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Tide gauge response to tsunamis: Measurements at 40 tide gauge stations in Japan

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ABSTRACT

The responses of tide gauges to tsunamis are examined by *in situ* measurements at 40 stations in northeastern Japan. Recovery of water level in the tide well is measured after the water is drained or added to create a water level difference between the inside and outside of the wells. The recovery times for a 1 m water level difference, estimated from the observations, vary from station to station and range from 65 to 1300 sec. Tsunami waveforms on tide gauge records from the 1983 Japan Sea earthquake are corrected for the observed response. For those stations with the observed recovery times longer than 300 sec, the corrected waveforms differ significantly from the originals and reproduce the inundation heights near the tide gauge stations, indicating that the tide gauge system significantly distorted the tsunami waveforms. At such stations, the correction for the response is necessary for quantification of tsunamis. The recovery time is also computed hydraulically on the basis of the structure of the tide gauge system. The ratio of the observed time to the computed one ranges between 1 and 10 which is attributed to environmentally-induced change of the tide gauge system.

1. Introduction

Tide gauge records are usually the only instrumental data of tsunamis. Tsunami waveforms recorded on tide gauges are used to quantify tsunamis or to study earthquake source processes. The Japanese tide gauge system is designed to observe the ocean tides, however, and the response of this system to tsunamis is not well known. In 1983, the Japan Sea earthquake (M_W 7.9; Satake, 1985) was accompanied by a large tsunami which caused much damage along the Japan Sea coast of Japan and Korea. At that time, large discrepancies between the tsunami amplitude on tide gauge records and inundation heights were reported. For example, the visually observed inundation heights were about 1.5 m at the two tide gauge stations near the source area, Yoshioka and Fukaura, whereas the maximum tsunami heights recorded by the tide gauges were 0.96 and 0.65 m, respectively (JMA, 1984; Kinoshita *et al.*, 1984). The discrepancy is attributed to the response of the tide gauge system to tsunamis.

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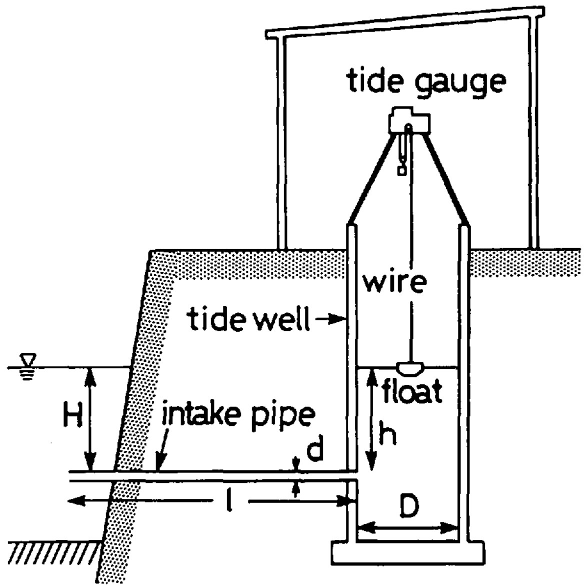

Figure 1. Structure and parameters of a typical tide gauge system in Japan.

Several studies have been made of the frequency response to tide gauges (Cross, 1968; Noye, 1974; Loomis, 1983). All of these studies treat a tide gauge consisting of a stilling well which is set in the water and connected to the outer sea by an orifice. The Japanese tide gauge systems, however, have a different structure. The stilling well is generally dug into a wharf and connected with the ocean by an intake pipe (Fig. 1). A long and narrow intake pipe strongly affects the response of the system to tsunamis. After the 1983 tsunami, theoretical estimates (Murakami, 1983) and *in situ* measurements (Okada, 1985) of tide gauge responses were made for a few stations. Okada (1985) showed that the observed inundation height, which was much larger than the tsunami amplitude recorded by tide gauges, could be reproduced if the measured response function was used to correct the tide gauge records. In this paper, we perform *in situ* measurements of the tide gauge response function for 40 stations, compare them with theoretical computations, and use the results to correct the tide gauge records of the 1983 Japan Sea tsunami.

2. Theoretical tide gauge response

We take a similar approach to Cross (1968) and Loomis (1983), who discussed the nonlinear response of a tide gauge system. According to Bernoulli's theorem, the velocity of water in the intake pipe, u (taking positive for incoming water), is proportional to the square root of the difference in water level outside the well, H, and that inside the well, h,

$$u = \operatorname{sgn}(H - h)\sqrt{2g\,|H - h|/F} \tag{1}$$

where sgn is the sign function, either 1 or -1 depending on the sign of $(H - h)$, g is the gravitational acceleration, and F is a nondimensional friction coefficient, which will be discussed in detail in Section 4. We assume steady flow; i.e., we neglect unsteady oscillations. Also, continuity requires that the time rate of change of well water volume be matched by flow through the intake pipe; i.e.,

$$D^2\frac{dh}{dt} = Nd^2u \tag{2}$$

where D and d are the respective diameters of a circular well and the intake pipe, and N is the number of the intake pipes (generally equal to one). From (1) and (2), we have

$$\frac{dh}{dt} = W\operatorname{sgn}(H - h)\sqrt{2g\,|H - h|} \tag{3}$$

where

$$W = N(d/D)^2/\sqrt{F} \tag{4}$$

is a nondimensional constant characterizing each tide gauge system. We will call it the well constant hereafter.

