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EVALUATION OF TSUNAMI STRENGTHS OF HOUSES SUBJECTED TO A TSUNAMI WAVE LOAD

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Abstract: The damage of confined-masonry-brick and concrete-block houses is assessed subjected to a tsunami wave load due to the recent three earthquakes and tsunamis at the 2001 Near Coast of Peru, the 2009 Samoa Islands, and the 2010 Maule, Chile. We analyze 13 data surveyed for affected houses, which are single-storey ones located along the coastlines, focusing on the evaluation of tsunami wave pressure distribution on a house inferred by various failure modes when subjected to an inundation depth. Based on the related formula by Asakura et al. (2000) hydraulic experimental results, we identify the required tsunami strength of a wall which is not suffered with an inundation depth.

1. INTRODUCTION

Recent severe earthquakes and tsunamis in the world cause many fatalities and missing: the 2001 Near Coast of Peru, June 23 (UTC 20:33:14, M_W=8.4) (2001 Peru tsunami), the 2004 Sumatra, Indonesia, Dec.26 (UTC 00:58:53, M_W=9.1) (2004 Indian Ocean tsunami), the 2006 South of Java, Indonesia, July 17 (UTC 08:19:28, M_W=7.7) (2006 Java tsunami), the 2009 Samoa Islands, Sept. 29 (UTC 17:48:10, M_W=8.1) (2009 Samoa tsunami) and the 2010 Maule, Chile, Feb.27 (UTC 06:34:14, M_W=8.8) (2010 Chile tsunami) as well as the Great East Japan earthquake and tsunami occurred on March 11, 2011 in Japan (UTC 05:46:24, M_W=9.0) (2011 Japan Tohoku tsunami). The reason of the catastrophe is that houses located within few kilometers from a coastline are suffered severely by a tsunami wave. Therefore it is very essential to clarify the mechanism of a tsunami wave load acting on a structural component of a house, based on the tsunami damage assessment for suffered houses.

Matsutomi and Izuka (1998) propose the simple formulation to derive the tsunami fluid velocity on a house, based on the results of hydraulic experiments. Matsutomi et al. (2004) clarify the dependence of tsunami fluid force on a house on hydraulic quantity such as a drag coefficient. Asakura et al. (2000) propose the formula (Asakura formula) to evaluate tsunami wave pressure distribution on a structure located at the land behind on-shore structures and this formula is used for designing a tsunami evacuation building (Japanese Cabinet Office 2005). Shoji et al. (2007) discuss validness of Asakura formula from damage assessment for suffered houses at the 2006 Java tsunami. Regarding the research on development of tsunami damage functions of structures, Matsutomi and Shuto (1994) reveal relations between the inundation depths and velocities, and damage ranks of suffered houses. Koshimura et al. (2009) propose the methodology to develop tsunami damage functions by using tsunami damage data from remote sensing, field survey and numerical analysis.

From the reason above, we analyze the tsunami damage data of confined-masonry-brick and concrete-block houses affected by the 2001 Peru tsunami, the 2009 Samoa tsunami and the 2010 Chile tsunami. Based on the Asakura formula, we identify the required tsunami strength of a wall which is not suffered with an inundation depth.

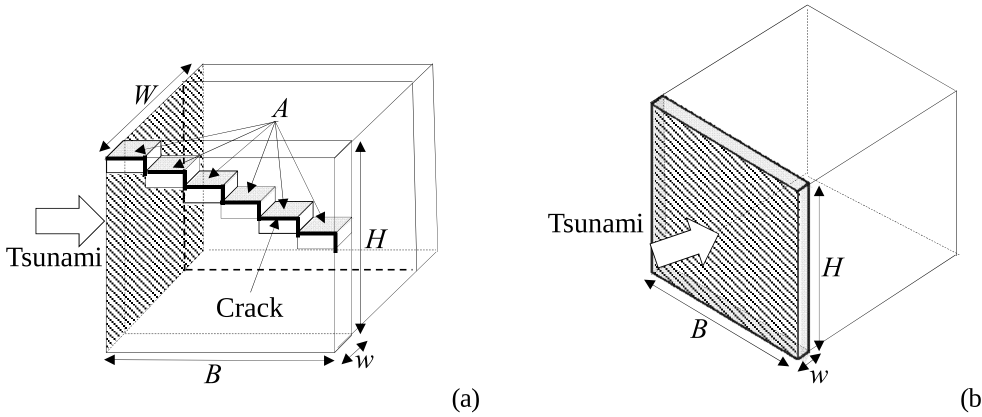
2. SUBJECT EARTHQUAKE TSUNAMIS AND STRUCTURES

