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A Note on Numerical Evaluation of Tsunami Threats by Simple Hydrodynamic and Stochastic Models Referring to Historical Descriptions

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Abstract

This work is a speculative study to clarify what is essential for hydrodynamic or stochastic studies of the tsunamis and what are important in the historical descriptions and the tsunami catalogs for numerical simulation and prediction and for stochastic evaluation of practical tsunami protection works. First, a brief description of the historical documents of past tsunamis are introduced and evaluated in order to give a local chronological tsunami catalog which will aid in understanding what should be remarked at reading the tsunami descriptions. Next to the descriptive tsunamis, numerical simulation of the past tsunamis were reviewed and evaluated. The author's finite difference method with a uniform grid spacing is introduced in order to show an agreable result as a simulation of a tsunami. The author has used a uniform grid spacing in his numerical model because he knows that it is helpful in minimizing the truncation error in a numerical model of a finite difference method. In any numerical simulation case, the historical descriptions are the essential references to confirm how successful the simulation is. Although, no numerical model can predict when the next tsunami occurs. The stochastic model is now very useful in making probabilistic prediction. This measure is for long-term practical planning of tsunami protection works with reliable references selected out of the historical documents of the past tsunamis and the tsunami catalogs well revised.

1. Introduction

The Circum-Pacific seismic zone has always been threaten by severe tsunami damage, which can be understood when we open the pages of a tsunami catalog. Historic records have shown repeated tsunami occurrence in this zone, nevertheless, recent coastal development trends are surging, hence leaving these coastal areas under an extreme tsunami hazard.

It is necessary now to determine methods by which these highly-developed coastal communities can be protected from the inevitable tsunami occurrence.

In the past many methods of various effectness were devised in order to minimize tsunami damage. These methods, which were developed over the many years, have evolved into the various kinds of coastal protection works which, despite their initial tsunami protection aim, have guarded coastal communities against both storm surges and high waves.

The first step taken to understand the nature of tsunamis appeared in Japan long before other countries were aware of the problem. One of the significant contributions was to compose the first edition of the seismic and tsunami hazards in form of a chronological list, which was a part of the big project started in Meiji era and completed in Taisho era in Japan. They, as well as we do, had to distinguish the reliable data for the tsunami catalog through their works. No subjective part should be excluded in it in a scope of "natural science '. The old tsunami descriptions have been compiled from year to year in order to improve and revise the tsunami catalog which is in present use. This effort is still continued by many scientists successively. Here, the author's information is found in what is written in the historical descriptions along with the essential information necessary for tsunami protection works of the future. This will be better understood by what is discussed in the second chapter of this manuscript.

The second step must be an introduction of a hydrodynamic approach to learning the theoretical properties of the tsunamis. This approach was followed by a recent numerical computations by using the various schemes of hydrodynamic modelling, for example, finite difference methods, finite element methods, finite segment methods and some other possible methods. However, these methods can not necessarily solve well all of the tsunami problems completely even at present. Some of these methods will be successful in simulation and predicting some limited cases of the local tsunamis. Although, this numerical technique can not give any information about when the next tsunami occurrence is possible even in a local coastal zone. This is one of the reasons that a stochastic modelling of tsunami occurrences is applied to specific local coastal zones. Of course, some assumptions are required to promote this modelling. This is the third step of the tsunami research.

In the third chapter an overview of numerical simulations are briefly given along with an introduction to and discussion of one of the author's numerical computations for tsunami simulation. This numerical model uses a finite difference method with a uniform grid spacing. The author used this uniform grid spacing because the truncation error is minimum in the model as far as he trust a simple difference expression of a function f with a variable t, $(\Delta f/\Delta t)$, which is equivalent to an expression of differenciation df/dt. As for the truncation error minimum, a note is added as an appendix at the last part of this manuscript.

As seen above, an outline of this work must clarify that it is not possible to predict the forthcoming tsunami in any local coastal zone, even when a numerical model of the hydrodynamics could be developed in near future. The numerical model simply informs us of a reasonable solution for given conditions and for assumed tsunami source parameters.

In the fourth chapter, a brief history of stochastic studies is presented on local tsunami occurrence. Because the tsunami occurrence on Japanese Islands are not as frequent as storm surge, it is necessary to consider the extremal events of the past tsunamis. The coastal damages caused by a tsunami will surely be more significant than that caused by storm surge, therefore, there is a strong desire to know or predict when the next tsunami will hit their coastal areas. This is the starting point to introduce the technique of extremal statistics as a tool to find a mathematically possible extremal event of the tsunamis in near future in relation to their own interest, though the author knows that this tool cannot provide acceptable results without careful processing of the historical data or descriptions. It should be possible for any one to understand that one of the best ways to introduce a stochastic model is after some repeat of his trials and errors in applications. One of the author's example is introduced in the fourth chapter. His idea is to utilize an extended or modified stochastic model, though he shows only a simple application of so-called "Poisson process" to a local exceedance probability of tsunami occurrence.

In this work, it is necessary to point out that no numerical simulation or stochastic model can be useful for practical tsunami protection plannings and its protection works except as pertinent reference to the historical tsunami documents and the tsunami catalogs. Numerical simulation methods should not be utilized independently without any consideration for local exceedance probability of tsunami occurrence which must be obtained by an application of a stochastic model. A more effective way would be to consider a set of numerical and stochastic models and the reference tsunami documents or the tsunami catalogs to get a more effective planning and designing a tsunami protection works.

