

# Wave Force of Tsunami Bore on a Vertical Wall

by

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As regards wave force of tsunami bore acting on a structure, there are several problems left to be resolved. Above all, in a case where tsunami overflows some structure after colliding against it, the generation mechanism and the magnitude of dynamic wave force due to mean water particle velocity of tsunami bore reflected from the structure are not yet elucidated.

In the paper, the structure is treated as a vertical wall model simulating a tsunami protection gate against river run-up tsunami or a land dike protecting against land run-up tsunami. Profiles of wave height and cross-sectional mean velocity of both partial clapotis bore in front of wall and transmitted surge to rear of it are experimentally obtained, by which wave force of tsunami bore on a vertical wall is evaluated and mechanism of wave force is tried to make clear. As the result, it became evident that the dynamic wave force is mainly generated by drag force and the magnitude of it is some 10~40 % of static wave force.

## I. INTRODUCTION

When some structures are broken down or flowed away by tsunami, one of the reason of which is considered to be due to wave force of tsunami acting directly on a structure, and such a tsunami would be a fairly big one of the magnitude.

The object of the present study is a tsunami bore such that becomes bore after breaking from near wave front in the sea, which runs against a tsunami protection gate in the case of river run-up or runs against a tsunami protection wall like land dike in the case of land run-up. And, the purpose of the study is experimentally to investigate the hydraulic mechanism of tsunami bore reflected from a vertical wall and the mechanism generating dynamic wave force on a vertical wall.

Incidentally, there are so far some investigations in relation to the dynamic wave forces of run-up tsunami on a structure<sup>1),2),3),4)</sup>. All of these, however, treated surge forces caused by the leading edge of the surge impinging on a structure, which are different from the treatment of the problem like wave forces of tsunami bore in the case where flow overtops the structure of finite height that becomes the object of this study.

In the study of Fukui *et al*<sup>2)</sup>, tsunami overtopping a land dike was the object, so it looks like similar treatment to this study in appearance. However, hydrodynamic forces are presented by celerity of bore front of tsunami approaching shoreline, so that they all the same are considered as the surge forces. And, although the object of the study by Nakamura<sup>4)</sup> is tsunami protection gate, his study as well pays mainly attention to the surge forces comparing with the methods by Cumberbatch<sup>2)</sup> and Cross<sup>3)</sup>, accordingly it is hardly referred to hydrodynamic forces of partial clapotis bore in cases with flow overtopping the gate or the vertical wall.

Therefore, the treatment of this study about tsunami bore, especially using mean velocity, would be the first trial as far as wave forces, not surge force, are concerned.

## II. EXPERIMENTAL EQUIPMENTS AND PROCEDURES

The equipment consists of a wave generator of pneumatic type and a two dimensional wave flume of 1.0 m deep and 60.0 m long, in which a sloping bottom model of composite type beach is installed being combined with two kinds of sea bed slopes ( $S=1/50$ ,  $1/20$ ) and a river bed or land slope ( $S=1/600$ ) as shown in Fig. 1. Wave gages are of capacitance type and current meters are of screw type of small size. Pressure gages of small size are set to the foreface of vertical wall. An incident wave profile at the toe of sea bed slope is non-periodic and analogous to a solitary wave, the shape of which is a kind of sinusoidal wave on a still water level. There is an intumescence only.

An incident wave breaks like a surging breaker on the slope from near the end of the slope  $S=1/50$  to the slope  $S=1/20$ , and it becomes the weak bore and reaches the shoreline.

An incident surge runs up with a violent velocity like a supercritical flow on a mild slope  $S=1/600$  near horizontal and runs against a vertical wall and finally overflows it.

