CHAPTER 58

ON THE OVERLAND FLOW OF TSUNAMI AND EFFECTIVENESS
OF WALL AS A COUNTER MEASURE

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SYNOPSIS

When a tsunami of large magnitude strikes a coast line, various kinds of disaster such as loss of lives, properties or public investments are caused by inundation of tsunami over nearly horizontal area. Although tsunami runup has been investigated for the sloping beach, these populated area is bordered on sea by a vertical wall such as a quaywall or a highway revetment. In this paper, transformation of tsunami waves at a vertical quaywall is analysed using U-C characteristics and overland flow is treated. Effectiveness of a vertical land dike aiming to stop running water is investigated also. Theoretical results are verified by experiments.

INTRODUCTION

Tsunami is caused by a mid-ocean earthquake of large magnitude, having very flat steepness, very long wavelength of several hundred kilometers and wave period of several ten minutes in the ocean. When it approaches to a coast, wave height is increased by effect of shallowness as understood easily by the Green's theorem. Moreover tsunami is amplified by diffraction and reflection owing to favorable nearshore topography and also by harbour resonance. As a result, several or several ten meters of wave height is not unusual which results catastrophic disaster.

In Japan, 101 tsunamis have been recorded since 687, in which 18 tsunamis caused catastrophe. Sanriku Coast is situated in northern part of Honshu, the main island of Japan and faced to the Pacific seismic belt, so this coast has been attacked by tsunamis most frequently in Japan. As this coast is a rias type, there are various kinds of bays in their scale and shape, which depth is usually over 10 or 20 meters at their mouth and have vertical cliffs on most of coastline leaving scarce flat land at the innermost part, where fishery ports and harbours are located with populated area behind it. Stepping over quaywalls of ports and harbours or highway revetments, tsunami waves cause overland flow. Although tsunami runup on a sloping beach has been investigated extensively by various authors, overland flow of this type seems a problem to be solved still now.

This paper deals with mechanism of transformation of tsunami wave at a quaywall and that of overland flow and effectiveness of a land dike as a counter measure.

U-C CHARACTERISTICS OF LONG WAVES OF FINITE AMPLITUDE

As long waves of finite amplitude, following relationships hold also for tsunami waves,

for C+ characteristics $P = c_* 2(C-1) + U$ (1)

for C- characteristics $Q = c_* 2(C-1) - U$ (2)

in which analysis is confined to one dimensional and the slope of the sea bottom is assumed horizontal. c_* is $\sqrt{gh}$, $C = (1 + \eta/h)^{1/2}$ and $U = u/c_*$ where h is the depth, g is the acceleration of the gravity and u is the horizontal velocity. (Lamb 1932)
     Eq. (1) implies a U-C characteristics in a U-C plane corresponding to a C+ characteristics in a X-T plane has negative slope of 1/2 which intersects the horizontal axis at a point $(P/c_*, 0)$ which is shown in fig.1. Also by eq. (2), a U-C characteristics corresponding to a C- characteristics has positive slope of 1/2 which intersects the horizontal axis at a point $(-Q/c_*, 0)$
     In the progressive wave, $Q=0$. Hence $U_1 = 2(C_1-1)$, $P/c_* = 4(C_1-1)$ and this is expressed by a point A, namely A_1, A_2, A_3 or A_p corresponding to their value of P/c_* or $4(C_1-1)$ which can be determined by η or surface elevation of each wave element, where suffix 1 refers to values of incident waves and suffix p refers to values at the peak. When these wave elements are stopped at the vertical quaywall, $U=0$. So, point A moves to point B, namely B_1, B_2, B_3 or B_p which shows U-C characteristics of a perfect clapotis. Then,

$$Cc - 1 = 2(C_1 - 1)$$ (3)

where $Cc = (1 + \frac{\eta_c}{h})^{1/2}$ and $C_1 = (1 + \frac{\eta_1}{h})^{1/2}$ in which suffix c refers to a clopotis.
     The reflected wave elements can be expressed by points C_1, C_2, C_3 and C_p as these characteristics must pass points B and $U_r = -2(C_r-1)$ since $P=0$, where suffix r refers to a reflected wave.
     When C_1-1 is larger than $1/2(C_w-1)$, overruning flow takes place, where $C_w = (1 + \frac{H_w}{h})^{1/2}$ in which H_w is the quaywall height above still water.   Then the clapotis at the quaywall is imperfect. Assumption is made for these reflected wave elements that the velocity is same with incident wave elements, but the surface elevation cannot be higher than $h + H_w$, or $C_r - 1 = 1/2 \cdot (C_w - 1)$.
     Then Cc-1 can be given by two characteristics through C_1 and C_r as shown in fig.2. So,

$$C_c - 1 = \frac{3}{2}(C_1 - 1) + \frac{1}{4}(C_w - 1)$$ (4)

$$U_c = (C_1 - 1) - \frac{1}{2}(C_w - 1)$$ (5)

Where $C_w - 1$ is smaller than $2(C_1-1)$. That is,

$$C_w - 1 < 2(C_1 - 1) \qquad (6)$$

It may seem interest that when water level is equal to the height of the quaywall, reflection is took place only as time sequence of the velocity without wave configuration as shown in fig.3. In this case,

$$C_c - 1 = 3/2(C_1 - 1) \qquad (7)$$

and

$$U_c = C_1 - 1 \qquad (8)$$

as $C_w - 1 = 0$. And since U_c and $C_c - 1$ are positive, these wave elements invade into land causing overland flow.