Thus, from tide gauge records of the stilling well, $h(t)$, the corrected tsunami waveform outside the well, $H(t)$, can be estimated from (3) as

$$H = h + \operatorname{sgn}\left(\frac{dh}{dt}\right)\left(\frac{dh}{dt}\right)^2 \bigg/ 2gW^2. \tag{5}$$

This is the equation of the correction for tide gauge response. Although W completely describes the response of the tide gauge system, we have found it convenient to define a second parameter, T, corresponding to the time required to reach equilibrium ($h = H$) from a hypothetical 1 m water level difference, i.e., $|H - h| = 1$ m. Utilizing these conditions as limits for the integration of (3), we obtain

$$T = \sqrt{2\Delta h/g}/W \tag{6}$$

where $\Delta h = |H - h| \equiv 1$ m.

3. Measured tide gauge response

The well constant W can be estimated by *in situ* measurements. We made measurements at 40 stations in northeastern Japan. The location of each station is given in Figure 2 and Table 1. In Table 1, the structural parameters of the tide gauge system are also listed.

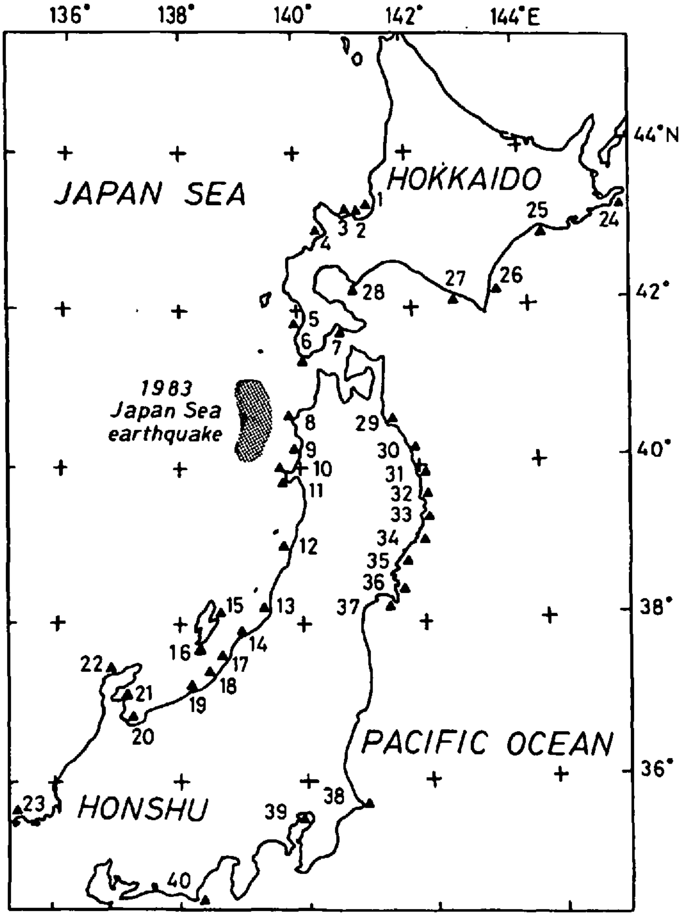

Figure 2. Tide gauge stations (solid triangles) whose responses are compiled in this paper. Attached numerals are the station numbers. The source area of the 1983 Japan Sea earthquake tsunami is also shown.

Table 1. Location and structure of tide gauge stations.

No	Station	Lat.	Lon.	D(m)	pipe*	d(m)	l(m)	Remarks
1	Ishikari	43°13′	141°19′	1.0		0.15	12.48	
2	Otaru	43°10′	141°02′	1.2	*A*	?	2.55	4 bends
					B	0.125	12.5	
3	Oshoro	43°12′	140°52′	0.8		0.1	10.0	damper

Table 1. (continued)