2. Historical documents

In order to truly understand the meaning of local tsunami threat, it is essential to refer to a tsunami catalog first. Such a catalog has been composed after compilation and analyses of the historical documents. Iida, Cox and Pararas-Carayannis[1] (1967) completed a preliminary catalog of tsunamis in the Pacific. Soloviev and Gao published a Russian edition for the western[2] (1974) and eastern[3] (1976) Pacific. Japanese edition was published in 1904 (Meiji 37) by Shinsai-yobo Chosa-kai (an Association for survey of seismic hazards mitigation)[4,5]. It's title was "Dai-nippon Zishin Shiryo (Historical data of the past earthquakes in the Great Japan)" and it consisted of the ancient part[4] plus the successive part up to 1865 (Keio 1). This compilation was first proposed by Sekiya then completed by Tayama with Omori's support. Successive revisions have appeared. For example, a convenient brief edition was distributed by Imamura[6] (1942). Recently, Watanabe[7] (1968) composed a catalog of tsunami around the Japan Islands and revised it[8] (1983). He published a new Japanese edition of the tsunami catalog with an overview concerning the tsunami itself[9] (1986). Iida[10] (1984) has also completed an English revision of his tsunami catalog. Usami's catalog of hazardous earthquakes in Japan[11] (1974) also includes some brief description of the tsunamis which accompanied some past significant earthquakes.

The first step to compose these tsunami catalogs was to uncover old descriptions which described the occurrence of various tsunamis. Of course, it is necessary to confirm whether the descriptions are reliable or not as they are being compiled. Even at present, continuous effort is made to search for and reveal the historical documents concerned.

These documents take various forms such as parts of personal diarys, governmental documents, records from Shinto shrines and Buddhist temples or simple personal descriptions. Additional findings were compiled by Tsuji[12] (1981). Nakamura [13,14,15] (1984a, b, 1985) is also continuing the process of uncovering historical descriptions which include any note concerning significant tsunamis of the past in order to get more precise information which may be utilized for dorthcoming tsunamis.

As as example, the author now introduces a local tsunami list for the area of Tanabe and Shirahama, where they have had repeated suffers from the past tsunamis accompanied by the earthquakes. Tanabe and Shirahama are facing the Pacific and there are yet many of unpublished materials which inform us new facts about the tsunamis (Nakamura[13], 1984).

A local tsunami catalog can be composed by referring to the catalogs introduced above and adding the newly revealed facts culled from the unpublished materials. By adding information from the local documents, a detailed local tsunami catalog for Tanabe and Shirahama has been formed. The format first gives both western and (Japanese) dates, the estimated location of the epicenter taken from Watanabe's catalogs (for example, from 1986 catalog)[9], the magnitude of the earthquake denoted by M, the tsunami magnitude denoted by m and finally, brief descriptions of each event.

2.1 684 AD Nov. 29 (Temmu 2) A strong earthquake, land slides, destruction of the governmental offices, warehouses, shrines and temples. Fields were covered by the sea waters. Hot spring ceased at Iyo (Ehime). Tsunami hit Kumano. Hot spring at Muro also ceased. This is in the oldest description around the area in Nihon-shoki and cited also in local documents.

2.2 887 AD Aug. 26 16h (Ninna 9) 135.3E, 33.0N, $M=8.6$, $m=3$. Strong earthquake. Tsunami hit and many lives lost.

2.3 922 AD (Engi 22) 137.7E, 33.8N, $M=7.0$, $m=1$. A strong earthquake with tsunami.

2.4 1360 Nov. 23 0h (Shohei 15) 136.2E, 33.4N, $M=7.0$, $m=2$. Repeated large-scaled earthquakes. On the next day also a big earthquake. Tsunami hits in morning of the second day after the last shock.

2.5 1361 Aug. 3 (Shohei 16) 135.0E, 33.0N, $M=8.4$, $m=3$. Description merely says that an earthquake struck around Kii and a tsunami hit Settsu (Osaka).

2.6 1403 (Ouei 10) 136.5E, 33.7N, $M=7.0$, $m=1$. Strong earthquake in Kumano. Tsunami hit.

2.7 1408 Jan. 21 18h (Ouei 14) 136.9E, 33.8N, $M=7.0$, $m=1$. Strong earthquake in Kumano. A tsunami possibly hit.

2.8 1498 (Meio 7) High water caused hazards on the coast of Kii district.

2.9 1510 Sep. 21 4h (Eisho 7) 135.7E, 34.6N, $M=6.7$, $m=1$. Estimated epicenter is located in Osaka Bay. Tsunami hit.

2.10 1520 Apr. 4 18h (Eisho 17) 136.3E, 33.6N, $M=7.0$, $m=1$. Temple buildings destroyed by the earthquake. Houses inundated.

2.11 1605 Feb. 3 (Keicho 9) 134.9E, 33.0N, $M=7.9$, $m=3$. Big waves at Kumano. Hiro, consisting of 1700 families, lost 700 families when the tsunami hit.

2.12 1707 Oct. 28 12h30m (Hoei 4) 135.9E, 33.5N, $M=8.4$, $m=4$. Detailed descriptions concerning the earthquake and tsunami have been left in order to warn of the hazards for their successors and official descriptive reports which noted the damage and requested fast aid of food and living materials. Identifying the location appeared in the descriptions, a map of the aftermath of the tsunami of the 1707 Hoei event could be drawn (**Fig. 1**).

