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9. *A Study of the Damage to Houses due to a Tsunami.*

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1. Introduction

The damage to houses due to a tsunami is caused not only by the water flow but also by collision of heavy flowing bodies such as ships or timbers. In general the extent of damage is a function of the inundation height and the water velocity of a tsunami. If one compares the cases of tsunamis of 1933 (Sanriku) and 1960 (Chile) along the coast of Sanriku district, it is found that the houses suffered severer damage from the 1933 Sanriku tsunami although the inundation heights were almost the same in both cases.

In order to explain such a difference, the velocity of sea water overflowing the land is calculated by means of a hydraulic formula when the slope of the water surface on land is known. The distribution of inundation height at several towns has been surveyed in detail for the tsunamis of Sanriku (1933)[1], Nankaido (1946)[2),3)] and Chile (1960)[4),5)]. Making use of the water velocity thus estimated, the relation between the total pressure of flow acting on the houses and the percentage of damaged houses is discussed.

2. Relation between the inundation height above M.S.L. and the percentage of damaged houses

Causation factors for the damage that tsunamis cause to structures

1) N. NASU, "Heights of Tunamis and Damage to Structures," *Bull. Earthq. Res. Inst., Suppl.*, **1** (1934), 218.

2) R. TAKAHASI, I. AIDA and T. HATORI, "The Tsunami of 1946 at Susaki and Shin-Usa in Kochi Prefecture," Nankai Earthquake, Published by Kochi Prefecture (1949), 114, (in Japanese).

3) N. NASU and T. SHIRAI, "Local Phenomena of Tsunami (Part 1)," *Bull. Earthq. Res. Inst.*, **25** (1947), 81.

4) GEOGRAPH. SURVEY INST. MINIST. CONST., *Report on the Survey of the Abnormal Tidal Waves Tsunami Caused by the Chilean Earthquakes on May 24, 1960* (1961), 58, (in Japanese).

5) Courtesy of the Municipal House of Ōfunato, (1960).

are, as has already been said, the inundation height above ground and the water velocity. In this chapter, inundation heights above M.S.L. are used instead of inundation heights above ground in order to utilize as much data as possible.

According to I. Aida and M. Kageyama[6], the percentage of damaged houses D has been defined as follows:

$$D=\frac{a+b+c/2}{a+b+c+d}\times 100 \quad (\%) ,$$

where a is the number of houses washed-away, b, destroyed houses, c, half-destroyed houses, and d, inundated houses (including the inundation under-floor). From statistical data of the damage in urban areas in cases of tsunamis of 1933 (Sanriku)[7], 1944 (Tonankai)[8,9], 1946 (Nankaido)[10,11,12], and 1960 (Chile)[13,14], the values of D were calculated and H was plotted against the inundation height of the location, as shown in Fig. 1. In calculating D, the damage caused directly by the earthquake shock has been omitted for the case of the 1946 Nankaido earthquake. We have considered only such damage that was caused by the tsunami. These plotted circles are scattered as shown in Fig. 1, because of various factors such as the high elevation of the ground, the existence of a powerful sea wall, or other topographical conditions of the locality. The damage due to the 1933 Sanriku tsunami was generally severer than that due to other tsunamis for the same inundation height, suggesting that the Sanriku tsunami might have had a larger water velocity than other tsunamis.

6) I. AIDA and M. KAGEYAMA, "Report of Investigation from Onagawa to Ishinomaki in Miyagi Prefecture," *Rep. Chilean Tsunami, Field Invest. Comm. Chilean Tsunami* (1961), 289, (in Japanese).

7) *Bull. Earthq. Res. Inst., Suppl.*, **1** (1934).

8) S. OMOTE, "The Tsunami, the Earthquake Sea Waves, that Accompanied the Great Earthquake of Dec. 7, 1944," *Bull. Earthq. Res. Inst.*, **24** (1946), 31, (in Japanese).

9) CENTRAL METEOROL. OBS., *Report on the Tonankai Eerthquake of Dec. 7, 1944* (1945), (in Japanese).