OVERLAND FLOW OF TSUNAMI

Experiments shew that when overland flow was occured, water depth decreased abruptly at the brink of the quaywall as shown in fig.4 and flow was assumed being transformed from subcritical to supercritical.

For overland flow no-dimensional wave celerity is defined as

$$C' = \sqrt{\frac{\eta'}{h}} \qquad (9)$$

Where η' is measured from the horizontal bed.
Then since

$$\eta_c' = \eta_c - H_w \qquad (10)$$

$$C_c' = \sqrt{\frac{\eta_c - H_w}{h}} = \sqrt{C_c^2 - C_w^2} \qquad (11)$$

As $U_c' = U_c$, the following relation can be obtained.

$$C_c'^2 - U_c'^2 = 5/16 \ J^2 + 3/2 \ JC_w \qquad (12)$$

in which

$$J = 2C_1 - C_w - 1 \qquad (13)$$

Since J is positive when overrunning is occured, the right hand side of eq.(12) is positive which means C_c' is larger than U_c', or flow is subcritical at the brink of the quaywall.

Then a critical flow section A is assumed established at some distance from the brink followed by supercritical flow. As this distance has not been decided yet, an assumption is made here that this distance is infinitely small and the section of critical flow is situated just next to the brink of the quaywall.

For calculation of overrunning flow, the origin of x-axis is taken at the brink of the quaywall. C_+ characteristics emerging from t-axis are expressed by

$$\frac{dx}{dt} = U_c' + C_c' \tag{14}$$

and on which

$$U_c' + 2C_c' = U_A' + 2C_A' \tag{15}$$

As mentioned above,

$$U_A' = C_A' \tag{16}$$

Then from (15) and (16)

$$U_A' = C_A' = 1/3(U_c' + 2C_c') \tag{17}$$

, in which $U_c' = U_c$ and C_c' are given already. As the distance between O and A is infinitely small, the two points are coincided practically and are considered to give a boundary condition.

C- characteristics emerging from A-axis are given by,

$$\frac{dx}{dt} = U_A' - C_A' = 0 \tag{18}$$

, which shows C- characteristics are parallel with t-axis and range of influence is limited to the right half of x-t plane as accepted in practice.

Overrunning flow is resembled with flow after the breaking of a dam in which various assumptions has been presented for the front condition. According to the theory originally proposed by St. Venant, the front depth is zero and so C_+ and C_- characteristics coincide with each other to compose the characteristic envelope. However a more general relation is

$$C_f' = aU_f' \tag{19}$$

for the front condition, in which a is a constant and a reciprocal of the Froude number and suffix f refers to the front. (Abbot, 1961) (Méhauté, 1964) Then the characteristic equation for the leading wave element is,

$$d(U' + 2C') = -f\left(\frac{U'}{C'}\right)^2 \frac{dx}{U' + C'} \tag{20}$$

in which f is a friction coefficient and $X = x/h$. From eq. (20),

$$\frac{U'^2}{2} = \frac{U_A'^2}{2} - \frac{f}{a^2} \cdot \frac{X - X_A}{(1+a)(1+2a)} \tag{21}$$

for the horizontal bed after Freeman and Méhauté. The front is the envolope of the leading wave element given by

$$\frac{dX}{dT} = U' \tag{22}$$

Eliminating U' from eq. (21) and (22), the leading front characteristics
are given.

As shown in fig.5, the succeeding C_+ characteristics emerging from a
point F takes over the leading front emerging from a point E. Then on the
C_+ characteristics,

$$U_f' + 2C_f' = U_F' + 2C_F' - f\left(\frac{U_F'}{C_F'}\right)^2 \cdot \varDelta T_{FG} \tag{23}$$

and on the leading front

$$C_f' = a U_f' \tag{24}$$

Then from eq. (23) and (24)

$$C_f' = \frac{a}{1+2a} \cdot \left[U_F' + 2C_F' - f\left(\frac{U_F'}{C_F'}\right)^2 \cdot \varDelta T_{FG}\right] \tag{25}$$

and also

$$U_f' = \frac{1}{1+2a} \left[U_F' + 2C_F' - f\left(\frac{U_F'}{C_F'}\right)^2 \cdot \varDelta T_{FG}\right] \tag{26}$$

After this intersection G, velocities are changed in accordance with eq.
(21) until a next C_+ characteristics takes over.

Internal zone bounded by the t-axis and the characteristic envelope
of the leading front can be analysed by two sets of characteristics as
usual.

Froude number of the leading front or $1/a$ is normally assumed as 2
from works by Keulegan, Abbott, Méhauté and others.

REFLECTION AND OVERFLOW AT THE LAND DIKE

Along the Sanriku coast, many land dikes have been constructed to
protect resident quarters as one of counter measures for running water of
tsunami. Although their height was designed in accordance with the highest
trace of inundation, its reliability has not been checked until tsunamis
struck these areas by chile earthquake in 1960 which stimulated us beginning
this research.