2.13 1854 Dec. 24 16h (Kaei 7 or Ansei 1) 135.6E, 33.2N, $M=8.4$, $m=4$. More detailed descriptions concerning the earthquake and tsunami have been compiled so that a more detailed tsunami map could be drawn (**Fig. 2**). Comparing

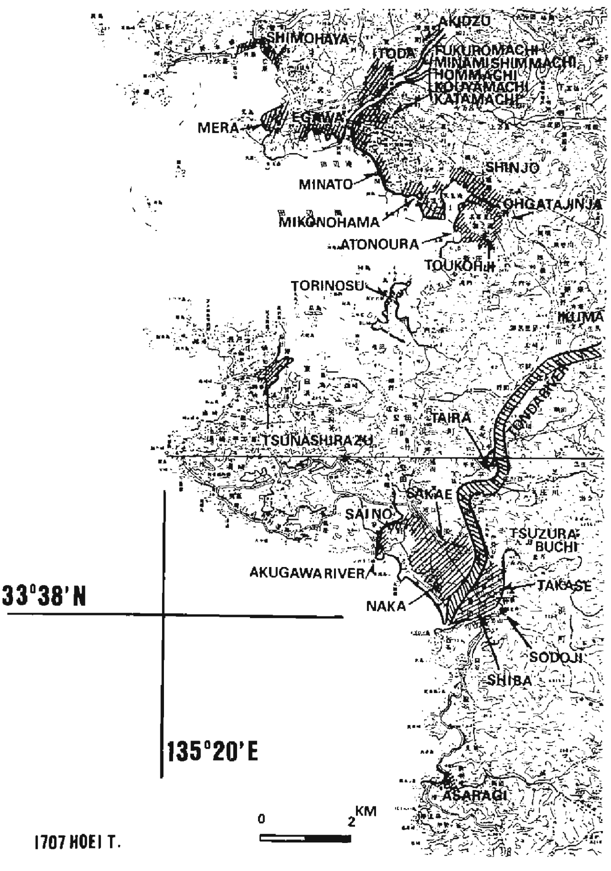

Fig. 1. Local hazard map of the 1707 Hoei Tsunami for the area of Tanabe and Shirahama. The hatched areas on the coasts and along the rivers show the inundated areas by the tsunami. The thick lines drawn in encre-de-chine are also the inundated areas of Egawa, Itoda and the urban district around the Aidzu River. No protection works were both for the Aidzu River and the Tonda River. The tsunami run-up was up to the area of Ikuma district about eight kilometers distant from the mouth of the Tonda River. This map shows that the areas where any people had lived on the coast correspond to those where damages were recorded, in the historical descriptions. The highest tsunami were recorded as about thirteen meters at the Ohgatajinja (shrine) and Tohkohji (temple) located almost at the head of the Tanabe Bay.

Fig. 2 with **Fig. 1**, we can find that the same areas had suffered repeatedly from the tsunami. We have to be careful when utilizing the descriptions whether what is written is objective or not.

2.14 1944 Dec. 7 13h35m (Showa 19) 136.2E, 33.7N, (depth 30 km), $M=8.0$, $m=3$. On the east coast of Kii Peninsula, houses were washed away by a tsunami hit. However, no record was left except only a limited number of tide records which included the tsunami on the day.

2.15 1946 Dec. 21 4h19m (Showa 21) 135.6E, 33.0N, (depth 30 km), $M=8.1$, $m=3$. Some scientific records have been kept. It seems that the descriptions are correct to the details. Old people have told the author what was happened at that

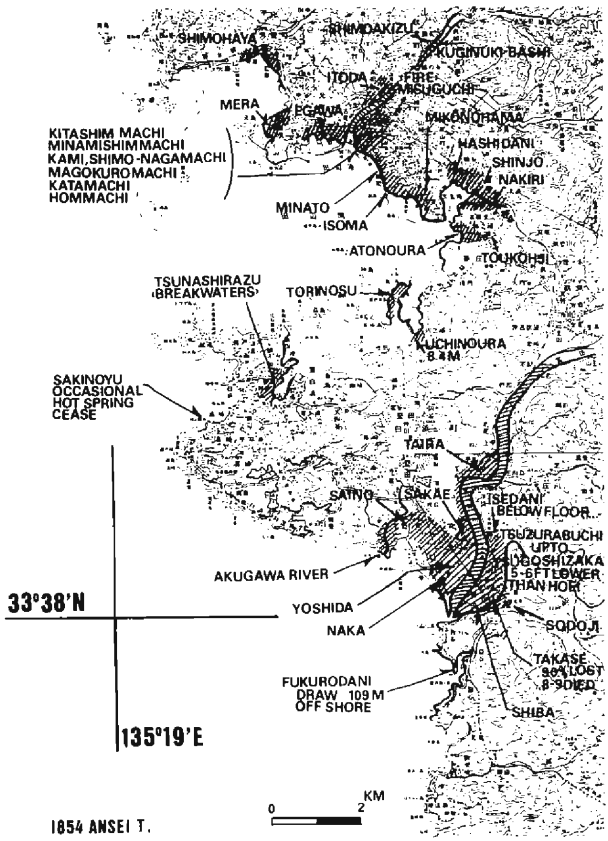

Fig. 2. Local hazard map of the 1854 Ansei Tsunami for the area of Tanabe and Shirahama. Same as those in **Fig. 1** essentially. In addition, the more detailed descriptions were found for the 1854 Ansei Tsunami rather than the case of the previous 1707 Hoei Tsunami. A document for requesting to construct a set of breakwaters along the coast of Tsunashirazu in Shirahama is found. The hatched areas in this map is wider than that in Fig. 1 as a total. This suggests an increase of people who had lived and utilized the coastal area in the last hundred years by the time of the event of the 1854 Ansei Tsunami. The highest tsunami was a little less than that at the previous 1707 event.