10) *Spec. Bull. Earthq. Res. Inst.*, **5** (1947), (in Japanese).

11) CENTRAL METEOROL. OBS., *The Nankaido Earthquake of Dec., 21, 1946* (1947), (in Japanese).

12) KOCHI PREFECTURE, *Nankai Earthquake* (1949), (in Japanese).

13) COMM. FIELD INVEST. CHILEAN TSUNAMI, *The Chilean Tsunami of May 24, 1960* (1961).

14) SENDAI METEOROL. OBSERV., *Report on the Chilean Tsunami of May 24, 1960* (1961), (in Japanese).

According to the field investigation, in fact, the nature of the tsunami invasion was considerably different in each case of tsunami and from place to place. Although the 1933 Sanriku tsunami attacked houses in the

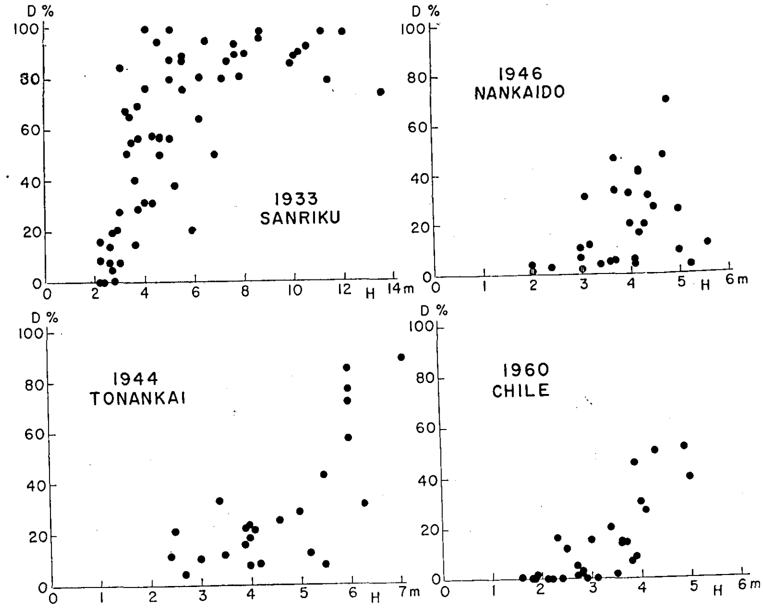

Fig. 1. The relation between the inundation heights above M.S.L. and the percentage of damage to houses.

shape of a wall of running water, the tsunami waves acted like a tide in the cases of the 1946 Nankaido[15] and the Chile tsunamis.

3. Velocity of water overflowing land

The water velocity of a tsunami that flows into a bay is difficult to estimate, because it depends on various factors, such as the directivity and length of wave etc., and what is worse, because of the complexity of flow conditions the velocity of water invading dry land can only be speculated from meager evidence collected at the time of a field investigation.

In the case of the 1933 Sanriku tsunami, the velocity of water overflowing the land was calculated by M. Ishimoto, T. Hagiwara[16] and T.

15) HYDROGRAPHIC OFFICE of JAPAN, "Information about Earthquake Calamity of Nankai District 1946 (Ports and Harbours)," *Hydrogr. Bull.* No. 201, (1948), 35, (in Japanese).

16) M. ISHIMOTO and T. HAGIWARA, "The Tsunami considered as a Phenomenon of Sea Water overflowing the Land," *Bull. Earthq. Res. Inst., Suppl.*, **1** (1934), 17.

Matuzawa et al.[17] respectively at Kamaishi and Sasu (Tōni) in Iwate prefecture. In the present paper, the author estimated the surface inclination of the water that overflows into streets, and used the hydraulic formula of Forchheimer to calculate the water velocity.