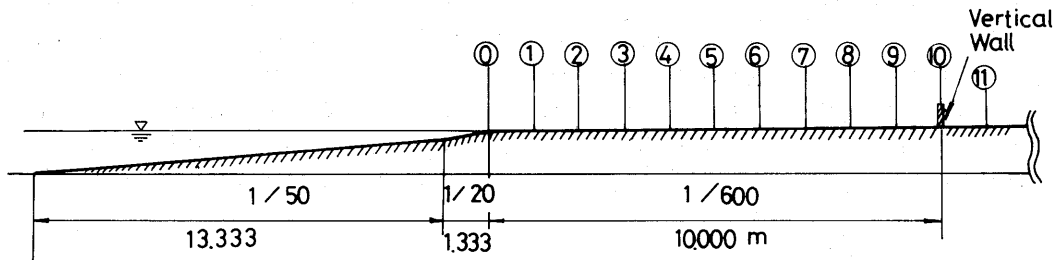


Fig. 1 Side view of experimental bed slopes.

The point of the problem is the effect of an unsteady flow of wave overtopping on wave force and is how to successfully grasp velocity of reflected bore in front of a vertical wall. In order to investigate it, wave height, velocity in front of the vertical wall and wave pressure on the wall are necessary to be simultaneously measured. Therefore, measuring points were set at the wall site and several positions in front of the wall, where measured velocities were averaged vertically from several values of every 5 cm high in a section at any locations.

## III. RESULTS AND DISCUSSIONS

According to the author's previous investigations regarding the case study on tsunami protection gate<sup>5)</sup>, the result was obtained that the maximum wave pressure of bore reflected from the flood gate was round 10 % larger than hydrostatic pressure at the site of the flood gate overflowing. The mechanism, however, generating the hydrodynamic pressure was not clarified. Therefore, the present experiment focuses on measuring velocity of reflected bore and investigating velocity contributing to generation of hydrodynamic pressure.

### 3. 1 Wave profile of incident surge, reflected bore and transmitted surge

A Side view of the experimental bed slopes is shown in Fig. 1. A vertical wall model is installed at the position of 10.0 m landward from shoreline. Four kinds of wall heights  $H_d=4, 8, 12$  and  $16$  cm high were used, each of which corresponds to round 0.5, 1.0, 1.5 and 2.0 times as high as the maximum height  $H_{i,max}$  of incident surge in the case with no wall at the wall site.

Figure 2 is an example of wave profiles of bore height and velocities with respect to time at the position of 10 cm just in front of the wall in the case of P-2 ( $H_d=H_{i,max}$ ) which is typical of construction design in general. As the position is just in the foreface of the wall, the wave profiles are regarded as partial clapotis nearly at the wall site. A mean velocity in the section was obtained by averaging four points of values of 2,

5, 10 and 15 cm high above bottom. However, when the surge height is too small to touch the current meter, the mean velocity was obtained from velocities less than three points. In figures following after this, the origin of time  $t (=0)$  is set at the moment when an incident surge front just arrived at the vertical wall.

Figures 3(a) and 3(b) too are in the same case as in Fig. 2 of standard wall height ( $H_d \doteq H_{i,max}$ ) which can be often seen as tsunami protection facilities today. Figure 3(a) shows wave heights only and Fig. 3(b) shows velocities only, and the profiles at the several measuring points are shown superimposed in each of the figures. Each of the solid lines is the wave height or velocity of the incident surge at the measuring point ⑧ (2.0 m distant from the wall) in the case without wall. It is clearly evident from Figs. 3(a) and 3(b) that, when an incident surge like this one were given as an input near at the wall, how wave profiles of bore reflected from the wall and transmitted surge to rear of it would be occurred as outputs at each of the measuring points. Wave profiles of reflected bore heights and velocities are nearly analogous to one another and almost the same magnitude as in each of them after initial transient state in spite of any positions.

Although, according to Fig. 3(a), bore height profiles are formed after about 1 sec from the instant when the shock front of reflected bore was appeared in the incident surge profile at each of the positions, the mean velocity profiles of bore shown in Fig. 3(b) seem to be settled down at certain considerably stable velocity like bore after 2~3 sec from the arrival time of reflected bore front as shown by arrow marks below abscissa, so phase shift between bore height and velocity is clearly seen. This is very important to know exactly the position and time of velocity which would act dynamic wave force on the wall face. That is to say, it is about 6 sec for shock front to arrive at the measuring point ⑧, however the velocity of partial clapotis (bore) following shock front which seems to act dynamic wave force on the wall should be considered as velocity after 8 sec becoming nearly in agreement with velocities at the other positions. In other words, it could be considered that, at the time ( $t \doteq 6$  sec) when shock front arrived at the position ⑧, the velocity of bore acting dynamic wave force on the wall is the one after 6 sec at the positions of 9.0, 9.5, 9.8 and 9.9 m closer to the wall. This is a standard of concept of how to evaluate velocity of partial clapotis in front of the wall.