Fig.6 shows schematically reflection and overflow of running tsunami
at a land dike. As the Froude number of the leading front is assumed as 2,
the incident flow is supercritical in section I. So a bore is occured by
reflection, behind which flow is subcritical. If the height of a land
dike is lower than that of the reflected bore, overflow takes place as
shown in fig.6.

Between section I and II, a shock condition exists as

$$h_1(u_1 - \omega) - h_2(u_2 - \omega) = 0 \tag{27}$$

$$u_1 h_1(u_1 - \omega) - u_2 h_2(u_2 - \omega) = \frac{g}{2} \cdot (h_2^2 - h_1^2) \tag{28}$$
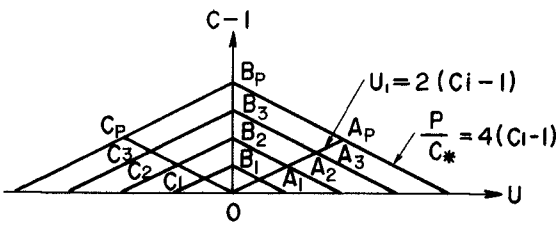
Fig 1   U-C characteristics of a long
wave of finite amplitude.
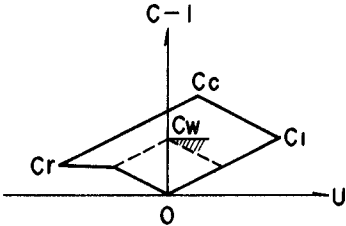
Fig.2   Partial clapotis
in U-C plane
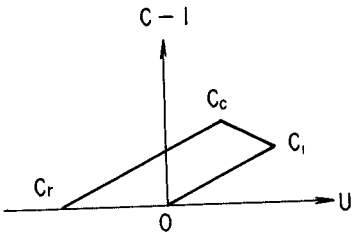
Fig.3   Partial clapotis in U-C
plane when $C_w = 1$
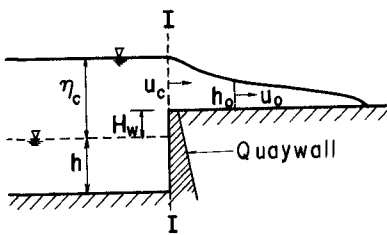
Fig. 4   Tsunami transformation at the
quaywall
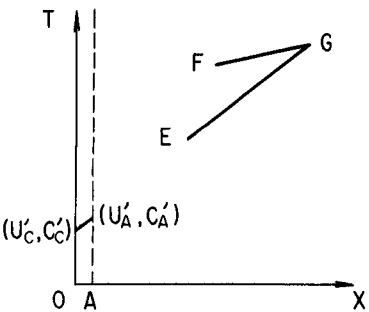

Fig.5   Characteristics at the
brink of the quaywall and that
of a leading front
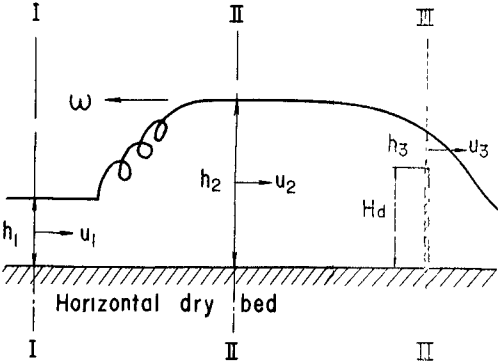
Fig.6   Reflection and overflow at a
land dike

where ω is the speed of propagation of the bore front and suffix 1 and 2 refers to values in section I and II respectively.

Between section II and III, an energy equation holds as,

$$h_2 + \frac{u_2{}^2}{2g} = h_3 + \frac{u_3{}^2}{2g} + H_d \qquad (29)$$

and

$$u_2 h_2 = u_3 h_3 \qquad (30)$$

, in which H_d is the height of the land dike and suffix 3 refers to values in section III. In section III, a critical condition is assumed as,

$$h_3 = \sqrt[3]{\frac{(u_3 h_3)^2}{g}} \qquad (31)$$

From (27) and (28),

$$\omega = u_1 = \sqrt{\frac{gh_2}{2h_1} \cdot (h_1 + h_2)} \qquad (32)$$

as ω is negative.

Putting eq. (32) into eq. (27), we get

$$u_2 = (1 - \frac{Y}{F_1}) u_1 = \frac{y}{F_1} u_1 \qquad (33)$$

, where

$$Y = (x_2 - 1) \sqrt{1/2(1 + \frac{1}{x_2})} \quad , \quad x_2 = \frac{h_2}{h_1} \, . \qquad (34)$$

and

$$F_1 = \frac{u_1}{\sqrt{gh_1}} \quad , \quad y = F_1 - Y \qquad (35)$$

From (30) and (33)

$$x_3 = x_2{}^{2/3} \cdot (F_1 - Y)^{2/3} = (x_2 y)^{2/3} \qquad (36)$$

, where $x_3 = h_3/h_1$

Putting (33) and (36) into (29), we get

$$z = x_2 + 1/2 \, y^2 - 3/2 \, (x_2 y)^{2/3} \qquad (37)$$

, where

$$z = \frac{H_d}{h_1} \qquad (38)$$

Fig.7 shows the relationship between x_2 and F_1 with a parameter z and between z and F_1 with a parameter x_2. The height of reflected bore is nearly proportional to the Froude number of the incident flow. Also to keep x_2 constant, z must be lowered when F_1 is increased. From eq. (33), overflow takes place when F_1 is larger than Y, which gives the lower limit of x_2 as the latter is proportional to x. This limit is designated as $x_2(L)$ and is equal to the wall height z as shown in eq. (37).