The mean water velocity is given by

$$v=\frac{1}{n}h^{0.7}i^{\frac{1}{2}}, \qquad \text{(Unit: m, sec.)}$$

where h is the mean inundation height above ground (m), i, the inclination of the water surface, and n, the coefficient for roughness of the bottom, which was taken to be $n=0.023$ from data of a flood[18]. This value corresponds to a full water level of a natural river according to Ganguillet-Kutter's study. As shown in Figs. 2 and 3, the water velocities

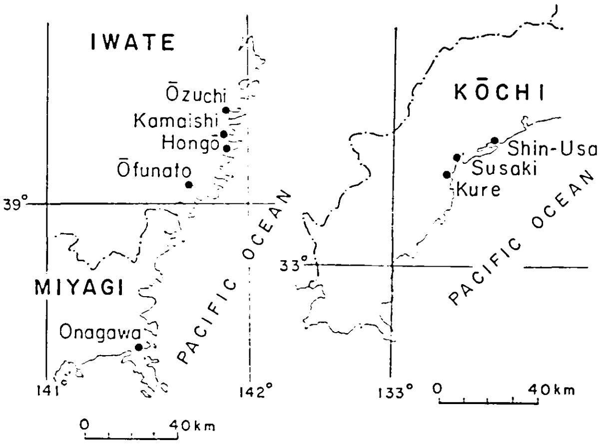

Fig. 2. Sanriku and Shikoku districts.

were calculated at the central part of the inundation area along the solid lines shown in Fig. 3. For Shin-Usa and Susaki additional lines Shin-Usa (B) and Susaki (B) were also taken where the damage percentages were 18% and 50% respectively. The mean inundation height and the inclination of the water surface have been read from the vertical section of water flow shown in Fig. 4. Which indicates that the inclination of the water surface is large at the rear side of the sea wall and at the end of the flow near the hill. Except for these places, the order of

17) T. MATUZAWA, K. KANBARA, and T. MINAKAMI. "Horizontal Movement of Water in the Tunami of March 3, 1933," *J. Astr. Geophys. Japan*, **11** (1933-1934), 11.

18) T. HATORI, "The Roughness Coefficient in a Town Area Observed in the Case of the Kanto Flood of Sept. 1947," *Bull. Earthq. Res. Inst.*, **41** (1963), 681.