Figure 4 shows difference of velocity changes of reflected bore when taking the wall heights as parameter at the position of 9.0 m specified as an example and in the figure the effect of the wall heights is evidently recognized, which results in the same way as at the other positions.

According to the examples of Figs. 3 and 4, in the case where the vertical wall site (10.0 m in the case) and

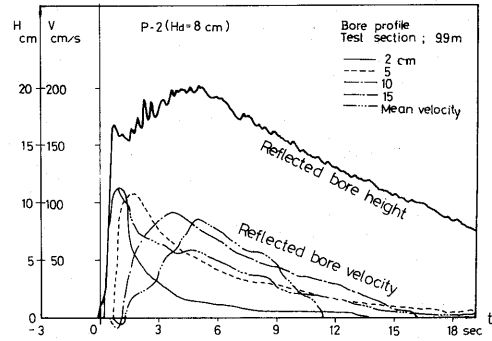


Fig. 2 An example of wave profiles of bore height and mean velocities.

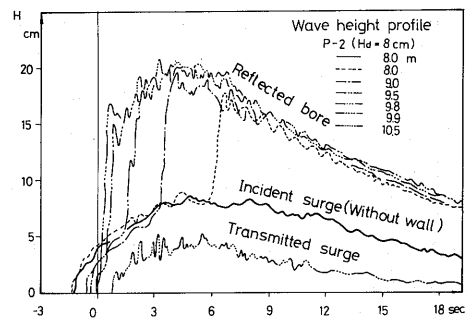


Fig. 3(a) Wave profiles of wave heights of bore and surge.

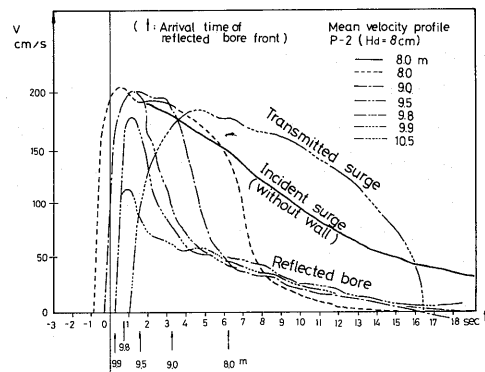


Fig. 3(b) Wave profiles of mean velocities of bore and surge

the wall height are given, the reflected bore height and velocity in the case with wall is seen to be obtained from the incident surge height and velocity in the case without wall at certain position (8.0 m in the case) in front of the wall. Therefore, if this can theoretically be explained to some degree, that would be useful to clarify the hydraulic mechanism of the reflected bore and the generation of dynamic wave force on the wall.

3. 2 Estimation of wave profile of reflected bore and transmitted surge from incident surge by application of steady flow theory

Figure 5 is a schematic diagram of steady flow model used for analyzing a typical tsunami phenomenon colliding against a vertical wall like a land dike.

As the method of analysis in this case was already presented by the authors<sup>6)</sup>, the results only are here shown. The points to be noted in Fig. 5 are the section I giving an incident surge as an input, the section II giving reflected bore and the section IV giving transmitted surge as outputs. The calculated results are shown by the thin solid lines in Figs. 7 through 9.

By the way, in Fig. 6, the two bold solid lines are experimental curves of incident surge as an input at the position ⑧ in the case without wall.

And, in a case where a wall with a certain height is installed at the position ⑩, wave profiles of reflected bore are experimentally obtained as shown by broken or chain lines as outputs at the positions between the points ⑧ and ⑩ in front of the wall, and the same thing is said of transmitted surge to rear of it.