We use the investigation data on damage of concrete-block houses at the 2001 Peru tsunami (Tani et al. 2010) (Peru data), data on damage of lifeline systems and confined-masonry-brick houses at the 2009 Samoa tsunami (Miyajima et al. 2009) (Samoa data) and data on damage of confined-masonry-brick houses at the 2010 Chile tsunami (Shoji et al. 2010) (Chile data). Walls in suffered houses are analyzed. Among all survey data we select houses for the analysis which are single-storey ones located along the coastlines and do not affected by floating debris as well as by seismic excitations. It means that houses for the analysis have no crack at joint parts of beams and columns, and related structural components such as a beam, a column and a wall get damaged dominantly due to a tsunami wave load.

Table 1 shows height H, width B and thickness w of subject wall. In addition Table 1 shows inundation depths h

Table 1 Height, Width and Thickness of Subject Wall and Related Observed Inundation Depth
(‘p’ denotes Peru, ‘s’ denotes Samoa and ‘c’ denotes Chile respectively)

House's number※	Wall's number	Latitude	Longitude	Wall's height *H* [m]	Wall's width *B* [m]	Wall's thickness *w* [m]	Inundation depth *h* [m]	References for inundation depths
p1	p1	S16°39'19.6"	W72°40'35.1"	2.35	3.50	0.16	2.60	Inundation depth measured 3.3km in the nearest direction (Tani et al., 2010)
p2	p21	S16°39'31.8"	W72°38'45.3"	2.60	3.20	0.16	2.60	Inundation depth mesured in the house (Tani et al., 2010)
	p22			2.60	3.60	0.15	2.60	
p3	p3	S16°39'36.0"	W72°38'04.7"	0.65	4.95	0.16	2.13	Inundation depth obtained near the investigation spot(Koshimura, 2001)
p4	p4	S16°39'35.9"	W72°37'59.9"	2.20	3.30	0.16	2.13	Inundation depth obtained near the investigation spot(Koshimura, 2001)
p5	p5	S16°39'35.8"	W72°37'57.2"	2.50	2.80	0.16	2.28	Inundation depth masured in the house (Tani et al., 2010)
s1	s11	S14°15'06.7"	W170°33'53.5	2.00	2.53	0.15	2.55	Inundation depth measured at the front wall in subject house(Miyajima et al., 2009)
	s12			2.03	3.96	0.15	2.55	
s2	s21	S14°15'15.5"	W170°33'51.9"	1.80	2.68	0.15	2.55	Inundation depth measured 0.3km in the nearest direction(Miyajima et al., 2009)
	s22			1.80	2.16	0.15	2.55	
c1	c1	S36°33'9.69"	W72°57'25.33"	2.33	3.82	0.15	0.97	Inundation depth measured at the side wall in subject house(Shoji et al., 2010)
c2	c2	S36°32'14.89"	W72°57'32.42"	2.07	1.35	0.15	0.81	Inundation depth measured at the side wall in subject house(Shoji et al., 2010)
c3	c3	S36°44'48.72"	W73°5'3.57"	2.67	2.90	0.15	1.00	Inundation depth measured at the side wall in subject house(Shoji et al., 2010)



(a) (b)

Figure 1: Relation between Direction of a Tsunami Wave and Longitudinal Axis of Subject Wall: (a) Paired Walls placed at Right Angles to a Coastline, and (b) Wall out of Placed along a Coastline

and the related references. Height *H*, width *B* and thickness *w* of subject wall are basically from Peru, Samoa and Chile survey data. When the related data are lacked, we detect those parameters by analyzing the digital pictures for subject walls.