No	Station	Lat.	Lon.	D(m)	pipe*	d(m)	l(m)	Remarks
4	Iwanai	42°59′	140°31′	1.2		0.15	16.74	
5	Esashi	41°52′	140°07′	0.9	*A*	0.25	2.0	
					B	0.05	2.125	pipe *b* × 4
6	Yoshioka	41°27′	140°15′	1.0		0.06	0.3	net
7	Hakodate	41°47′	140°44′	0.8		0.1	3.7	
8	Fukaura	40°39′	139°56′	1.0	*A*	0.15	6.15	
					B	0.06	0.3	
9	Noshiro	40°13′	140°00′	1.2	*A*	0.15	10.4	
					B	0.07	0.24	
10	Oga	39°56′	139°42′	1.0		0.1	3.0	damper
11	Funakawa	39°53′	139°51′	1.2		0.15	5.0	
12	Sakata	38°55′	139°50′	1.2		0.15	21.0	pipe × 2
13	Iwafune	38°11′	139°26′	1.2	*A*	0.3	5.9	
					B	0.12	0.2	
14	Niigata	37°56′	139°04′	1.2		0.1	0.7	pipe × 2
15	Ryotsu	38°05′	138°26′	1.5		0.075	0.95	
16	Ogi	37°49′	138°17′	1.2		0.12	10.0	
17	Teradomari	37°39′	138°46′	0.6		0.05	4.8	
18	Kashiwazaki	37°22′	138°32′	1.2	*A*	0.3	7.8	
					B	0.12	0.2	
19	Naoetsu	37°11′	138°15′	1.0		0.2	2.0	
20	Toyama	36°46′	137°14′	1.2		0.15	6.0	
21	Nanao 1(old)	37°02′	136°58′	1.2		0.10	23.8	-1988, 3 bends
	Nanao 2(new)			1.2		0.08	0.875	1985-
22	Wajima	37°24′	136°54′	1.2		0.13	17.1	
23	Maizuru	35°28′	135°23′	1.2		0.2	4.7	obstacle
24	Hanasaki	43°17′	145°34′	1.0		0.1	5.2	
25	Kushiro	42°58′	144°23′	1.0		0.1	2.0	
26	Tokachi	42°17′	143°20′	1.2		0.1	2.8	
27	Urakawa	42°10′	142°46′	1.0		0.1	6.0	
28	Muroran	42°21′	140°57′	1.2		0.12	2.0	
29	Hachinohe	40°32′	141°32′	1.0		0.10	2.0	
30	Kuji	40°12′	141°49′	—		—	—	no pipe
31	Shimanokoshi	39°54′	141°56′	1.0		0.15	10	
32	Miyako	39°38′	141°59′	1.0		0.20	5.0	
33	Kamaishi	39°16′	141°54′	1.0		0.0763	3.0	
34	Oofunato	39°01′	141°45′	1.0		0.2	2.0	
35	Kesennuma	38°46′	141°35′	0.57		?	?	
36	Tsukihama	38°34′	141°27′	0.69		?	?	
37	Ayukawa	38°18′	141°31′	1.0		0.2	16.8	
38	Choshi	35°44′	140°52′	1.2		0.1	4.2	
39	Tokyo	35°39′	139°46′	1.0		0.1	2.0	
40	Omaezaki	34°36′	138°14′	1.2		0.1	2.4	

**A* and *B* in the pipe column indicates part *A* and *B*, respectively in the case of variable cross section intake.

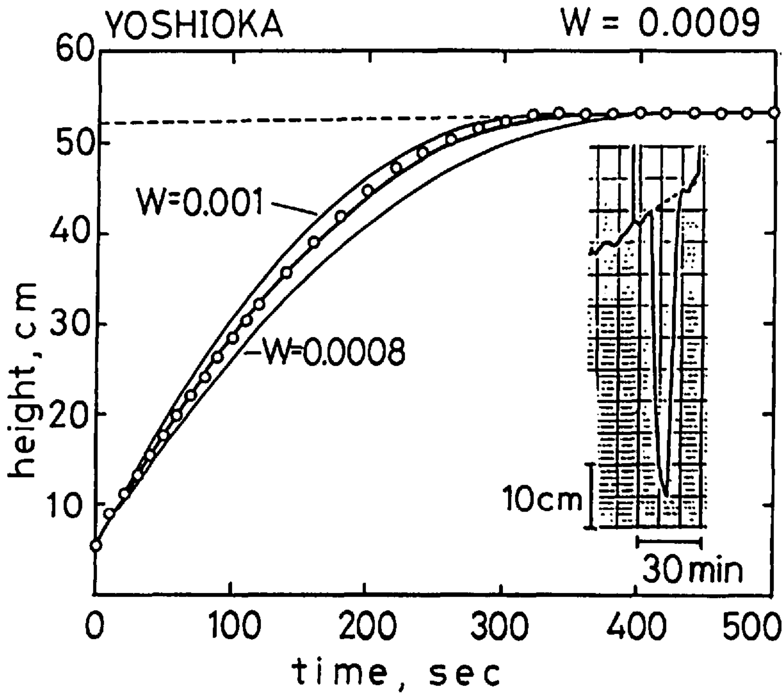

Figure 3. The temporal change of the water level inside the well after the water is drained from the well at Yoshioka. Computed curve for three different well constants are shown by solid lines. Dashed line is water level change outside the well estimated from the inset tide gauge record.