In the same way as in the experiment, theoretical wave profiles by the theory mentioned before are simultaneously obtained of both reflected bore and transmitted surge as outputs from the incident surge as an input at the position ⑧.

However, as the figure including the both wave heights and mean velocities like this is fairly complicated and hard to see, it seems to be better to divide them into two separate figures, so that each of them consists of wave heights or velocities only. Therefore, in Figs. 7 through 9, figures are separately drawn and discussed in regard to wave heights and velocities.

In Figs. 7(a), 7(a)' and 7(b), the two thin solid lines are results computed theoretically from the incident surge shown with the thick solid line in the case of P-1. Applicable range of theory is for small interval from 7 to 12 sec. As the top of the wall is lower than the incident surge height as a whole, the surge easily overtops the wall presenting behaviour like a supercritical flow for initial several seconds and bore is not formed before 7 sec. And after 12 sec, the overtopping discharge becomes zero and perfect clapotis bore is formed theoret-

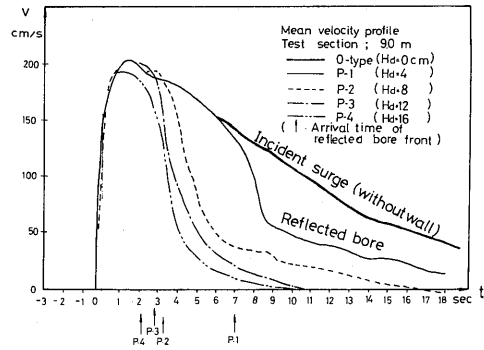


Fig. 4 Difference due to wall heights of mean velocity changes of reflected bore

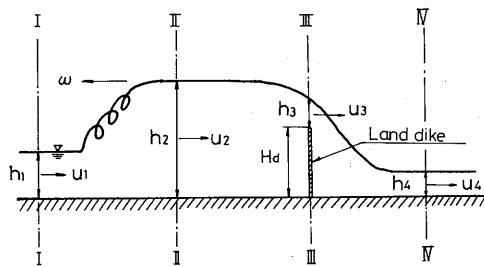


Fig. 5 Schematic diagram for analysis of tsunami phenomenon overflowing a vertical wall

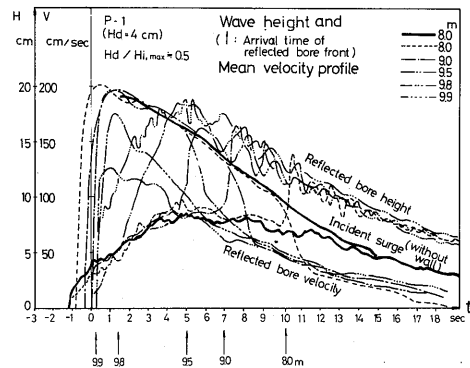


Fig. 6 Superposition of wave profiles of wave heights and mean velocities of incident surge and reflected bore

cally, however in fact the wave heights of bore and surge gradually decrease, for which the theory is not covered.

Tendency of the computed results is not so good in agreement with the experimental results, but values near peak are roughly in agreement with the experimental ones. That could be understood by shifting the phase for about 1.5 or 3.0 sec as shown in Fig. 7(a)'.

Figures 8(a), 8(a)' and 8(b) are in the case of P-2. Difference from P-1 is that applicable range appear in a little earlier time than P-1 as a whole and bore is formed near at 4 sec as shown in Figs. 8(a) and 8(b). It means that the wall height is higher than P-1 and the reflected bore is easily formed. The whole tendency and values near peak are almost the same as in the case of P-1, however the computed results of which phase are shifted for 1.5 or 3.0 sec in Fig. 8(a)' are fairly well in agreement with the experimental curves.