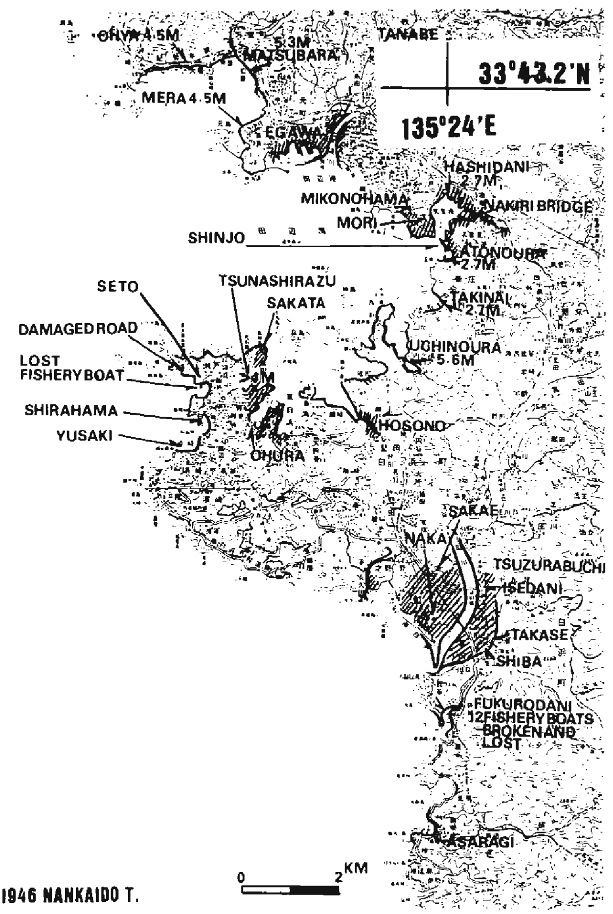

Fig. 3. Local hazard map of the 1946 Nankaido Tsunami for the area of Tanabe and Shirahama. Same as those in Figs. 1 and 2 essentially. In addition, the hatched areas around the Aidzu River near Egawa and the Tonda River show the significant effect of the protection works of the flood in the Rivers at the 1946 event of the tsunami. Descriptions are found as well as more scientific records based on the surveys after the event so that the local highest tsunami can be found in the metric expression. No repeat of copying the details of the records on the map is considered so that those are requested at those wish to refer to the reports or works found on the "References" of this article in order to help them to learn the tsunami hazards at the time to the details as well as the cases of the 1707 and 1854 Tsunamis. On the other hand, the author has to give some remarks that the increase of the population in this area after the second world war resulted to cause of an unexpected damage by the tsunami in the other districts where no such damages were recorded in the past, i.e., Takinai in Tanabe and Sakata, Ohura and Hosono in Shirahama. These districts were developed to support their living after the second world war. After the 1946 Nankaido Tsunami, simple soil mounds were constructed along the coast as a countermeasure for tsunami protection works in Shinjo district from Hashidani to Atonoura through Nakiri in Tanabe. This mound can be seen even at present aside of the national high way of No. 42 in the district. The bridges at the most down reach of the rivers in Shinjo had worked well to block an amout of the floating timbers in the Mori at the head of Tanabe Bay. However, it is the fact that the tsunami brought the timbers into the almost all of the streets and lanes. This made them to feel a desperative feeling of their fates, though they have recovered well by this time.

time vividly even after time elapse of fourty years since the event. A tsunami hazard map was constructed (**Fig. 3**) based on what was found in the records and descriptions. The descriptions tell us successful protection works around the