At each station, the water was drained from the well and poured into the well by using a small pump (750 Watt) or two. The intake pipe is not plugged because of the practical reason. After an artificial hydraulic head is created, we stop the pump and observe the following water level change. We directly measure $h(t)$ in every 3 to 10 seconds, rather than depend on the much less accurate tide gauge recorder; the paper speed of the recorder is generally 2 cm/hour and the scale is 1/10 or 1/20. Since the intake pipe is kept open, the maximum hydraulic head we could create was about 50 cm.

On the other hand, the water level $h(t)$ can also be computed by integrating (3) for a given value of W and can be compared with the observations. Thus, by a trial and error approach, we can estimate a best-fit value of W. The values of W estimated in this way and the corresponding T are referred as W_o and T_o, and distinguished from those theoretically calculated.

Figure 3 shows the water level change at Yoshioka after about 50 cm of the water was drained from the well. The following water level changes as a quadratic function of time. The temporal change of the water level outside the well, H, during the pouring or draining process was estimated from the tide gauge records obtained at the time of the measurement (inset of Fig. 3); H was assumed to be a simple linear function of time as shown by the dashed line in the figure. The water level inside the well, $h(t)$, can be computed by integrating (3) for given values of W and H. We use Runge-Kutta method to numerically integrate (3) for different trial values of W_o until we get a best-fit value by a visual inspection of the graph.

As an example of the trial and error procedure and the magnitude of error involved, three curves for different values of W are shown in Figure 3. The best-fit W_o is estimated to be 9×10^{-4}. If the value of W_o is changed by about 10%, it is clear that this results in a poorer fit. Therefore, the estimated error in W_o can be regarded as less than 10% at this station. We note that the recovery time T_o is relatively long for this station; as a consequence, the response can be estimated quite accurately. The error for other stations may be larger, so that we estimated that the error is less than 30% for any station.

At several stations, the response is very good. In such a case, since the intake pipe is kept open, it is difficult to create an artificial hydraulic head larger than a few cm and the recovery of water level is too quick to be observed accurately. The observable upper limit of W is about 5×10^{-3}, corresponding to the recovery time of 90 sec. We assign $W_o > 5 \times 10^{-3}$ or $T_o < 90$ sec for such stations. The recovery time after the drain test sometimes differs significantly from that after the pour test. When the difference is much larger than the estimation error, namely greater than 50%, we assign different estimates of W_o for inflow and outflow.

4. Computation of theoretical response

The well constant W or the recovery time T can also be estimated theoretically from the structure of the tide gauge system (Murakami, 1983); we will refer to those calculated values as W_c and T_c. The frictional coefficient F in (4) is a function of the tide gauge system structure, which we can group into 4 types (Fig. 4).

a. Single uniform intake. In the simple case shown in Figure 4(a), which applies to most of the stations, F can be given as

$$F = f_e + f\,l/d + f_o \tag{7}$$

where the pipe entrance loss $f_e = 0.5$, the pipe exit loss $f_o = 1.0$, the loss $f\,l/d$ is due to surface friction along a circular pipe of length l and diameter d, with

$$f = 8gn^2\,(4/d)^{1/3}, \tag{8}$$

where n is the Manning's roughness coefficient (e.g. Streeter, 1950). A Hume tube, constructed of concrete, is generally used for the intake pipe; $n = 0.013$ m$^{-1/3}$ s for this material (Murakami, 1983). The total loss is the same for inflow and outflow.

b. Multiple uniform intakes. At several stations, namely Esashi, Sakata and Niigata, two or four intake pipes connect the well with the outer sea as shown in Figure 4(b). In

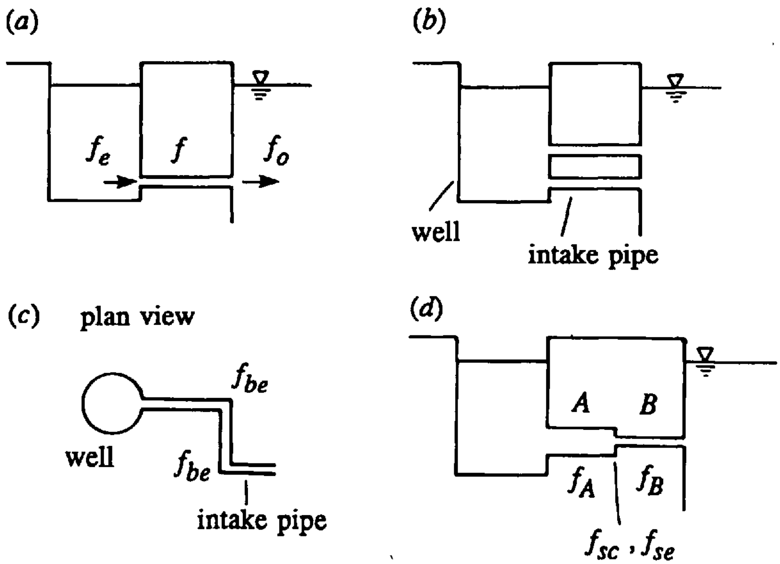

Figure 4. Representative structures of the tide gauge system. (a) single uniform intake, (b) multiple intake (c) bent intake, and (d) variable cross section intake.