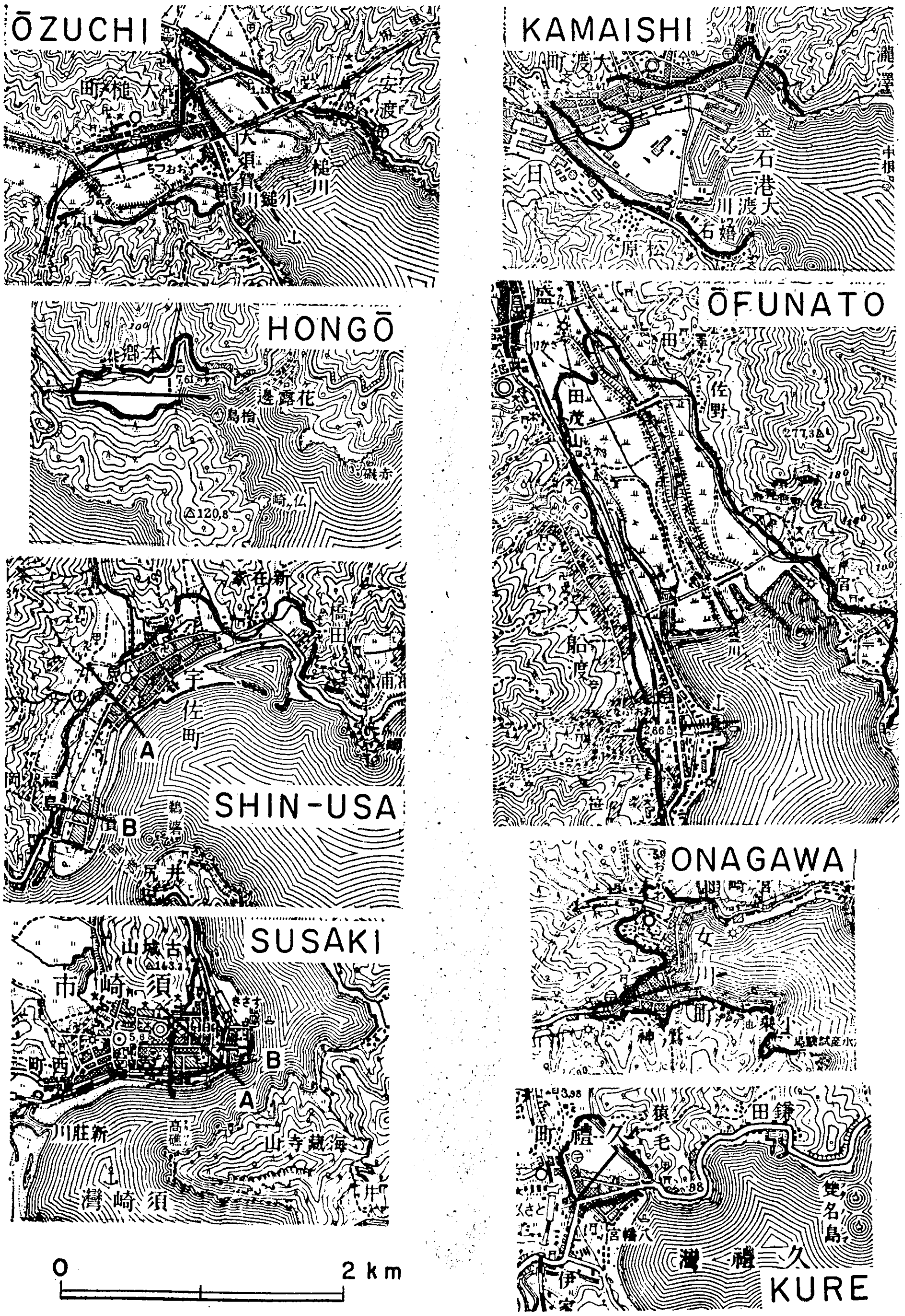

Fig. 3. Maps showing the inundation area and locality of the profile line.