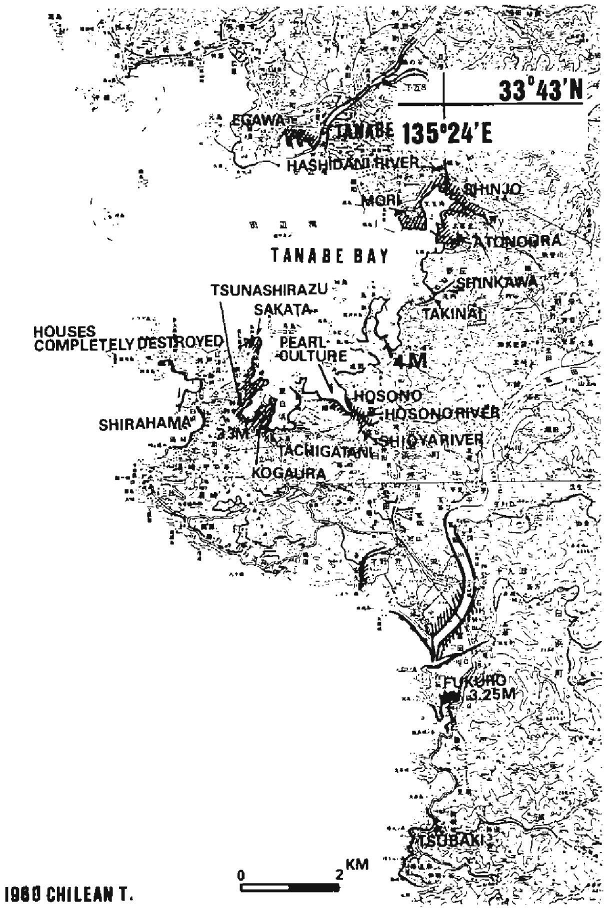

Fig. 4. Local hazard map of the 1960 Chilean Tsunami for the area of Tanabe and Shirahama. Same as those in Fig. 1, 2 and 3. In addition, the areas around the river mouth, i.e., Egawa and the urban area of Tanabe and the mouth of the Tonda River were a little less of damage than that in the case of the 1946 event. The more detailed reports and works were published and distributed already so that it can be easily found by those who have interested in to know about the event to the details. Even though, it should be remarked that the 1960 Chilean Tsunami hit the coast after crossing the Pacific in about twenty-four hours later and the damage on the coast at the event shows that there is a new type of the tsunami threat in the areas and districts where no people has considered ever at development for utilization of the coastal zones effectively. One of examples is damage of the planting for pearl-culture happened in a small inlet "Hosonoura" which is connected to the Pacific through Tanabe Bay. As for the Cilean tsunami hit, we have repeated cases for the Japanese Islands' coast facing the Pacific at least since 1568. This cannot be the new type of the tsunami hazards. Contrally, the big tsunamis ever hit the Pacific coast of the South America after crossing the Pacific from the source off south of Japan or east of Japan.

mouths of Aidzu River and Tonda River so that the author takes that the tsunami affected smaller areas than ever. This can be seen by comparing the hatched areas where the tsunamis inundated at the events in 1707, 1854 and 1946 as shown in **Figs. 1, 2** and **3** respectively. However, another new hazardous area appeared in the Hosono district where no one had ever lived before that time. Except for the above, the common areas afflicted by tsunamis in **Figs. 1, 2** and **3** can be found, that is, Egawa and the urban area in Tanabe and Mikonohama, Shinjo and Atonoura, and Tsunashiradzu of Shirahama.

2.16 1960 May 22 19h11mGMT (Showa 35) 73.5W, 41S, $M=8.25$, $m=4$. A tsunami hit the Japanese Islands on 24 May 1960 after crossing the Pacific. The highest tsunami was 20 to 25 m at Isla Mocha in Chile. Even in Japan, 119 persons died, 29 persons lost, 872 persons injured and 2830 houses destroyed, 19863 houses inundated as well as damage to boats. In Chile, 909 persons died, 834 persons lost, 667 persons injured and many buildings had severe damage. As can be seen in **Fig. 4**, inundated areas in 1960 were almost common to those in 1707, 1854 and 1946 when the inundated areas were recorded and shown by the hatched areas in **Figs. 1, 2** and **3**.

At the end of the listing a tsunami which had hit the local coastal areas, the author have to add some remarks about a flood protection works around the rivers which are included in the interested area. After learning about the tsunamis on the coast and the floods around the rivers, the author cannot aware of that the flood protection works in these fifty years have been effective to protect the coastal areas out of the recent tsunamis, for example, the events in 1946 and 1960. A construction of a high way from Tanabe to Shirahama resulted inundation in the other area on the coast in Uchinoura, though the high way protected the head of a small inlet "Uchinoura" in 1960. The struck areas in the figures (the hatched area along the coast and in the rivers) correspond to the areas where the highest amplitude appears in a numerical model of resonant modes of Tanabe Bay (Nakamura[16], 1986a). As far as we are concerned, the new problem for us must be to consider the most effective way to protect even recently-developed coastal areas. In such problem, the historical documents are useful as a reference for the present and for the future.

3. Numerical modelling

There are two or possibly three ways to utilize numerical models for solving tsunami problems. The first one is to simulate the sea level variations as far as possible even when the source mechanism of a tsunamigenic earthquake is not known. The second way is to predict numerically a tsunami on the coast referring to a parameterized source factor of a tsunamigenic earthquake. The third one must be essential and very difficult to do. It is to simulate and predict tsunamis on the coast using a set of more exact seismological parameters which characterize the source mechanism of the tsunamigenic earthquakes.

Hatori utilized an inverse refraction diagram of a tsunami (Hatori[17], 1974) to estimate source area of the past tsunamis by his own hand-tracking technique. Aida developed his numerical model of finite difference method in order to simulate the historical tsunamis, for example, generated off the Tokai district in central Japan facing the Pacific (Aida[18], 1983). After an extensive study of Aida's model, Iwasaki[19] (1983) developed a hybrid simulation system for model tests of tsunamis in a harbour. On the other hand, Iida et al.[20] (1983) utilized a finite element method for tsunami wave propagation in the Tokai district of Japan.

Working from the opposite end, Ando[21] (1982) tried to construct a fault model of the 1946 Nankaido earthquake derived from the available tsunami data.

In the author s numerical study, a finite difference method has been utilized which was developed first by Loomis[22] (1972) for time-stepping long waves into coastal regions with application to Haleiwa Harbor in Oahu and has been improved and adapted to fit a numerical modelling of tsunami by the author. The details of mathematical background for this improvement will be discussed at the other chance for those who do not simply trust the finite difference method. Nakamura[23,24] (1981,