this case, the frictional coefficient F can also be evaluated by (7), since F is a sum of the losses along a stream line. However, the equation of continuity is modified, so that the factor N, i.e. the number of pipes, appears in (2) and (4).

c. Bent intake. At Otaru and Nanao 1 (old one used until 1988; since 1985, new one has been used), intake pipe has several bends (Fig. 4c). In such a case, F can be computed as

$$F = f_e + f\,l/d + j f_{be} + f_o \tag{9}$$

where j is the number of bends and f_{be} is the loss at a bend. We assume that each bend is an elbow with right angle, and use $f_{be} = 0.99$.

d. Variable cross section intake. At Otaru, Esashi, Fukaura, Noshiro, Iwafune and Kashiwazaki, the diameter of the pipe is not constant (Fig. 4d). Because of severe winter weather along the Japan Sea coast, the pipe is narrowed down at the outer part to reduce unnecessary surf beats. Except Otaru where the diameter of the inner part is not known, we divide the intake pipe into two parts, A and B (Table 1), and evaluate the losses separately. Since a loss at a sudden contraction is different from that at a sudden expansion, the total loss is different for inflow and outflow. For inflow, F can be computed as

$$F = f_e + f_B \frac{l_B}{d_B} + f_{se} + \left(f_A \frac{l_A}{d_A} + f_o\right)\left(\frac{d_B}{d_A}\right)^2. \tag{10}$$

For outflow,

$$F = \left(f_e + f_A \frac{l_A}{d_A}\right)\left(\frac{d_B}{d_A}\right)^2 + f_{sc} + f_B \frac{l_B}{d_B} + f_o \qquad (11)$$

where subscripts A and B refer to part A and B, respectively, f_{se} is a loss due to a sudden expansion and f_{sc} is a loss due to a sudden contraction. Both values are function of d_B/d_A (e.g. Streeter, 1950). A damper inserted in the pipe, a net or other obstacle attached to the exit limits flow through the intake pipe of several other stations along the Japan Sea coast (Table 1). We do not attempt to account for such a effect.

5. Response at 40 tide gauge stations

The observed and computed tide gauge responses are compiled in Table 2. The calculated recovery time T_c ranges from 15 to 260 sec. The observed recovery time T_o, on the other hand, ranges from 65 to 1300 sec, significantly longer than T_c. These recovery times, T_o and T_c, are plotted in Figure 5. The different values of T_o for inflow and outflow are shown by different symbols. Since the difference in T_c for inflow and outflow is generally very small, as shown in Table 2, they are treated as one value in the figure. At Fukaura, the results of two measurements of T_o made in 1983 and 1986 are also shown. The recovery time T_o for inflow was 410 sec in November 1983 but it becomes 790 sec in June 1986, almost doubling in two and a half years.

Two lines indicating $T_o = T_c$ and $T_o = 10T_c$ are also shown in Figure 5. Most of the data fall between these two lines, meaning that the ratio T_o/T_c ranges between 1 and 10. Among those 12 stations where the recovery time is different for inflow and outflow, T_o for outflow is larger than that for inflow at 9 stations. There seems to be a tendency for fast inflow and relatively slow outflow. This is opposite to the standard

Table 2. The responses of tide gauge stations.

No	Station		W_c	T_c(sec)		W_o	T_o(sec)	Observed date	Remark*
1	Ishikari		1.0×10^{-2}	44		$>5 \times 10^{-3}$	<90	86. 9.17	
2	Otaru		3.5×10^{-3}	130	out	5.4×10^{-4}	840	86. 9.16	be
3	Oshoro		6.4×10^{-3}	71		2.8×10^{-3}	160	86. 9.16	
4	Iwanai		6.4×10^{-3}	70	in	3×10^{-3}	150	86. 9.18	
					out	2×10^{-3}	230		
5	Esashi	in	6.1×10^{-3}	74		5×10^{-3}	90	86 6. 9	se
		out	6.1×10^{-3}	74					sc
6	Yoshioka		2.7×10^{-3}	170	in	9×10^{-4}	500	86. 6. 9	
					out	5×10^{-4}	900		
7	Hakodate		8.8×10^{-3}	52	in	7.4×10^{-4}	610	86. 6. 8	
					out	1.7×10^{-3}	270		
8	Fukaura	in	2.6×10^{-3}	170		1.1×10^{-3}	410	83.11.10	se
		out	2.5×10^{-3}	180					sc
						5.7×10^{-4}	790	86. 6.10	