From eq. (32), the bore must be stopped resulting a hydraulic jump when ω =o, or

$$F_1=x_2\sqrt{\frac{1}{2}(1 + \frac{1}{x^2})} \tag{39}$$

, which gives the higher limit of x_2 or $x_2(U)$ since the bore is flushed away when   o. In this case the wall is no longer useful for a counter measure of the tsunami running flow. From (37),

$$z=z(U)=x_2(U)+ \frac{1}{2}(\frac{F_1}{x_2(U)})^2- \frac{3}{2}(F_1)^{2/3} \tag{40}$$

in which $z(U)$ means the wall height ratio for this limit case.

Eliminating x_2 from eq. (36) and (37), the relationship between x_3 and F_1 is given taking z as a parameter which is shown in fig.8. It is found that x_3 is almost linearly proportional to F_1.

As shown in fig.9, flow runs still after overflowing the dike. Between section III and IV, following relations are hold, if energy loss is neglected.

$$h_3+ \frac{u_3^2}{2g} + H_d= h_4+ \frac{u_4^2}{2g} \tag{41}$$

$$u_3h_3=u_4h_4 \tag{42}$$

From eq. (41) and (42), the following equations is given together with eq. (31).

$$x_4^3 - (2+ \frac{3}{2} x_3)x_4^2+ \frac{1}{2} x_3^3= o \tag{43}$$

in which $x_4=h_4/h_1$. And

$$F_4 = \frac{u_4}{\sqrt{gh_4}} = (\frac{h_3}{h_4})^{3/2}= (\frac{x_3}{x_4})^{3/2} \tag{44}$$

However it is convenient that x_4 is expressed as a function of F_1 taken z as a parameter, which is given in fig.10. It is shown that as z is higher, x_4 becomes smaller. Since at the front Froude number is between 1 and 2, height of land dikes is acceptable when it is designed by $0.4 < z < 2.2$.

By difinition,

$$\frac{u_4}{u_1} = \frac{F_4}{F_1} \cdot x_4^{1/2} \tag{45}$$

$$\frac{q_4}{q_1} = \frac{F_4}{F_1} \cdot x_4^{3/2} \tag{46}$$

These are related to F_1 taking z as a parameter, in fig.11. As expected
normally, invading flow decreases when the hight of a land dike increases.
However velocity ratio increases causing stronger tractive force.

EXPERIMENTAL PROCEDURE

Experiments were conducted in a wave basin 23m long, 0.5m wide and
0.5m high. A pneumatic wave generator was installed at one end of the
basin which dimension was 2.5m long, 1.5m wide and 1.5m high and was
capable to produce a very long solitary wave. At the other end a horizontal
dry bed model 10m long was installed which had a vertical quaywall of the
height 0.312m.

Resistance type wave gauges were set 6m and 1m off the quaywall res-
pectively. Fig.12 shows an example of recorded waves. Photographs of
running water on the horizontal bed were taken by a motor driven camera
and a 16mm movie camera at the rate of 3 frames and 24 frames per second
respectively. Scales were marked on the bed and the wall, by which depth
of wave front and water sheet were taken their co-ordinates using a pro-
file-projector. Fig.13 and fig.14 show an example of wave fronts just
after the quaywall and of waves overflowing the land dike respectively.

The depth of still water was set among 20 and 30cm. As a solitary
wave, an incident wave element is expressed by

$$\eta_1 = H_1 \ \mathrm{sech}^2(\frac{x}{h} \sqrt{\frac{3}{4} \frac{H_1}{h}}) \tag{47}$$

, where H_1 is the wave height of the solitary wave, in which 98% of total
wave volume is included between ± 3.8 of x/h where the x origin is taken
at the summit. So, for numerical calculation $_1$ is measured from the
elevation at $x/h = \pm 5$. Then H_1 was chosen among 5 and 15cm. Also the
period T is taken for the part of $x/h = \pm 5$ in a wave, which was set among
4.7 and 28.5 sec. The height of land dikes was chosen between 3 and
12.5cm and these are located among 50 and 500cm from the quaywall.

Total 426 runs were tested and several runs were compared with results
of theoretical calculation.