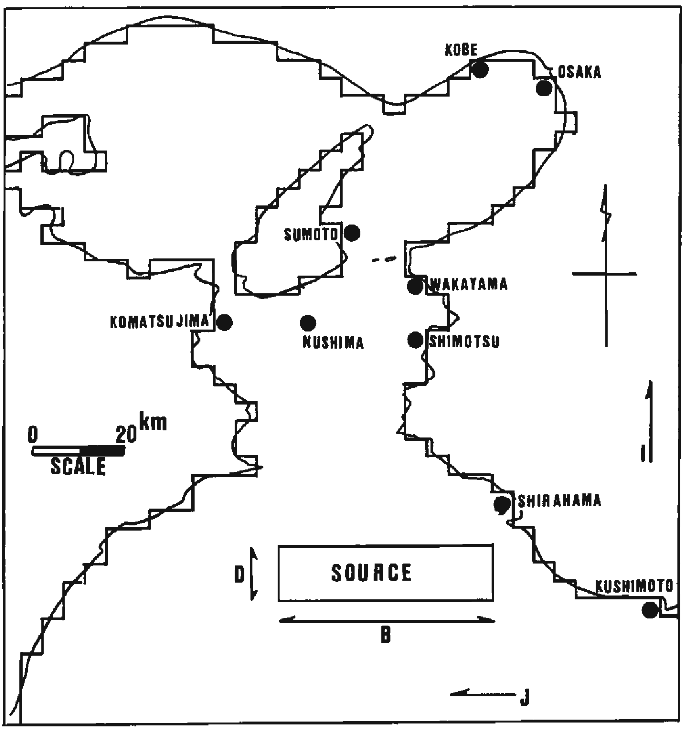

Fig. 5. A numerical model of a finite difference method.
The boundaries of the model area are the lines along 134°15'E, 135°45'E, 33°10'N and 35°00'N. Each of the dots corresponds to the nearest location of the tide station where the mareograms are available. In the model, the I and J axes are taken corresponding to the X and Y axes respectively. The size of the tsunami source area is expressed by the width D and length B in this model.

1983) obtained successful numerical solutions by his application of his model to the sea area including Osaka Bay, Kii Channel and Harimanada. One of the solutions is introduced in this article as shown in **Fig. 5**. In this case, the area was covered by a orthogonal mesh with a grid spacing of 4540 m to the west and to the north. The bathymetric profile was given for each grid point by an interpolation of the data out of nautical chart No. 100A published by the Hydrographic Office, the Maritime Safety Agency of Japan. The deepest grid point in the area was 2600 m deep.

For convenience of analysis, the author has introduced two parameters which characterize the tsunami source, i.e., a raised amount w of the sea level after an earthquake and its duration time T in an equivalent source area. The source area was first taken to be a rectangular area as shown in **Fig. 5**. And later, the effect of the source area on the tsunami was studied for some selected values of width D and length B of the source. In the previous study (Nakamura[24], 1983), it was clarified that the raised amount of the sea level resulted in a proportional increase of the tsunami height on the coast numerically within a range of 0 to 1000 seconds of the duration time. It was considered that one case of the best fit for the 1944 Tsunami was for $T=400$ sec within the range of 0.1 to 3 m for the value of W.

A combination of the two equivalent parameters T and w, with time step of $\Delta t=14.2$ sec, gives a numerical result for a tsunami as shown in **Fig. 6** by full lines for the selected points which correspond to the location of the nearest tidal stations, i.e., Shimotsu, Wakayama, Sumoto, Kobe and Osaka. In **Fig. 6**, the dotted lines show the adjusted mareograms of the 1944 Tonankai tsunami (cf. Nakamura[13], 1984a). In **Fig. 6**, the effect of the main shock was used to adjust the exact time in the mareograms at Kobe and Osaka in order to get more reasonable comparisons

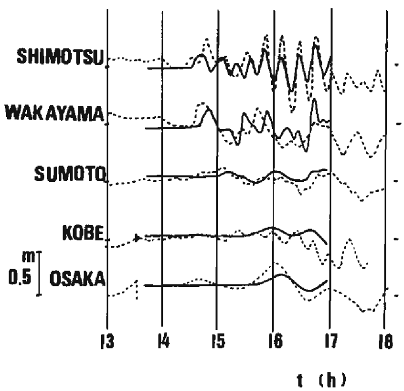

Fig. 6. A tsunami in the numerical model and the mareogram of the 1944 Tonankai Tsunami. Each one of the local tsunamis in the model is shown by a thick line drawn by encre-de-chine for about 3.5 hours from the time of the disturbance's start, at Shimotsu, Wakayama, Sumoto, Kobe and Osaka respectively. Each one of the mareograms of the 1944 Tsunami is shown by a dotted line after an adjustment of the time mark of the tide gauge. In this figure, the mareograms at Shimotsu, Wakayama, Sumoto, Kobe and Osaka were shown for about five hours from 13hoom to 18hoom on the day so as to include the seismic effects of the main shock to the mareograms.

between the numerical result and the observed tsunami. Looking at **Fig. 6**, we can see remarkable signals of the main shock of the earthquake at Kobe and Osaka. At Kobe, the mareogram tells us the time when the main shock happened and vertical motion of the tide gauge relative to sea level (for the sake of precision, time at Kobe was adjusted well referring to the mark of the commencement of the earthquake on the mareogram compared to the correct occurrence time of the main shock of the earthquake). At Osaka, the mareogram shows a gradual subsidence of the tide gauge in advance of the sudden rise of the gauge at the main shock. This can be the correct time mark for the adjustment.

In case that any information about a tsunami is not available through lack of a mareogram of a tsunamigenic earthquake, we would have to confirm whether a numerical model could properly reproduced the actual profile after referring to all other sources that described the tsunami in the old documents and in the tsunami catalogs.