3. COMPUTATION OF TSUNAMI STRENGTHS OF SUBJECT WALLS

3.1 Calculation of Tsunami Strengths

As shown in Figure 1(a), when shear cracks occur in paired walls which are placed at right angles to a coastline, we classify the failure mode of a wall as type1 failure mode (hereinafter ty1). Shear strength of a wall with ty1 V_1 is calculated as the following equation, by setting $W=W/2$ when adapting Asakura formula,

$$V_1 = \tau_1 A \tag{1}$$

Table 2 Computed Ty1 Shear Strength V_1 ,Ty2 Tensile Strength T_2 and Ty2 Shear Strength V_2 , and the Parameters related with Tsunami Wave Pressure on Subject Wall

Wall's number	Failue mode number	Tensile stress [kN]	Shear stress [kN]	***η′***	***a***
p1	p1-ty2-m1	449.28	-	6.75	2.60
	p1-ty2-m2	-	168.48	3.26	1.25
p21	p21-ty2-m1	445.44	-	6.76	2.60
	p21-ty2-m2	-	167.04	3.35	1.29
p22	p22-ty1	-	108.00	2.77	1.07
	p22-ty2-m1	446.40	-	6.16	2.37
	p22-ty2-m2	-	167.40	3.12	1.20
p3	p3-ty2-m1	215.04	-	7.14	3.35
	p3-ty2-m2	-	80.64	2.88	1.35
p4	p4-ty1	-	105.60	2.66	1.25
p5	p5-ty2-m1	407.04	-	7.18	3.15
	p5-ty2-m2	-	152.64	3.47	1.52
s11	s11-ty2-m1	326.16	-	7.57	2.97
	s11-ty2-m2	-	122.31	3.46	1.36
s12	s12-ty2-m1	431.28	-	6.49	2.55
	s12-ty2-m2	-	161.73	3.06	1.20
s21	s21-ty2-m1	322.56	-	7.72	3.03
	s21-ty2-m2	-	120.96	3.46	1.36
s22	s22-ty2-m1	218.88	-	8.38	3.29
	s22-ty2-m2	-	82.08	3.70	1.45
c1	c1-ty2-m1	442.80	-	6.23	6.77
	c1-ty2-m2	-	166.05	3.07	3.34
c2	c2-ty1	-	70.88	3.57	4.41
c3	c3-ty1	-	152.25	5.12	5.12

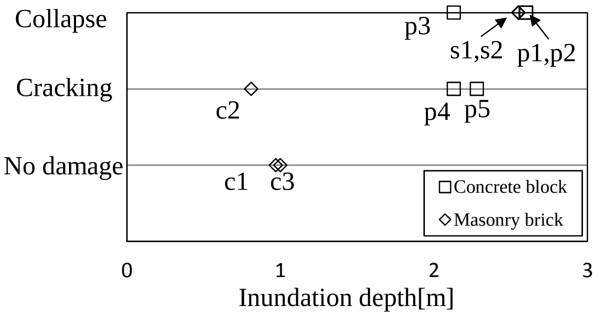


Figure 2 Relation between Inundation Depth and Damage Rank of Subject Wall

where A is cumulative surface areas of bricks and concrete-blocks with shear cracks, since a wall is made by bonding bricks and concrete-blocks with mortar. In Eq. (1) τ_1 is shear stress and we set the value of τ_1 based on the following procedure by referring the value of 0.4 N/mm^2 by previous research (Nakano 2005, Nakano and Park 2005a, 2005b). For dealing with Peru data (concrete-blocks) τ_1 is assumed to be 0.2N/mm^2 which is 1/10 of compression strength of a concrete-block used for a non-proof-strengthening wall (Ministerio de Vivienda, Republica del Peru 2006). For dealing with Chile data (masonry-bricks) τ_1 is assumed to be 0.35N/mm^2, which is conservative value, and is 1/20 of compression strength of a brick used for a prism-type wall specimen (Yanez et al. 2004).

