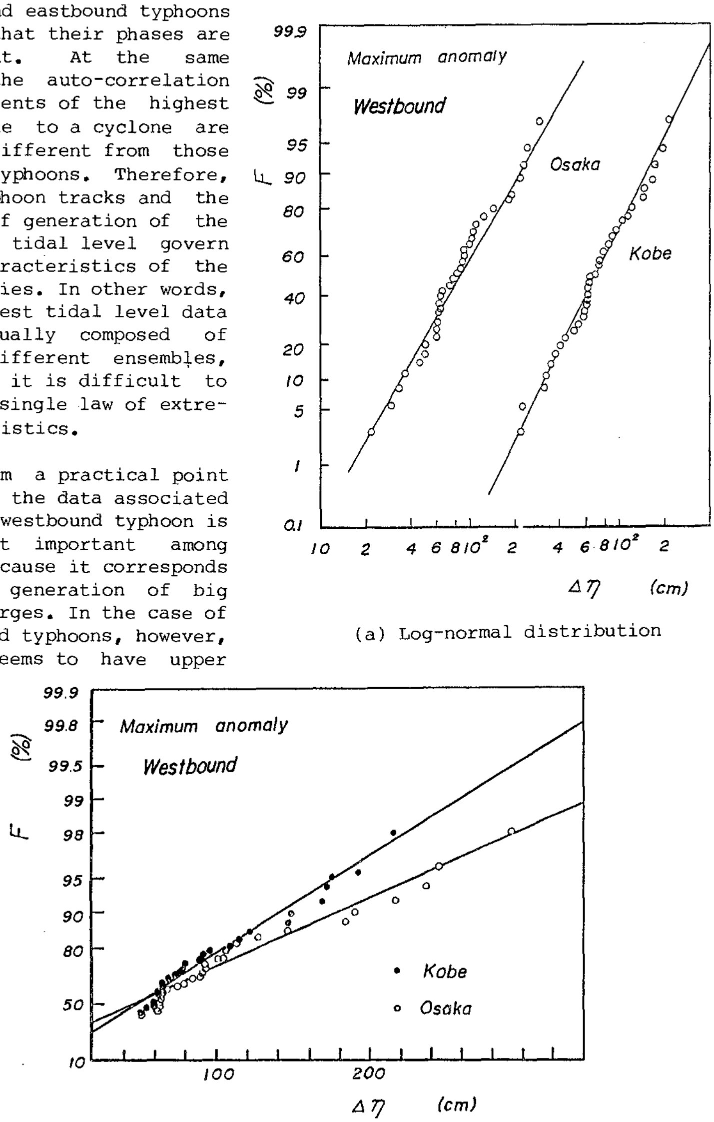


FIG. 14 Auto- and serial-correlation coefficients of maximum anomaly in the case of westbound typhoons

bound and eastbound typhoons shows that their phases are different. At the same time, the auto-correlation coefficients of the highest tide due to a cyclone are quite different from those due to typhoons. Therefore, the typhoon tracks and the source of generation of the highest tidal level govern the characteristics of the time series. In other words, the highest tidal level data are usually composed of three different ensembles, so that it is difficult to make a single law of extremal statistics.

From a practical point of view, the data associated with a westbound typhoon is the most important among them because it corresponds to the generation of big storm surges. In the case of eastbound typhoons, however, there seems to have upper



(a) Log-normal distribution

(b) Gumbel distribution

Fig. 15 Probability of occurrence of maximum anomaly generated by typhoons passing through area west of Osaka and Kobe limit of wind speed in their west side, a scale of storm surges may be under certain level.

Fig. 14 shows the auto and serial correlation coefficients of the maximum anomaly for westbound typhoons. In comparison with Fig. 13, the overall characteristics of the maximum anomaly in Osaka are governed by the typhoons which pass through its western side. In the figure, the data are divided into two groups, just before and after 1950. In both groups, an eleven-year period can be seen. This periodicity coincides with that of the typhoons striking Japan.