As far as we trust numerical result obtained by the finite difference or element methods, we can utilize a numerical model to simulate and predict tsunami only for satisfying the given source condition without any consideration about disturbances just outside of the modelled area. No effects just outside of the model area can affect to the result of the numerical computation, though those who utilize any techniques for their own purposes often are unaware of this. Adding to the above, we have to be aware of an effect of selection of the model area. This must be appear any disturbance generated at the boundaries in the model, however the author would not consider here discuss in a scope of mathematics.

As seen above, the numerical modelling cannot be simply helpful to know when any next tsunami will be but is useful to reproduce the past tsunami for the local mitigation or evacuation planning. Now, we have to consider introducing some other techniques to predict when the next tsunami occurrence may be occur in a specified area. This is discussed in the following section where the tsunami catalogs are fully utilized as reference data.

4. Stochastic model

The probability of tsunami occurrence frequency on the coast of California was evaluated by Wiegel[25] (1970) first. Rascon and Villareal[26] (1975) considered a stochastic evaluation of the possibility of tsunami hit on the eastern Pacific coast of Mexico. They have used "tsunami height", Nakamura has utilized "tsunami magnitude" (for example[27,28] 1979, 1980). If all of the mareograms for any past tsunami could be obtained, it would be preferable to use tsunami height which is defined as an abnormal increase in sea level above the predicted astronomical tides as Wigen[29] (1978) proposed.

The original definition of "tsunami magnitude" was introduced first by Imamura[6] (1942) and revised by Iida later so that it is known as Imamura-Iida's scaling of the past tsunamis, though it was a subjective scale for their convenience. However,

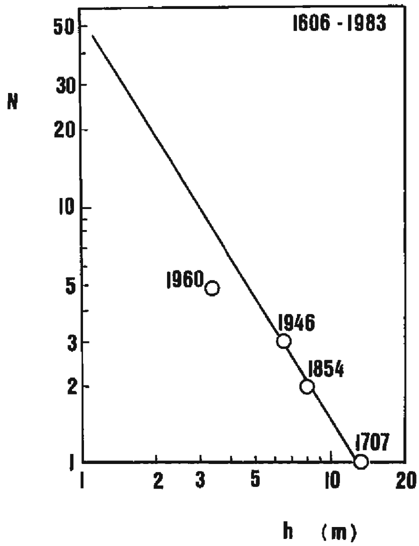

Fig. 7. An exceedance frequency (N) of tsunami height (h) in metric unit for the area of Tanabe and Shirahama.
The data source available were taken from the tsunami catalogs for a time period from 1606 to 1983 after reconfirmation of the evaluated tsunami heights. The focus here is to learn the problem of the big tsunamis so that only the four significant events were plotted by the circles in the diagram, though this does not mean to neglect the other minor events. The curve in the diagram was obtained by referring to the all of the events.

Watanabe[7,8,9] (1968, 1983, 1986) follows their scaling. Some of the scientists introduced an objective tsunami magnitude (Murty and Loomis[30], 1980). Abe[31] (1983) have defined the other tsunami magnitude. Soloviev and Gao[2,3] (1974, 1976) have proposed and used "tsunami intensity" instead of "tsunami magnitude" in order not to confuse the term of "magnitude" used in the field of seismology. The tsunami magnitude still useful to learn the historical data, though it's notation "m" is at present not appropriate because the notation is same to that for length in the metric unit "m" which means 'meter or meters'. After that, Nakamura[32] (1986b) has recently proposed to read "tsunami scale" instead of "tsunami magnitude" or "tsunami intensity" and to denote by "S" instead of "m" or "i". Although tsunami magnitude m is used in this article because the author cited it directly referring to Watanabe's catalogs (for example[8,9], 1983, 1986). This seems not essential at a glance, though this affects to the result of a stochastic study of tsunamis.

In almost all of the studies on tsunami occurrence frequency as a stochastic problem, it is assumed that the process can be taken as a Poisson process. Recently, Nakamura[32] (1986b) introduced an extensive or modified Poisson process in order to better fit the exceedance probability of local tsunami.

Referring to the tsunami catalogs, we can prepare a sequence of annual tsunami occurrence for an pertinent local area.

Nakamura's modification[32] (1986b) for the process can include a case so-called

"Poisson process" as one of specific cases.

For the case of Tanabe and Shirahama, the tsunamis exceeding one meter high hit the coast by the 58 events of the earthquakes during the time period of 378 years, from 1606 to 1983, when the tsunami data was available. And only one case during the above period was the case of the highest tsunami of thirteen meters or more. When a Poisson process fit well for the estimation of an exceedance probability in the area of Tanabe and Shirahama, Nakamura s case[32] (1986b) can be applied successfully. That is, the exceedance probability of tsunami occurrence P for a time interval t is written as follows:

$$P=1-\exp(-\Lambda t), \qquad (1)$$

with

$$\Lambda=(58/378)\exp(-0.34\,(h-1)^{1.0}), \qquad (2)$$

where the value of Λ is inverse of the annual return period for tsunami height h. Especially when $h=13$ m, the value of Λ is 1/378 in this case. With this, exceedance probability of local tsunami occurrence with a parameter of time period t is expressed as a function of h in **Fig. 8**. Using this diagram, we can have an exceedance probability of 25% for a tsunami occurrence of the 1707 class ($h=13$ m) at least once in a time period of 100 years.

In order to concentrate the author's discussion and consideration about the problem of tsunami threat, the author dare excluded the mathematical basis which make surely clarify the process and concept of this work. The author always believes that it is necessary to study like this work on the basis of mathematics and dynamics. The author cannot be a manipulator of mathematics and dynamics.