As shown in Figure 1(b), when tensile and shear failures occur out of a wall placed along a coastline, we classify the failure mode of a wall as type 2 failure mode (hereinafter ty2). Ty2 is classified into two mechanisms: tensile failure between bricks and concrete-blocks bonded with a frame by mortar (mechanism 1; ty2-m1) and shear failure between those (mechanism 2; ty2-m2).

We calculate tensile strength T_2 and shear strength V_2 by the following equations, by setting $W = B$ when adapting Asakura formula,

$$T_2 = 2\left(B + H\right) w \sigma_2 \tag{2a}$$

$$V_2 = 2\left(B + H\right) w \tau_2 \tag{2b}$$

where σ_2 is tensile stress between bricks and concrete-blocks bonded with a frame by mortar, and we use the value of σ_2=0.24N/mm^2 by referring Architectural Institute of Japan Standard Specifications for Concrete-Block Structures (1997). τ_2 is shear stress between bricks and concrete-blocks bonded with a frame by mortar, which value is assumed to be 0.09N/mm^2 from the

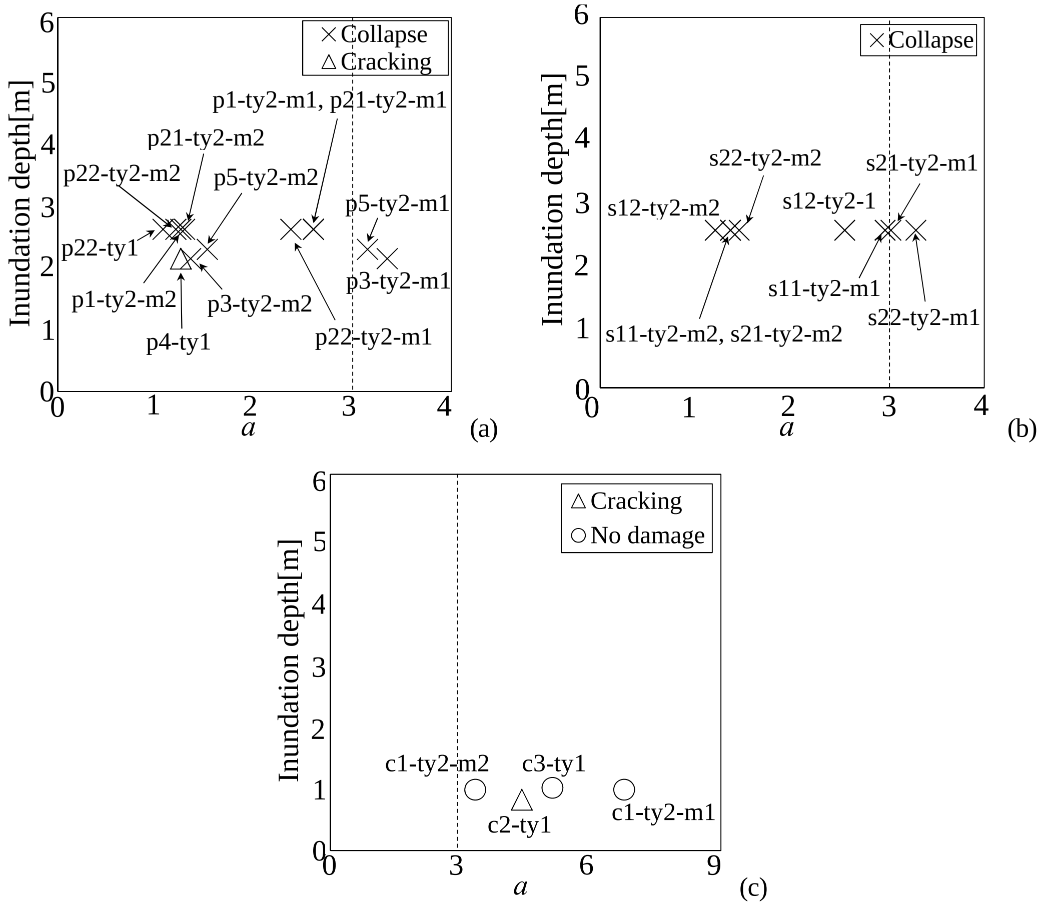


Figure 3 Relation between Computed Horizontal Wave Pressure Index a and Observed Inundation Depth h for Peru, Samoa and Chile Data:
(a) Peru Data, (b) Samoa Data, and (c) Chile Data

research by Sanada et al. (2006).

3.2 Results on Tsunami Strengths

Table 2 shows results of ty1 shear strength V_1, ty2 tensile strength T_2 and ty2 shear strength V_2, and the parameters related with tsunami wave pressure on subject wall as we mention later.

Wall p1 failure mode is assumed to be ty2 since p1 failed out of the plane. Based on ty2-m1, T_2=2×(2350mm+3500mm)×160mm×0.24N/mm^2=449.28 kN, while based on ty2-m2, V_2=2×(2350mm+3500mm)× ×160mm×0.09N/mm^2=168.48kN. Similarly, wall p21 failure mode is assumed to be ty2 since most part of it was collapsed in the