In Figs. 9(a) and 9(b) in the case of P-3, the top of the wall is considerably high, so bore is nearly

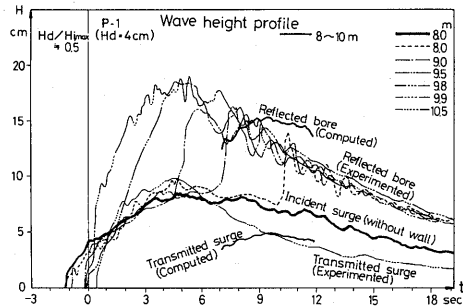


Fig. 7(a) Comparison of computed results with experimental wave heights in the case of P-1

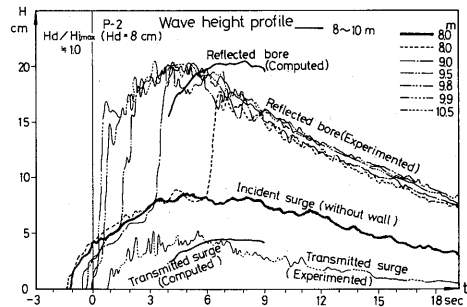


Fig. 8(a) Comparison of computed results with experimental wave heights in the case of P-2

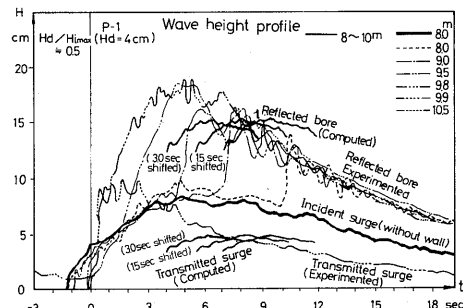


Fig. 7(a)' Comparison of computed results with experimental wave heights by phase shift in the case of P-1

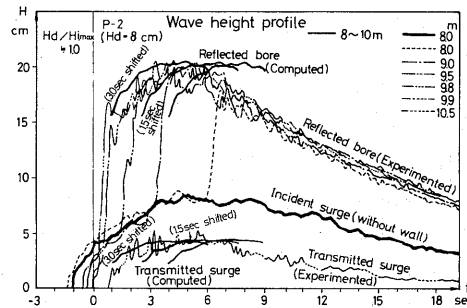


Fig. 8(a)' Comparison of computed results with experimental wave heights by phase shift in the case of P-2

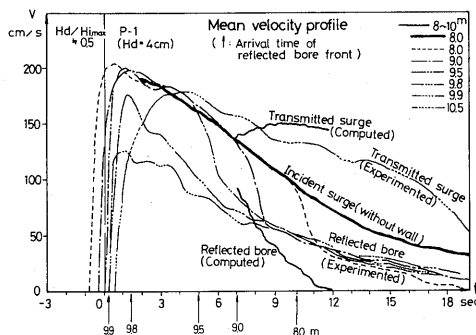


Fig. 7(b) Comparison of computed results with experimental velocities in the case of P-1

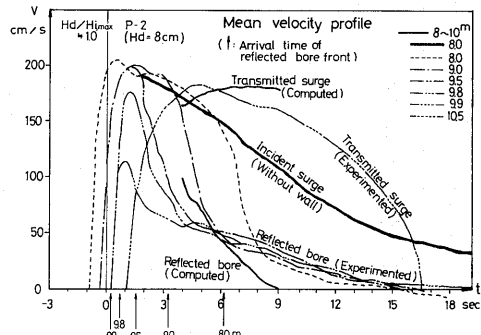


Fig. 8(b) Comparison of computed results with experimental velocities in the case of P-2

instantaneously formed just after when the incident surge front reached the wall. Agreement of the computed results with the experimental curves is good on the whole. Others are almost the same as in the cases of P-2 and P-1.

Therefore, according to Figs. 7 through 9, if steady flow theory by the author is applied to wave height and velocity of both reflected bore in front of the vertical wall and transmitted surge to rear of it, the values near peak were seen to be roughly explained by the theory, although there is a little time lag affected by rising surge front portion.

This is very important thing to design some tsunami protection facility, because the most tsunami protection facilities are designed based on the maximum inundation trace height of the past tsunamis.

### 3. 3 Numerical estimation of dynamic wave force on the wall by observed velocity

Two methods of estimation are here presented. One of them depends on successive computation of form drag by momentum change over the interval putting the wall between the both two sections for every time increment  $\Delta t = 0.1$  sec as an example case shown in Fig. 10. This method is comparatively well applied only to the case of wave overtopping phenomenon like a supercritical flow as shown by the thick dotted line in Figs. 11 or 12, and the computed results show qualitatively similar tendencies to the measured values, though the data are fairly scattered.