CALCULATION AND EXPERIMENTAL VERIFICATION

Using one of test conditions, following numerals are used for calcu-
lation.

$$h = 28.1cm, \ H_1 = 7.7cm$$

The distance of a land dike from the quaywall L_d is 120 cm and its height
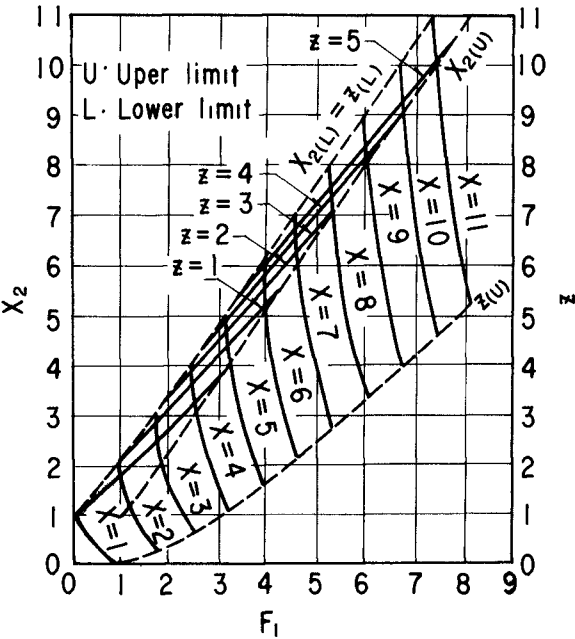
Fig.7   Relationship between x_2, z and F_1.
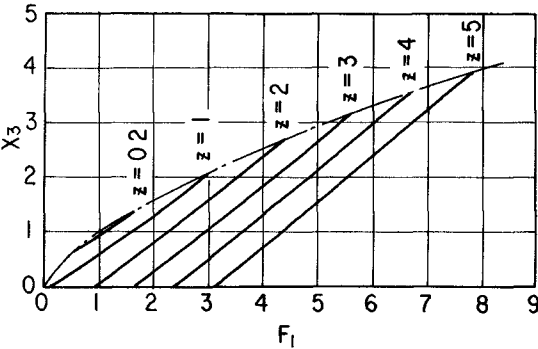
Fig.8   Relationship between x_3 and F_1
with a parameter z.
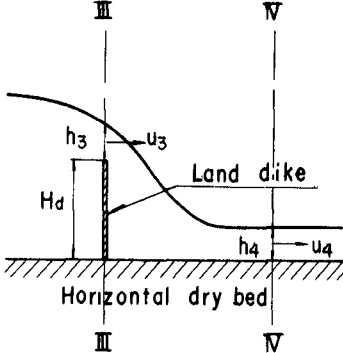
Fig.9   Flow after over-
flowing the dike.
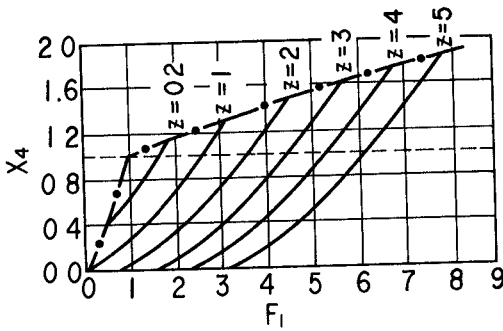
Fig.10   Relationship between x_4 and F_1 with a parameter z.
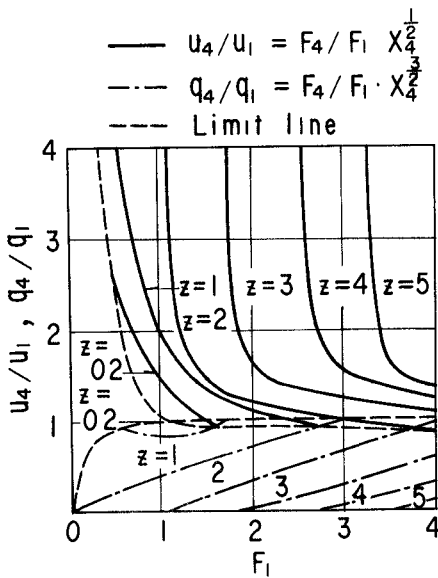
Fig.11   Relationship between u_4/u_1, q_4/q_1 and F_1 with a parameter z.
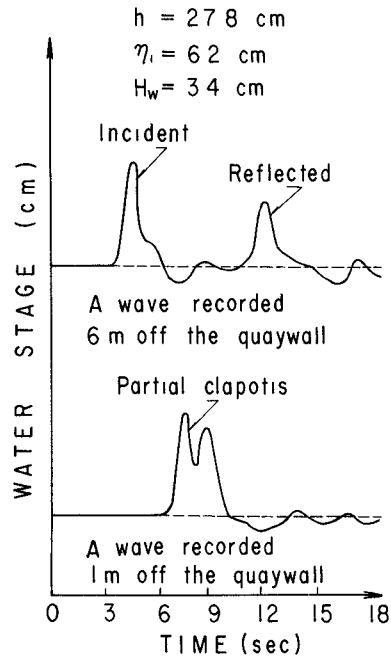
Fig.12   An example of recorded waves

Fig.13 A wave front just after the quaywall.

Fig.14 A wave over the land dike.

H_d is 3.0 cm. Then from eq. (47)

$$_1 = 7.7 \; \text{sech}^2(0.453 \; x) \tag{48}$$

, where X=x/h. In table 1, some specific values are given for points equally spaced on X-axis.

The height of a quaywall is taken as H_w=3.1cm. U-C characteristics give values of the reflecting wave in table 2 following to the theory proposed. X-T and U-C characteristics are given in fig.15 and fig.16 respectively.