same failure modes as wall p1. Hence, for p21 T_2 and V_2 are computed respectively as shown in Table 2. In contrast, wall p22 is placed at right angles to the coastline in the same house as wall p21, then the failure mode is assumed to be ty1. Based on ty1 for wall p22 V_1=0.2N/mm^2×3600mm×150mm=108.00kN. On the other hand we can suppose wall p22 failed out of the plane after the tsunami flow attacking wall p21. Viewed in this light wall p22 failure mode is assumed to be ty2, and the related values of T_2 and V_2 are computed as shown in Table 2. Wall p3 failure mode is assumed to be ty2 since most part of it was collapsed as well as wall p1. By considering wall p3 boundary conditions as upper and one side boundaries are free, we compute T_2 and V_2 by modified Eq (2a) and (2b): $T_2 = (B + H)w\sigma_2$ and $V_2 = (B + H)w\tau_2$ as shown in Table 2. In the same way, for rest of Peru data (p4, p5), Samoa data (s11, s12, s21, s22) and Chile data (c1, c2, c3), the related wall failure modes are classified into ty1 and ty2, and we compute V_1, T_2 and V_2 as shown in Table 2.

4. TSUNAMI WAVE PRESSURE DISTRIBUTION ON SUBJECT WALLS

4.1 Relation between Inundation Depth and Damage Rank

Figure 2 shows relation between observed inundation depth and damage rank of subject wall. We categorize wall damage into three damage ranks: completely and mostly collapse (collapse), partially collapse and occurrence of cracks (cracking), and no structural damage (no damage). Damage ranks of ‘collapse’ and ‘cracking’ for concrete-block houses (Peru data) show in the range of inundation depth from 2.13m to 2.60m. Damage ranks of ‘no damage’ and ‘cracking’ for masonry-brick houses (Samoa and Chile data) show with inundation depth from 0.81m to 1.00m, and damage rank of ‘collapse’ with