The nondimensional wave force  $p/wH$  on the left side of ordinate is the ratio of dynamic wave force  $pH_d$  to hydrostatic force  $wHH_d$  which are measured for the different wall height  $H_d$  in each of cases shown in Figs. 11 through 14, where  $p$  is the dynamic wave pressure which the hydrostatic pressure  $wH$  is subtracted from the total wave pressure, each of which is the value averaged on the wall. And  $w = \rho g$ , where  $\rho$  is the density of water and  $g$  is gravitational acceleration.

The above description is referred in the same way to the nondimensional drag force  $C_D U^2 / 2gH$  on the right side of ordinate as well.

Then, another method is evaluation by drag force calculated from mean velocity of reflected bore shown in Figs. 11 through 14. Here, drag coefficients  $C_D$  are approximately used by assuming from analogous example in steady flow theory following after Camfield<sup>7)</sup>. The results are not necessarily good on the whole range,

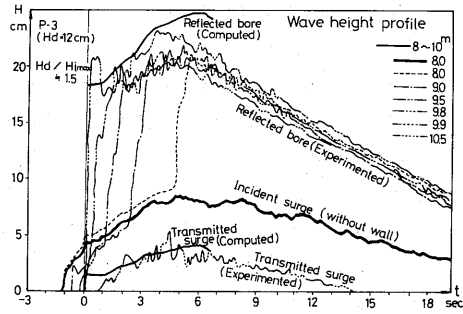


Fig. 9(a) Comparison of computed results with experimental wave heights in the case of P-3

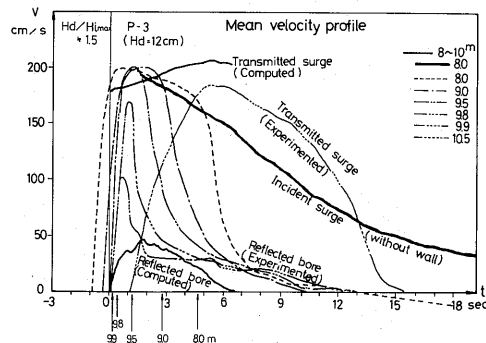


Fig. 9(b) Comparison of computed results with experimental velocities in the case of P-3

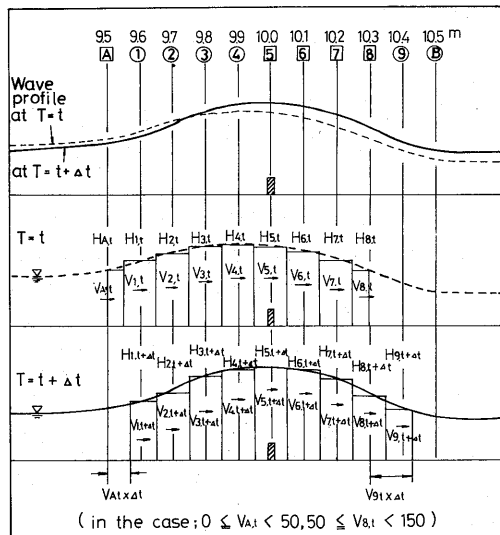


Fig. 10 An example case showing how to compute form drag by momentum change

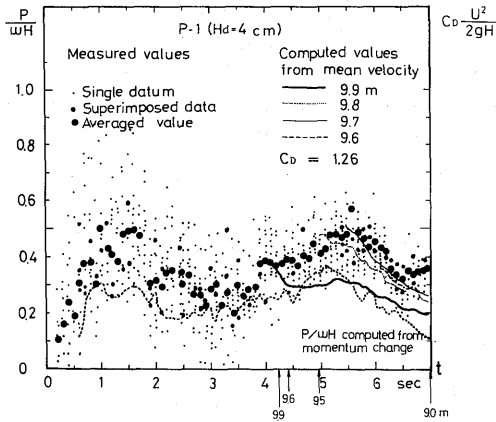


Fig. 11 Comparison of computed drag forces with experimental dynamic wave forces in the case of P-1