[b] Extremal statistics of storm surges

Fig. 15 shows the probability of occurrence for the maximum anomaly generated by typhoons passing through the western side of the bay. From this figure, it is clear that the fitness of the data to a Gumbel distribution or a log-normal distribution improves in comparison with Fig. 3. In Fig. 16, data smaller than 50cm are included in order to obtain a larger sampling period. Every newspapers, weather charts and meteorological reports show that there was no storm surges at those years. The fitness of the data in Fig. 16 also improves over that in Fig. 15. From these figures, it is clear that Osaka is more susceptible to storm surges than Kobe. In this analysis the distance between the eye of a typhoon and the tidal measuring points has not been included. Its consideration would further improve this method.

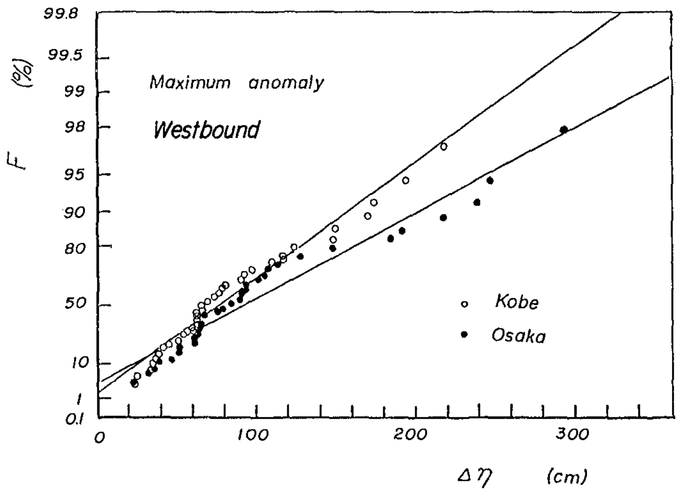


Fig. 16 Gumbel distribution of maximum anomaly in which data less than 50cm are newly added to those in Fig. 15

The frequency distributions for the highest tidal level in Osaka analyzed by the method proposed here are shown in Fig. 17. It is found that the fitness of the data to a Gumbel distribution is fairly good in comparison with Fig. 3. In particular, the scattering of the data is much improved for portion of relatively large tidal levels generated by typhoons passing through the western side of the bay. For eastbound typhoons, a certain upper limitation for the highest tidal level can be observed. Therefore, this classification of typhoon by track contributes much to the improvement of fitness.

CONCLUSIONS

We have developed a method for estimating the occurrence probability of abnormal tides by considering the characteristics of typhoon tracks. It is clear that the fitness of the data to any probability density function cannot be improved by lengthening the period of tidal data or by taking into consideration the effects of extensive reclamation on characteristics of tides. It is concluded that this method has high applicability for determination of the return periods of abnormal tides due to storm surges.

The study reported here was supported by Grant-in-Aids for Scientific Research from the Ministry of Education, Science and Culture of Japan, under Grant No. 302027.

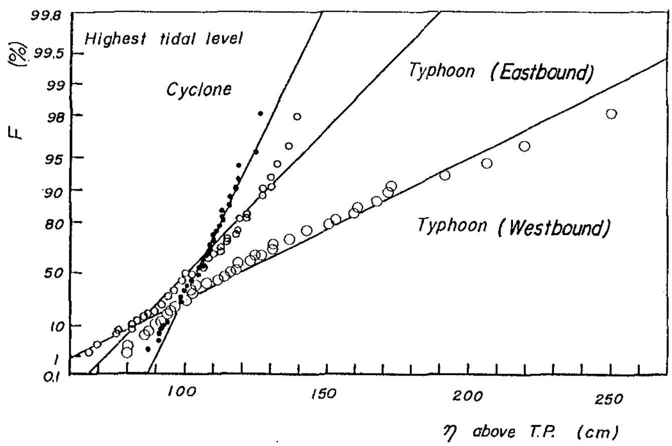


Fig. 17 Gumbel distribution for the highest tidal level in Osaka for east- and westbound typhoons and cyclones

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