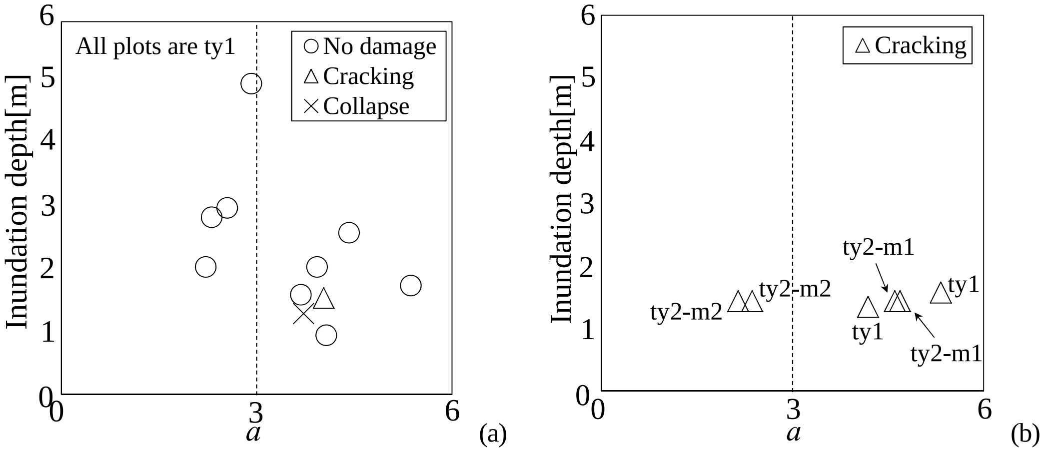


Figure 4 Relation between Computed Horizontal Wave Pressure Index a and Observed Inundation Depth h for Sri Lanka and Thailand Data (Nakano et al. 2005), and Java Data (Shoji et al. 2007):
(a) Sri Lanka and Thailand Data, and (b) Java Data

inundation depth of 2.55m.

4.2 Evaluation of Tsunami Wave Pressure Distribution based on Observed Inundation Depth

Tsunami wave pressure distribution on subject wall in horizontal direction is computed by the following Asakura formula (Asakura et al. 2000),

$$p_x(z) = \rho g(a\eta_{\max} - z) \tag{3}$$

where $p_x(z)$ is horizontal wave pressure, $\eta_{\max}$ is maximum run-up height, ρ is density of mass of sea water in a unit volume and z is height from ground level. a is defined as horizontal wave pressure index which means magnification factor of hydrodynamic pressure on a rigid body due to a tsunami wave compared with hydrostatic pressure with $\eta_{\max}$. Asakura et al. indicate $a = 3.0$ for a non-breaking wave from their experimental results. Therefore it indicates that assumption of $a \geq 3.0$ is required theoretically to design a tsunami-proof structural component subjected to a non-breaking tsunami wave. To put it another way in case by subjecting by a non-breaking tsunami wave, horizontal wave pressure distribution of $a = 3.0$ on a structural component is the border that a structural component becomes whether damaged or undamaged.

In this study firstly we suppose ty1, ty2-m1 and ty2-m2 failure modes defined in Section 3.1 for subject walls exposed to a tsunami wave and calculate the corresponding tsunami strength R (including ty1 shear strength V_1, ty2 tensile strength T_2 and ty2 shear strength V_2). Second we compute inversely the value of a as the following equations by assuming $\eta_{\max}$ equal to be observed inundation depth h. By comparing the value of a with tsunami damage of subject walls, we discuss validness of Asakura formula.

$$a = \frac{1}{h}\sqrt{\frac{2R}{\rho g W}} \tag{4a}$$

$$a = \frac{1}{2h}\left(\frac{2R}{\rho g W H} + H\right) \tag{4b}$$

where W is width of a wall subjected to a tsunami wave as shown in Figure 1. When the value of $\eta' = a\eta_{\max}$ is less than or equal to a wall height H, horizontal wave pressure distribution is the triangle one and a is computed by Eq (4a). When the value of $\eta' = a\eta_{\max}$ is more than a wall height H, horizontal wave pressure distribution is the trapezoid one and a is computed by Eq (4b).

Table 2 also shows computed η' and a. Figure 3 shows relation of a with observed inundation depth h. Similarly, Figure 4 shows the results for Sri Lank and Thailand data at the 2004 Indian Ocean tsunami by Nakano et al. (2005) and Java data at the 2006 Java tsunami by Shoji et al. (2007) as well as in Figure 3, with showing the analytical results corresponding to ty1 and ty2 failure modes for subject walls.