Table 2. (continued)

No	Station		W_c	T_c(sec)		W_o	T_o(sec)	Observed date	Remark*
9	Noshiro	in	2.3×10^{-3}	190	in	4×10^{-3}	110	86. 6.11	se
		out	2.2×10^{-3}	200	out	2×10^{-3}	230		sc
10	Oga		5.9×10^{-3}	76		4.3×10^{-4}	1100	86. 6.11	
11	Funakawa		9.3×10^{-3}	49		$>5 \times 10^{-3}$	<90	86. 6.12	
12	Sakata		1.2×10^{-2}	38	in	4×10^{-3}	110	86. 6.12	
					out	2×10^{-3}	230		
13	Iwafune	in	8.1×10^{-3}	56		1.1×10^{-3}	410	86. 6.13	se
		out	7.6×10^{-3}	59					sc
14	Niigata		1.0×10^{-2}	44		$>5 \times 10^{-3}$	<90	86. 6.13	
15	Ryotsu		1.7×10^{-3}	260	in	3.7×10^{-3}	120	87. 9.10	
					out	2.0×10^{-3}	230		
16	Ogi		4.4×10^{-3}	100		1.2×10^{-3}	380	87. 9.10	
17	Teradomari		2.6×10^{-3}	170	in	7.0×10^{-3}	65	87. 9. 9	
					out	4.5×10^{-3}	100		
18	Kashiwazaki	in	8.0×10^{-3}	57		1.2×10^{-3}	380	87. 9. 9	se
		out	7.6×10^{-3}	60					sc
19	Naoetsu		2.9×10^{-2}	15		1.0×10^{-3}	450	87. 9. 8	
20	Toyama		8.9×10^{-3}	51		1.1×10^{-3}	410	87. 9. 8	
21	Nanao 1		1.8×10^{-3}	250		1.1×10^{-3}	410	87. 9. 7	be
	Nanao 2		3.1×10^{-3}	150		$>5 \times 10^{-3}$	<90		
22	Wajima		4.4×10^{-3}	100	in	2.2×10^{-3}	210	87. 9. 7	
					out	1.5×10^{-3}	300		
23	Maizuru		1.8×10^{-2}	25	out	6.6×10^{-4}	680	84. 8.25	
24	Hanasaki		5.1×10^{-3}	89		3×10^{-3}	150	87. 7.30	
25	Kushiro		6.4×10^{-3}	70	in	2×10^{-3}	230	87. 7.29	
					out	3×10^{-3}	150		
26	Tokachi		4.2×10^{-3}	110	in	1.7×10^{-3}	270	87. 7.29	
					out	1.1×10^{-3}	410		
27	Urakawa		4.9×10^{-3}	93		1.2×10^{-3}	380	87. 7.28	
28	Muroran		6.7×10^{-3}	67	in	6.5×10^{-4}	700	87. 7.27	
					out	9.0×10^{-4}	500		
29	Hachinohe		6.4×10^{-3}	70		2×10^{-3}	230	87. 7.25	
30	Kuji		—	—		$>5 \times 10^{-3}$	<90	87. 7.24	
31	Shimanokoshi		1.1×10^{-2}	41		2×10^{-3}	230	87. 7.24	
32	Miyako		2.6×10^{-2}	17		$>5 \times 10^{-3}$	<90	87. 7.23	
33	Kamaishi		3.1×10^{-3}	140		8×10^{-4}	570	87. 7.23	
34	Oofunato		2.9×10^{-2}	15		$>5 \times 10^{-3}$	<90	87. 7.22	
35	Kesennuma		—	—		3.8×10^{-3}	120	87. 7.22	
36	Tsukihama		—	—		$>5 \times 10^{-3}$	<90	87. 7.21	
37	Ayukawa		1.9×10^{-2}	24		$>5 \times 10^{-3}$	<90	87. 7.21	
38	Choshi		3.8×10^{-3}	120		3.5×10^{-4}	1300	84. 3.22	
39	Tokyo		6.4×10^{-3}	70	in	4×10^{-3}	110	86. 8.28	
					out	2.4×10^{-3}	190		
40	Omaezaki		4.3×10^{-3}	110		$>5 \times 10^{-3}$	<90	85. 3. 6	

*be, se and sc in Remark mean that bend, sudden expansion and sudden contraction, respectively, are accounted for the computation of W_c and T_c.