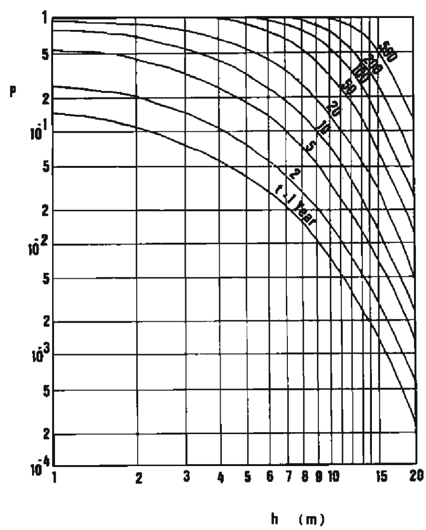

Fig. 8. Exceedance probability of tsunami occurrence (P) as a function of tsunami height (h in the metric unit) with a parameter of time interval (t years) for the area of Tanabe and Shirahama.

5. Conclusions

The author's speculative work enables him declare that no numerical or stochastic model can be useful if it is utilized independently of reliable historical descriptions and the tsunami catalogs for practical tsunami protection planning and design of protection works. These models and the historical data should be considered together in this problem.

(1) In order to aid in understanding of this, the author introduced and explained an evaluation of the historical tsunami documents or descriptions. This data is descriptive, though details are exact, except some subjective parts. This data can be utilized for present tsunami protection.

(2) Next, a brief note is given about numerical simulation of tsunamis. One of the numerical results of the author's finite difference method, with a uniform grid spacing, was shown in order to minimize the truncation error in his tsunami model. Of course, numerical simulation and prediction can be a powerful tool for the purpose of local prediction of a tsunami when the tsunami source parameters and the conditions are properly given. Although, no numerical model can predict when any forthcoming tsunami will occur in a specific coastal zone.

(3) Stochastic modelling is helpful, as mentioned above. This model is a useful tool to obtain a probabilistic prediction or a measure for long-term planning and designing of tsunami protection works in the local coastal zones.

With these studies, we can obtain more effective information for not only construction of protection works but short-term tsunami problems, for example, warning-systems, planning how to evacuate coastal residence out of the dangerous areas of the coast, establishing a system to mitigate the tsunami damages and to find the best guideline for the control of the tsunami similar to that of flood control of the river.

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Appendix

What must be the minimum error in a numerical model of a finite difference method?

In the present paper, the author has used a uniform grid spacing for a simple finite difference method to study problems of tsunamis. It is felt that this is the only way to arrive at a solution with minimum error caused by the selection of grid spacing in the model employed herein. One of the reasons is introduced as follows. This should be simple and clear as far as we trust the expression of the finite difference method by using

$$\frac{df}{dt}=\frac{\Delta f}{\Delta t}, \text{ or } \frac{df}{dt}=f' \text{ and similar to the higher order} \quad \cdots\cdots\cdots(\text{A-1})$$

for a function f about a variable t.

As we know well it, a Taylor expansion of f about t for a small Δt is

$$f(t+\Delta t)=f(t)+f'(t)\frac{\Delta t}{1!}+f''(t)\frac{\Delta t^2}{2!}+\cdots, \quad \cdots\cdots\cdots(\text{A-2})$$

then,

$$\frac{\Delta f}{\Delta t_1}=\frac{f(t+\Delta t)-f(t)}{\Delta t}=\frac{1}{1!}f'(t)+\frac{\Delta t}{2!}f''(t)+\cdots=\Delta f_{t1} \quad \cdots\cdots\cdots(\text{A-3})$$

for a single interval of Δt. In this case, error caused by a truncation negelecting the second and higher terms even if any order of the function's derivatives is continuous. This is the essential basis of a uniform grid spacing in a finite difference method for practical use. Although, some of the scientists and engineers utilize a non-uniform grid spacing recently without any confirmation of the truncation error's evaluation. By this time, we can see only successful results reported or published in any form so that the author feels here to clarify by the simplest way what is the truncation error of a uniform or non-uniform grid spacing for a finite difference method of a numerical computation in the model.

If a n time of Δt is taken instead of Δt in (A-1 to A-3) and the value of n is not necessarrily unity or integer, the expression of (A-3) is rewritten as

$$\frac{\Delta f}{\Delta t_n}=\frac{f(t+n\Delta t)-f(t)}{n\Delta t}=\frac{1}{1!}f'(t)+\frac{n\Delta t}{2!}f''(t)+\cdots=\Delta f_{tn} \quad \cdots\cdots\cdots(\text{A-4})$$

Using the expressions of (A-3) and (A-4), we have easily

$$\Delta f_{tn}-\Delta f_{t1}=\frac{\Delta t}{2!}(n-1)f''(t)+\cdots+\frac{(\Delta t)^{m-1}}{m!}(n^{m-1}-1)f^{(m)}(t)+\cdots \quad \cdots(\text{A-5})$$

This is the difference resulting from selecting $n\Delta t$ instead of Δt in a finite difference as an expression of the first derivative of the function f. If $n=1$, the above difference of (A-5) becomes zero. Hence, a uniform grid spacing minimizes the truncation error. Now, we may take the notation of n in (A-5) is an index of non-uniform grid spacing. If the value of n is not unity, the value of (A-5) cannot be zero anymore and it also depends on the value of n whether the value of (A-5) is positive or negative. Most of them seems never awared the cause of error shown above at their application of a non-uniform grid spacing except to trust the expression of (A-1) to be always correct in their numerical models.