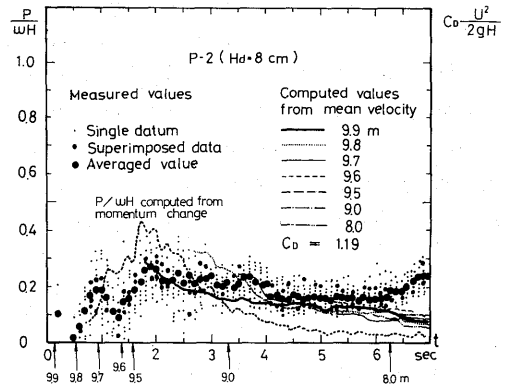


Fig. 12 Comparison of computed drag forces with experimental dynamic wave forces in the case of P-2

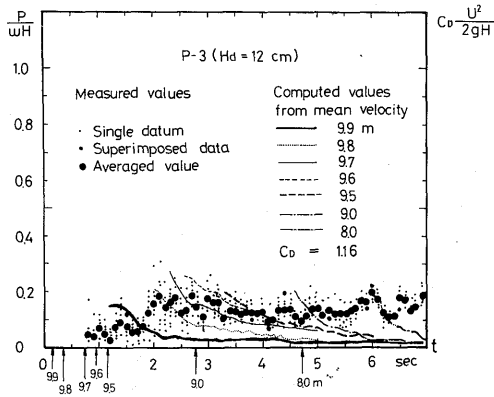


Fig. 13 Comparison of computed drag forces with experimental dynamic wave forces in the case of P-3

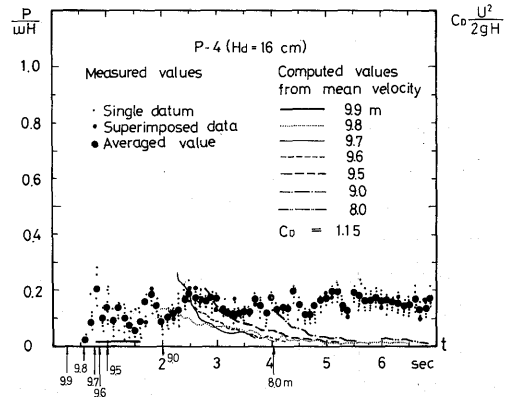


Fig. 14 Comparison of computed drag forces with experimental dynamic wave forces in the case of P-4

however the mechanism generating dynamic wave force on the wall seems to be roughly explained. Values calculated from mean experimental velocities would be obtained as an envelope of these groups of lines, if many measuring points are set.

Further, inertia force is generated by incident surge just after colliding of the surge front portion, however it is not so large and rather less than drag force by the reflected bore as a whole, so it is here disregarded.

In the result, dynamic wave force on the wall was found to be generated mainly by drag force and the magnitude of dynamic wave force of tsunami bore measured in the case was round 10~40 % of hydrostatic wave force.

#### IV. CONCLUSIONS

If steady flow theory by the author for analysis of tsunami when overflowing a wall is applied to wave height and velocity of both reflected bore in front of the vertical wall and transmitted surge to rear of it, the values near peak were seen to be roughly explained by the theory, though there is a little time lag affected by rising surge front portion.

Drag force was computed from the mean velocity in the section of reflected bore in front of the vertical wall

and was compared with measured dynamic wave force on the wall. Consequently, the dynamic wave force on the wall was found to be generated mainly by the drag force. And the magnitude of the dynamic wave force in the case was round 10~40 % of the hydrostatic force obtained from water level at the wall site.

Therefore, if wave height and velocity of an incident tsunami surge near at the site of tsunami protection wall are given by numerical computation in the case without wall, the wave height and velocity near the peak of both reflected bore in front of the wall and transmitted wave in rear of it are approximately computed by the steady flow theory in the case with wall, and the maximum wave force is computed at the same time as well, so it is possible to design the tsunami protection wall and to estimate its construction effect.

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