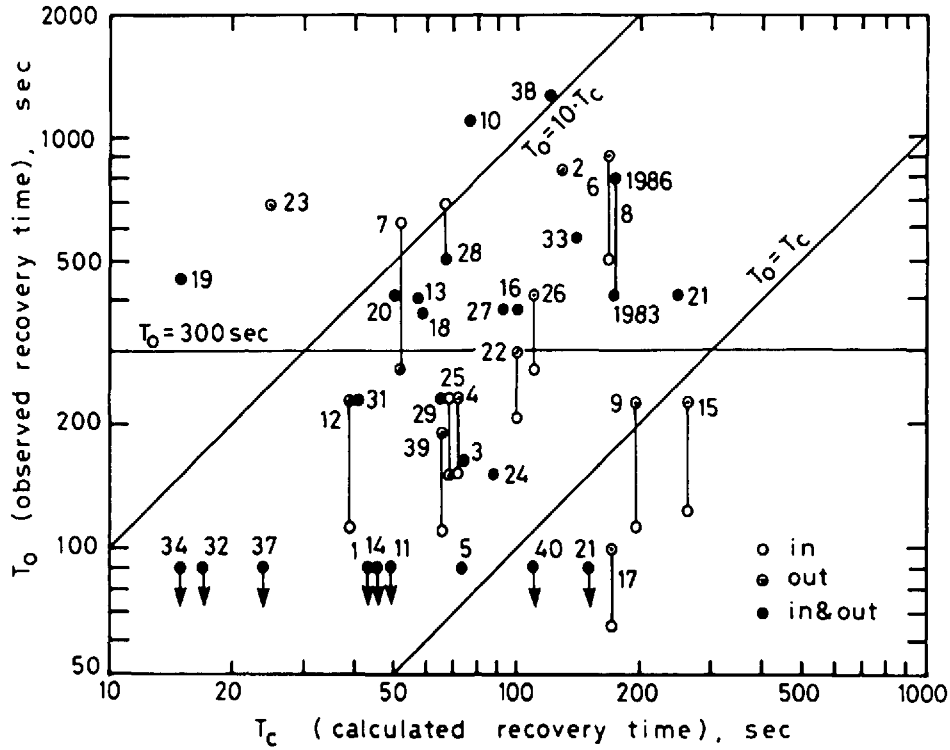

Figure 5. Comparison of the calculated and observed recovery times. The attached numerals are the station number. When T_o for the inflow and outflow differ by more than 50%, both are shown by different symbols. For Fukaura (No. 8), the results of the two measurements in 1983 and 1986 are shown.

U.S. stilling well tide gauge in which outflow is almost 20% faster than inflow (Cross, 1968; Loomis, 1983).

Tsunami periods are usually several to several tens of minutes. Since the calculated recovery time for a 1 m water level difference is less than 5 min at any station, the recorded tsunami waves would not be affected significantly by the tide gauge system if the actual response was equal to the computed response. However, the observed recovery time is longer than 5 min at about half of the stations. At such stations, the recorded tsunami waves must be considerably affected by the response of the tide gauge system, if the tsunami amplitude is large.

6. Correction of tsunami waveforms by the observed response

In this section, the waveforms outside the well are estimated by correcting the tide gauge records using the observed response. Tide gauge records of the 1983 Japan Sea earthquake tsunami were collected and digitized at an interval of 1 min, corresponding

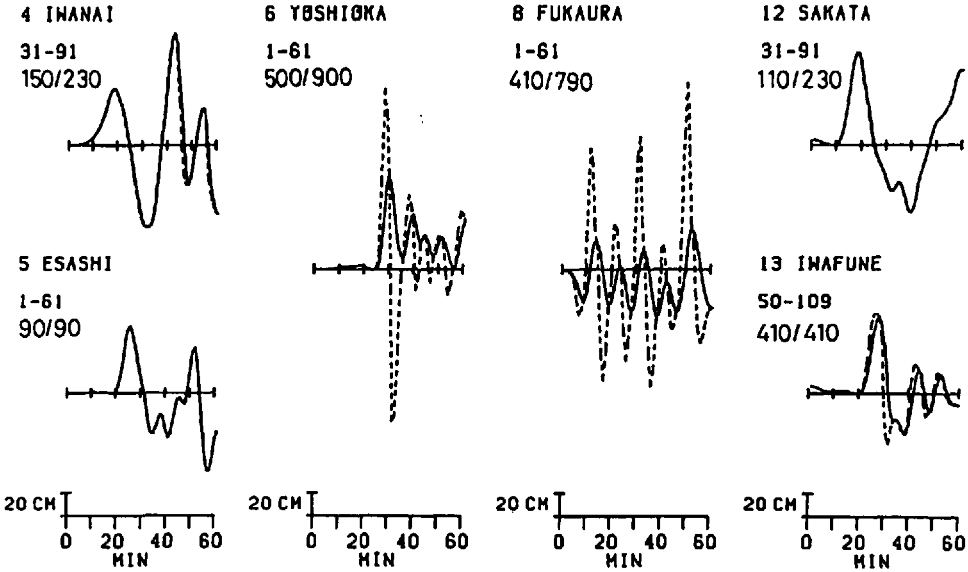

Figure 6. The tide gauge records of the 1983 Japan Sea earthquake tsunami (solid trace) and the corrected waveforms for the tide gauge response (dashed trace). In the station labels, top is the station number and the name, middle is the time range in min from the origin time of the earthquake, and the bottom is the inflow T_o/outflow T_o.