Table 1

Calculated point	(5)	(4),(6)	(3),(7)	(2),(8)	(1),(9)	(0),(10)
X	0	1	2	3	4	5
η_1	7.7	6.314	3.717	1.789	0.782	0
$M_1=\eta_1/h$	0.274	0.225	0.132	0.064	0.028	0
$C_1=\sqrt{1+M_1}$	1.129	1.107	1.064	1.031	1.014	1
$U_1=2(C_1-1)$	0.257	0.213	0.128	0.063	0.028	0
$(dX/dT)_+=U_1+C_1$	1.386	1.320	1.192	1.094	1.041	1

Table 2

Calculated point	(5)'	(4)',(6)'	(3)',(7)'	(2)',(8)'	(1)',(9)'	(0)',(10)'
η_r (X=0)	1.532	1.532	1.532	1.532	0.783	0
$M_r=\eta_r/h$	0.055	0.055	0.055	0.055	0.028	0
$C_r=\sqrt{1+M_r}$	1.027	1.027	1.027	1.027	1.014	1
$U_r=-U_1$	-0.257	-0.213	-0.128	-0.063	-0.028	0
$(dX/dT)_-=U_r-C_r$	-1.284	-1.240	-1.155	-1.090	-1.042	-1

Then values of surface elevation are given in table 3 and also are plotted in the left half of fig.17. It is cleary shown that the incident wave is transformed to the partial clapotis and is reflected at the quaywall.

Values of U and C at the quaywall just derived are converted to U' and C' by eq. (16) and $U_c'=U_c$. Then from eq. (17) U_A' and C_A' are calculated which gave boundary conditions for the overland flow. As shown in fig.16, the moment which the clapotis just touches the crest of the quaywall, is not coincided with an intersection of characteristics issuing from points given in table 1 and 2. So, assumption is made this moment is given by a fraction of time increment which is equal to that of U-C segment.

Then the first wave element emerges from (X=0, T=1.27 sec) on the X-T plane, from which a line of C_f characteristic is drawn by dx/dt=U_A' +C_A'=2U_A' since $U_A'=C_A'$ as shown in eq.17. Moreover a line of front
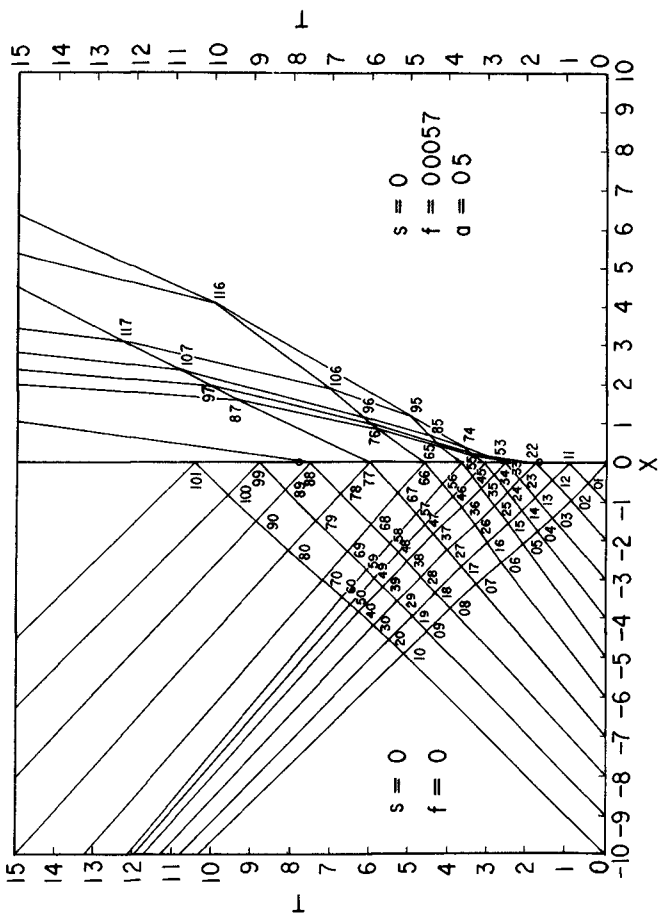
Fig. 15 X-T characteristics
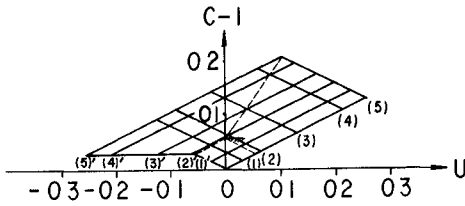
Fig.16   U-C characteristics
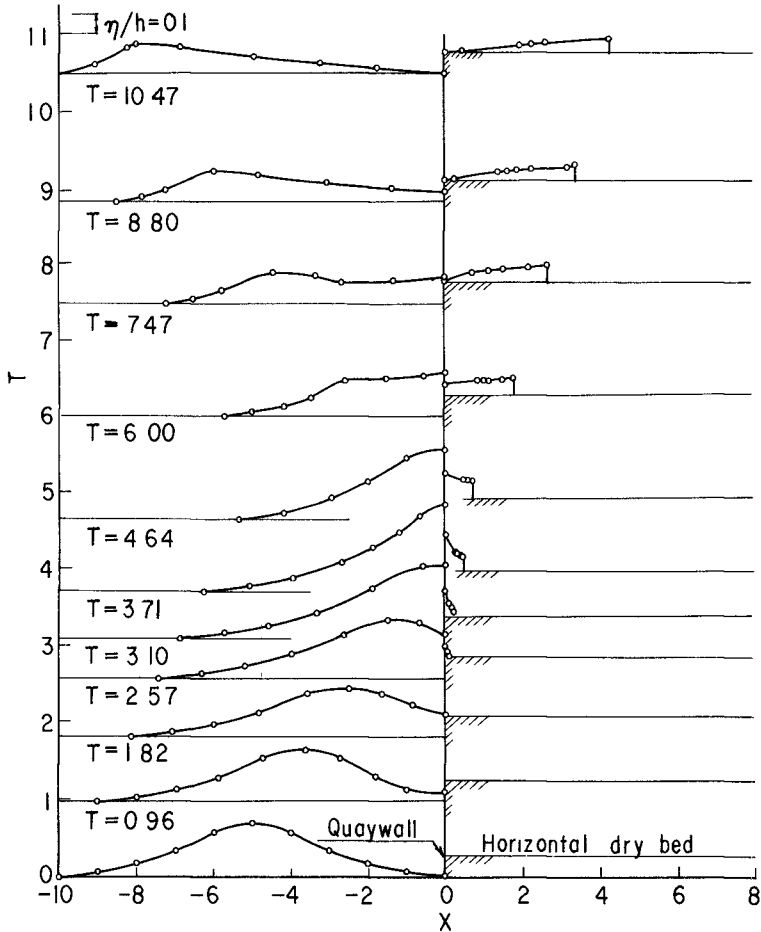
Fig.17   Calculated configuration of the tsunami overrunning
the vertical quaywall.