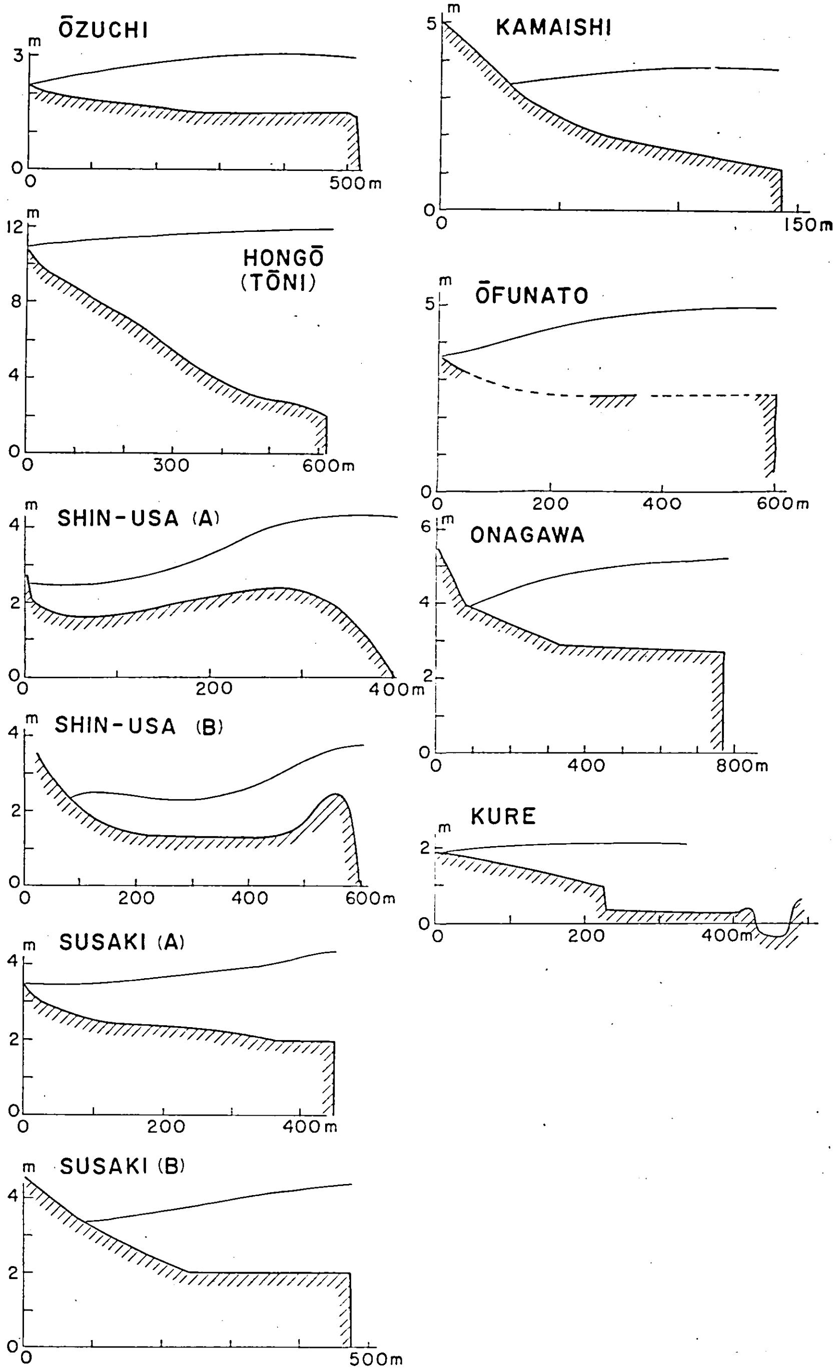

Fig. 4. The profile of the inundation height and the ground.

inclination of the water surface is approximately 1/1000. The calculated water velocity is shown in Table 1.

Table 1. Inundation height, water surface inclination and the calculated water velocity at various localities.

No.	Tsunami	Locality	h (m)	i	v (m/s)
1	1933 Sanriku	Ōzuchi	1.5	0.0026	5.6 (5·4)
2		Hongo (Tōni)	5.0	0.0010	4.2 (3.7)
3		Kamaishi	2.2	0.0011	2.5 (1.0)
4	1946 Nankaido	Shin-Usa (A)	1.2	0.0084	4.6 (2.8)
4′		Shin-Usa (B)	1.2	0.0018	2.1 (2.0)
5		Susaki (A)	1.8	0.0015	2.5 (2.2)
5′		Susaki (B)	2.0	0.0028	3.7 (3.4)
6		Kure	0·6	0.0020	1.3 (1.1)
7	1960 Chile	Ōfunato	2.0	0.0030	3.9
8		Onagawa	2.1	0.0013	2.6 (2.1)

( ) The water velocity calculated by M. Ishimoto and T. Hagiwara's method.

The water velocity at Ōzuchi in Iwate prefecture is calculated assuming $n=0.012$, because the water flows mostly through open field as shown in Fig. 3. The roughness coefficient $n=0.012$ corresponds to the case of the flooded water passing through open field[18].

M. Ishimoto and T. Hagiwara[16] calculated the water velocity by the following formula:

$$v=\cot\theta\,\frac{dH}{dt},$$

where θ is the slope of the ground, and dH/dt is the velocity of sea level change. We have tried to find the water velocity by this method too. H and θ are read from the profile of water flow in Fig. 4. The periods of tsunami were taken to be 10, 20, and 60 mins for the tsunamis of 1933 (Sanriku), 1946 (Nankaido), and 1960 (Chile) respectively. Results of calculation are shown in Table 1 with the bracket. The velocities estimated by Forchheimer's method are a little more rapid than those calculated by M. Ishimoto and T. Hagiwara's formula.

At Ryori in Iwate prefecture, or at Sasu (Tōni) for the case of the 1933 Sanriku tsunami, the wave-height increases towards inland, so that the Forchheimer's method cannot be applied. T. Matuzawa et al[17] made a study on the water flow in such special cases.