From Figure 3(a) among Peru data 10 data with $a \leq 3.0$ are observed. a shows 1.07~2.60 for inundation depth h of 2.13m~2.60m, which indicates Asakura formula is valid in these cases because these walls are actually suffered with the damage rank of either ‘collapse’ or ‘cracking’. On the other hand among Peru data 2 data with $a > 3.0$ are observed, showing the collapse: 3.35 with h of 2.13m and 3.15 with h of 2.28m. It is inferred from these data that when the value of a is slightly larger than 3.0, a wall has low possibility to actually collapse due to variation of strength of material properties and construction condition when fabricating a wall. For Samoa data (Figure 3(b)) 6 data with $a \leq 3.0$ are observed, showing 1.20~2.97 with h of 2.55m. These walls collapse actually, the reason is why Asakura formula is valid in these cases. In addition 2 data with $a > 3.0$ are observed as well as for Peru data: 3.03 and 3.29 with h of 2.55m. These walls also collapse although $a > 3.0$. From Figure 3(c) Chile data has 4 data with $a > 3.0$: they show 3.34~6.77 with h of 0.81m~1.00m. Among them we can say Asakura formula may be valid because 3 data have no damage although one data shows cracking.

When walls with a of slightly larger than 3.0 in Peru and Samoa data are assumed to be suffered by ty2-m2, a becomes less than or equal to be 3.0. It is quite likely that these walls actually collapsed with a failure mode by not ty2-m1 but ty2-m2.

By comparing Figure 3(a), (b) with Figure 4(a), no data with $a \le 3.0$ showing no damage in Peru and Samoa data are observed whereas 4 data with $a \le 3.0$ showing no damage in Sri Lanka and Thailand data are observed. In contrast, Sri Lanka and Thailand data have one data with collapse regardless of $a > 3.0$ as well as Peru and Samoa data. By comparing Figure 3(c) with Figure 4(b), as we mentioned above, there are one data with $a > 3.0$ showing cracking with ty1 failure mode in Chile data as well as two data in Java data, which a especially show 4.19~5.33. Therefore it is possible that a wall with a of around 4~5 beyond $a = 3.0$, that has larger tsunami strength, suffers with cracking failure mode due to a tsunami wave.

5. CONCLUDIONS

We analyzed the tsunami damage data of confined-masonry-brick and concrete-block houses affected by the 2001 Peru tsunami, the 2009 Samoa tsunami and the 2010 Chile tsunami. We classified them into three failure modes of a wall subjected to a tsunami wave: shear cracks induced in paired walls which are placed at right angles to a coastline (ty1), tensile failure induced out of a wall between bricks and concrete-blocks bonded with a frame by mortar (ty2 mechanism 1) and shear failure induced out of a wall between those (ty2 mechanism 2). Based on the formula proposed by Asakura et al. (2000) (Asakura formula) to evaluate tsunami wave pressure distribution on a structure located at the land behind on-shore structures, used for designing a tsunami evacuation building (Japanese Cabinet Office 2005), by assuming 24 failure modes for subject 13 walls, we identified the required tsunami strength of a wall which is not suffered with an inundation depth. Following conclusions were deduced.

(1) 16 data with $a \le 3.0$ show collapse and cracking failure modes, and 3 data with $a > 3.0$ show no damage among 24 assumed failure modes. Hence from these results, Asakura formula is almost valid to evaluate tsunami strength of a wall subjected to a non-breaking tsunami wave.

(2) When subject walls with a of slightly larger than 3.0 (3.03~3.35) in Peru and Samoa data are assumed to be suffered by ty2 mechanism 2, a becomes less than or equal to be 3.0. It is quite likely that these walls actually collapsed with failure mode by not ty2 mechanism 1 but ty2 mechanism 2.

(3) One data with $a > 3.0$ showing cracking with ty1 failure mode in Chile data is observed as well as two data in Java data, which a especially show 4.19~5.33. Therefore it is possible that a wall with a of around 4~5 beyond $a = 3.0$, that has larger tsunami strength, suffers with cracking failure mode due to a tsunami wave.

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