Table 3

		0	-1	-2	-3	-4	-5	-6	-7	-8	-9
T= 0	X	0	-1	-2	-3	-4	-5	-6	-7	-8	-9
	η/h	0	0.028	0.064	0.132	0.225	0.274	0.225	0.132	0.064	0.028
T= 0.96	X	0	-1	-1.80	-2.74	-3.65	-4.73	-5.88	-6.97	-8	-9.03
	η/h	0.053	0.064	0.132	0.225	0.274	0.225	0.132	0.064	0.028	0
T= 1.82	X	0	-0.83	-1.64	-2.50	-3.59	-4.83	-6.00	-7.08	-8.16	
	η/h	0.124	0.164	0.228	0.274	0.225	0.132	0.064	0.028	0	
T= 2.57	X	0	-0.67	-1.50	-2.62	-3.98	-5.20	-6.33	-7.45		
	η/h	0.231	0.295	0.309	0.225	0.132	0.064	0.028	0		
T= 3.10	X	0	-0.58	-1.90	-3.32	-4.62	-5.75	-6.90			
	η/h	0.374	0.371	0.263	0.132	0.064	0.028	0			
T= 3.71	X	0	-0.65	-1.20	-1.87	-2.68	-3.95	-5.11	-6.27		
	η/h	0.454	0.395	0.313	0.234	0.153	0.064	0.028	0		
T= 4.64	X	0	-1.03	-2.03	-2.03	-2.95	-4.20	-5.39			
	η/h	0.374	0.329	0.199	0.115	0.030	0				
T= 6.00	X	0	-1.53	-2.60	-3.50	-4.21	-5.00	-5.76			
	η/h	0.231	0.201	0.193	0.103	0.055	0.026	0			
T= 7.47	X	0	-1.35	-2.70	-3.37	-4.47	-5.82	-6.55	-7.25		
	η/h	0.124	0.115	0.111	0.136	0.160	0.055	0.026	0		
T= 8.80	X	0	-1.40	-3.07	-4.86	-6.00	-7.25	-7.90	-8.53		
	η/h	0.053	0.061	0.092	0.136	-0160	-0055	0.026	0		
T= 10.47	X	0	-1.78	-3.22	-4.95	-6.82	-8.00	-8.26	-9.08	-10.15	
	η/h	0	0.026	0.057	0.092	0.136	0.160	0.136	0.055	0	

characteristics is drawn also by

$$\frac{dX}{dT} = \sqrt{U_A'^2 - \frac{2f}{a^2} \cdot \frac{X-X_a}{(1+a)(1+2a)}}$$ (49)

in which a and f are given as 1/2 and 0.0057 respectively. In the right half of fig.15, X-T characteristics are obtained and in table 4 values of η/h are given. Also in the right half of fig.17, calculated values of surface elevation are plotted. Fig.18 shows the heighest traces of inci-dent, reflected and run-up waves. Agreement between results of experiment and of calculation is fine. Fig.19 shows the relationship between

$\frac{C_c-1}{C_w-1}$ and $\frac{C_1-1}{C_w-1}$, where a full line shows the relationship given by eq. (4)