4. Hydrodynamic pressure due to the water flow and the damage to houses

The damage to houses is caused directly or indirectly by the hydrodynamic pressure due to the water flow. This pressure p is proportional to the square of the velocity, so that, the total dynamic pressure that acts upon a house may be expressed as $p \propto hv^2$. We shall discuss the relation between hv^2 and the damage percentage D given in Table 2.

Table 2. Damage to houses.

No.	Tsunami	Locality	Washed away	Destroyed	Half-destroyed	Inundated above floor	Inundated below floor	D %
1	1933 Sanriku	Ōzuchi	135	57	48	113	72	50.8
2		Hongo (Tōni)	92		1			99.4
3		Kamaishi	117	123	78	199	472	30.0
4	1946 Nankaido	Shin-Usa	341	130	818	142		55.8
5		Susaki	45	136	218	1089		19.5
6		Kure	3		3	400		1.1
7	1960 Chile	Ōfunato	181	203	532	250	101	51.3
8		Onagawa*	37	157	288	566	93	29.6

* Counted by the number of household.

As shown in Fig. 5, we find that the percentage D of damage to houses can be expressed as follows:

$$D = 5.4\ (hv^2)^{0.64}, \qquad \text{(Unit: m, sec.)}$$

For practical use this equation may be simplified to

$$D = 9\sqrt{h} \cdot v\ .$$

The percentage of damage to houses may therefore be estimated roughly from the inundation height and the water velocity at the place. The hollow circles in Fig. 5 show the values computed by M. Ishimoto and T. Hagiwara's method.

In the case of the Sanriku tsunami of 1933, N. Nasu[1] found that ordinary Japanese wooden houses, both one and two-storied, were partially damaged when the water attained a height of 1.0~1.5 m above ground, and when the height of the water exceeded 2 m, the ground floor totally collapsed, so that one-storied houses and tall houses of poor construction

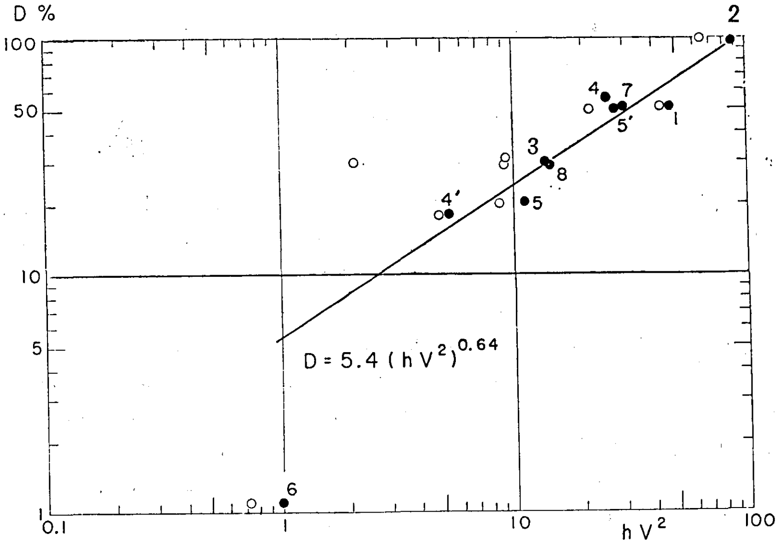

Fig. 5. The relation between the total pressure and the percentage of damage to houses.

could not escape from destruction. From these observations, N. Nasu estimated the velocity of the water did not much exceed 10 m/sec for the 1933 Sanriku tsunami.

By the present equation, the velocity of the water in the 1933 Sanriku tsunami is estimated to be about 4.5 m/sec or 7 m/sec corresponding to heights of 1.5 m or 2 m above ground respectively. According to the report of the field investigation of the 1960 Chilean tsunami by I. Aida and M. Kageyama[6], the number of half-destroyed houses were 25% and 50% of the total when the inundation heights were respectively 1.5 m and 2 m above ground. Thus, the velocity of water, as calculated by our formula, becomes about 2.5 m/sec and 4 m/sec in these cases. When the height of the water exceeded 2 m, the houses that were not fixed to their foundations began to float, so that in such cases the actual velocity of water could be less than that calculated on the basis of the formula.