to 1/30 cm in the tide gauge records. To reduce digitization errors, which are unavoidable because of the slow paper speed, a Hanning window was applied three times to the digitized time series. This operation is a kind of low-pass filtering; as a result, components with periods shorter than 4 min are reduced to less than 10% of the original amplitude (Blackman and Tukey, 1958). The waveforms were then corrected for the tide gauge response by using (5). If the well constant, W, is different for inflow and outflow, the different value is used depending on the sign of dh/dt in (5).

Figure 6 shows the original (solid curves) and corrected (dashed curves) waveforms at 6 tide gauge stations. Original and corrected waveforms almost coincide at Iwanai, Esashi and Sakata. At these stations, the observed recovery time T_o is less than 5 min. The effect of tide gauge response is not significant at such stations. The corrected waveforms differ from those recorded at Yoshioka, Fukaura and Iwafune, where T_o is longer than 5 min.

At Fukaura, the amplitude of the corrected waveform is significantly larger than the original. Further, the amplitude of the third peak at about 30 min, which was smaller than the first peak at 15 min in the original waveform, becomes larger than the first peak in the corrected waveform. The maximum amplitude is about 1.5 m, which is consistent with the inundation height at this station (JMA, 1984). At Yoshioka, the amplitude of the first cycle is significantly increased by the correction for the tide gauge response, and the first trough, which was positive in the recorded waveform, becomes negative in the corrected waveform. The abnormal shift to the positive side in the original waveform is due to the response of the tide gauge system. The maximum amplitude becomes 1.5 m, also consistent with the inundation height at this station (Kinoshita *et al.*, 1984).

Eq. (5) shows that the correction term is proportional to the square of dh/dt, i.e., temporal change of the water level inside the well, and is inversely proportional to the square of W, the well constant. This means that the correction is larger for a shorter tsunami period or a smaller well constant. The well constants are smaller, or the recovery times are longer at Yoshioka and Fukaura than other stations. Furthermore, the tsunami periods are shorter at these stations, because of the short distance from the source area (Fig. 2) and the deep propagation path. These facts qualitatively explain the large discrepancies between the originals and the corrected waveforms. We also made the correction of the tsunami waveforms by using the computed tide gauge response, W_c. The results show that at all the stations the corrected waveforms agree very well with the originals, indicating that the correction by using W_c is insignificant. Therefore, the discrepancy between the observed and corrected responses, between factor 1 and 10, is a considerable problem. The error of the estimating W_o, at maximum 30%, might be negligible comparing with it.

7. Discussion

Discrepancies between calculated and observed responses might be due to environmentally-induced changes in the tide gauge system. Attachment of shells or deposition of sediments can clog the intake pipe and alter the effective diameter or surface roughness. The temporal change in response revealed by a repeated measurement at Fukaura is evidence for this. As stated before, the recovery time roughly doubled in two and a half years. Nothing besides the environmental change causes this temporal change of T_o.

The different response for inflow and outflow is also due to the environmental change. As can be seen in Table 2, the recovery times for inflow and outflow are not so different according to the theoretical computations. However, the observed recovery time sometimes differs very much for inflow and outflow as shown in Table 2 and Figure 5. Shells or sediments in the intake pipe might also create different effective diameters for inflow and outflow.

The actual tsunami height is estimated by correcting the tide gauge records for the observed response. The amplitude and waveform change significantly at those stations where the observed recovery time is longer than 5 min. Thus for such stations, the response correction is essential. Since the response can apparently vary with time, it is also desirable to make *in situ* measurements periodically. A more suitable tide gauge system for tsunami would be characterized by a short recovery time and a digital recording system. A tsunami gauge instead of tide gauge (Curtis, 1986) is desirable for tsunami problems such as quantification of tsunamis or operational warning system. It is also important for earthquake source problem since tsunami has a potential advantage for a study of seismic source because the propagation effects can be more accurately evaluated than seismic waves (Satake, 1987).

8. Summary

In this paper, the response of tide gauge systems at 40 Japanese tide gauge stations is measured and compared with theoretically computed values. The observed recovery time for a 1 m water level difference is generally longer than the computed time, and the ratio ranges from 1 to 10. This is attributed to environmentally-induced changes occurring after construction of the system. The response seems to change with time. At stations where the observed recovery time is longer than 5 min, the amplitude and waveform of tsunami can be seriously distorted; in such a case, corrections for the tide gauge response are essential.

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