Table 4

T=2.57	X	0	0.03	0.05	0.08				
	η/h	0.059	0.034	0.029	0.003				
T=3.10	X	0	0.09	0.16	0.21				
	η/h	0.136	0.070	0.053	0.032				
T=3.71	X	0	0.23	0.30	0.42	0.45			
	η/h	0.181	0.098	0.092	0.077	0.074			
T=4.64	X	0	0.47	0.58	0.69	0.98			
	η/h	0.136	0.102	0.097	0.099				
T=6.00	X	0	0.82	1.00	1.11	1.48	1.77		
	η/h	0.059	0.081	0.080	0.081	0.086	0.097		
T=7.47	X	0	0.70	1.13	1.50	2.15	2.65		
	η/h	0.006	0.050	0.059	0.068	0.074	0.093		
T=8.80	X	0	0.21	1.35	1.60	1.83	2.25	3.18	3.37
	η/h	0	0.006	0.044	0.048	0.053	0.062	0.067	0.088
T=10.47	X	0	0.45	1.98	2.23	2.61	4.27		
	η/h	0	0.006	0.037	0.041	0.051	0.067		

and white circles show experimental results. Agreement is also very fine
which proves the assumption for the formation of imperfect clapotis. In
fig.20, the front characteristics in X-T plane is presented to compare
test results and theoretical ones, which were obtained by assuming f as
0.0057 and 0.01. It is concluded that a frictional coefficient must be
taken much larger than that ordinary expected.

The Froude number of the wave front was calculated for nearly 80 runs
and was found among 0.5 and 2.5 which might correspond to 1.0 and 2.0
given by Abbott and Méhauté.

Finally, test results of x_3 and $F_4=u_4/\sqrt{gh_4}$ are compared with theretical ones in fig.21 and fig.22 respectively, which also show good agreement with each other.

CONCLUSION

U-C characteristics are utilized to analyse perfect and imperfect
reflection at the quaywall. Condition of occurance of imperfect clapotis
is presented. No dimensional wave celerity and velocity are given by eq.
(4) and (5).

Overland flow is calculated assuming that critical flow takes place
at the quaywall and Froude number $F_1=U'_f/C'_f=1/a$ on the leading wave front
is 2. However whenever this front is took over by the succeeding elements,
abrupt change is occured in U' and C'.

Reflection and overflow of running tsunami at a land dike which is
designed to prevent the intrusion of tsunami are analysed using shock
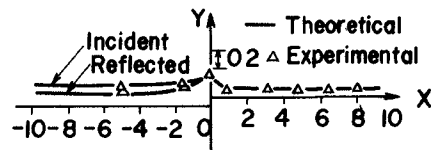
Fig.18 Max. traces of incident,
reflected and inundated waves.
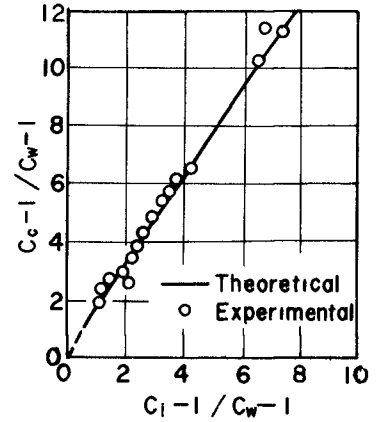
Fig.19 Relationship between $C_c-1/$
C_w-1 and C_1-1/C_w-1.
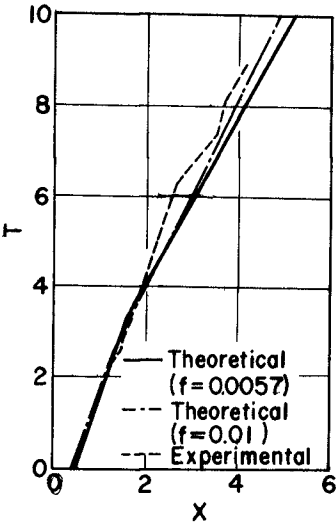
Fig.20 X-T characteristics of
the tsunami front on the land.
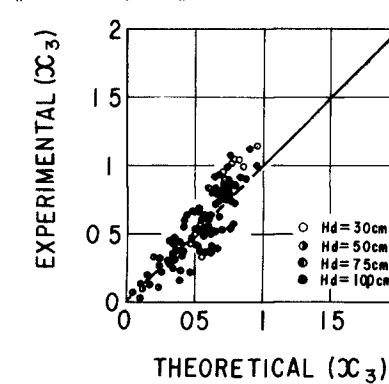
Fig.21 Comparison between theoretical
and experimental values of x_3.
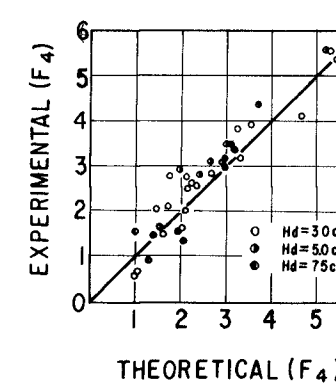
Fig.22 Comparison between
theoretical and experimental
values of F_4.

condition and an energy equation, in which also the critical depth is
assumed to occure at the summit of the dike.

Conditions of perfect reflection and of jet impact are given.   Also
depth, velocity and discharge behind the dike after overflow are presented.
It is found that as the height of a dike increases, overflow discharge
decreases as expected ordinary, but velocity increases which necessitates
careful inspection on safety of the land behind the dike.

Finally theories are examined by experiments of 426 runs and are
verified by comparison of test results and theoretical calculations.

ACKNOWLEDGEMENTS

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