The extent of damage to houses depends, as stated already, on various factors such as the structure, collision by flowing matter and local phenomena due to topography. Although precise calculations might be limited by the scantiness of data, the damage to houses may be estimated roughly from the inundation height and the water velocity with the aid of the present expression. On the other hand, it is of course possible to estimate the velocity of water at the place of damage.

5. Conclusion

Mechanism of damage to a house should be discussed by classifying the cases according to various conditions such as the locality, inundation height and water velocity. We have, however, little data of the phenomenon of sea water overflowing land, so in the present paper the mean velocity of water was calculated only at the place which seems to represent the area of damage. The damage to houses is then expressed as a function of water velocity and inundation height. The author hopes the present result will be useful for the advance of preventive measures against tsunami disasters.

In conclusion the author thanks Prof. R. Takahasi for his guidance and encouragement in the course of this study. His thanks are also due to Assist. Prof. K. Kajiura for his valuable advice in the preparation of the manuscript.

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9. 津波による家屋の破壊についての一考察

地震研究所 羽 鳥 徳 太 郎

津波による家屋の被害は，その家屋自身の強度以外に，船や木材などの重い巨大な漂流物の衝突などによるものがあるが，一般に津波の浸水高と速度の結合したものがある極限を越すとき，家屋は損傷する．

1933 年の三陸，1944 年の東南海，1946 年の南海道および 1960 年チリの各津波について，津波の高さ (M.S.L. 上) と相田・影山 (1961) が定義した家屋の破壊率 D:

$$D=\frac{a+b+c/2}{a+b+c+d}\times 100 \quad (\%),$$

a: 流失，b: 全潰，c: 半潰，d: 浸水

との関係について吟味すると，Fig. 1 に示すように地域性あるいは個々の立地条件で，点のばらつきがあるが，同一波高に対し三陸津波は被害が大きく，他の津波に比し大きな溢流速度をもつたことが言えるようである．

石本・萩原 (1934) および松沢ら (1934) は 1933 年の三陸津波の際，それぞれ岩手県の釜石および佐須(唐丹)における溢流速度を計算したが，この論文では市街地に溢流した津波の浸水面の斜傾に着目し，水理学の水流の問題として Forchheimer の公式を応用する．平均流速は

$$v=\frac{1}{n}h^{0.7}\,i^{\frac{1}{2}}\quad (\text{m}-\text{秒単位})$$

但し h: 平均浸水高 (m), i: 水流の勾配, n: 粗度係数である．ここで問題となる粗度係数は羽鳥 (1963) が，市街地を流れる洪水から得た値 $n=0.023$ を用いた．

取扱つた地域は Fig. 3 に示す 8 箇所で，浸水地域の内，被害状況を代表すると思われる地区の断面を求め (Fig. 4)，平均流速を推算した．

この方法と石本・萩原によつて得た流速を比較すると，Table 1 に示すように Forchheimer の式から得た流速の方が，やや大きな流速となつた．

今回計算に用いた浸水面の斜傾は，海岸および山地附近を除くと，Fig. 4 に示すようにその order は約 1/1000 であつたが，溢流する津波が地上を進むほど，波高が増加する地域での流速は，今回の方法で求めることはできない．

家屋に直接被害を与える水流の全圧は，$p\propto hv^2$ で表わされると考えられるので，この値と Table 2 に示す家屋の破壊率との関係は Fig. 5 に示すように

$$D=5.4(hv^2)^{0.64}\quad (\text{m}-\text{秒単位})$$

となり上式はおおよそ

$$D=9\sqrt{h}\cdot v$$

と書き変えられ，ある被害地域での浸水高と速度から大体の家屋の破壊率が推定できる．また当然ながら逆に被害状況から，その地域での速度の推定が可能である．

以上津波による家屋の被害について，浸水高と速度との条件を分けて考察すべきであつたが，資料が不十分のため結合した結果を検討した．