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Paper:

Evaluation of Tsunami Wave Loads Acting on Walls of Confined-Masonry-Brick and Concrete-Block Houses

Gaku Shoji[*1], **Hirofumi Shimizu**[*2], **Shunichi Koshimura**[*3], **Miguel Estrada**[*4], **and Cesar Jimenez**[*5]

[*1]Division of Engineering Mechanics and Energy,
Faculty of Engineering, Information and Systems, University of Tsukuba
1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan
E-mail: gshoji@kz.tsukuba.ac.jp
[*2]Formerly, Graduate School of Systems and Information Engineering, University of Tsukuba, Japan
[*3]International Research Institute of Disaster Science, Tohoku University, Sendai, Japan
[*4]Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID)
National University of Engineering, Lima, Peru
[*5]Fenlab, Universidad Nacional Mayor de San Marcos (UNMSM), Lima, Peru

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Damage to confined-masonry-brick or concrete-block house was assessed for being subjected to a tsunami wave load. This study was prompted by recent three tsunamis – one during 2001 on the Near Coast of Peru, one in 2009 in the Samoa Islands, and one in 2010 in Maule, Chile. We analyzed 13 damaged walls from 10 single-storey houses located near the coastline. We focused on evaluating the tsunami wave pressure distribution on house walls. Based on the formula proposed by Asakura et al. (2000) to evaluate tsunami wave pressure distribution on a structural component located on land behind on-shore structures, which is used for designing a tsunami evacuation building, we identify the values of horizontal wave pressure index *a* in Asakura's formula for walls and discuss the boundary value of *a* at which a wall presents structural damage, such as in collapse and cracking failure modes.

Keywords: tsunami wave load, confined-masonry-brick house, concrete-block house, wall, horizontal wave pressure index

1. Introduction

Severe earthquakes and tsunamis have caused fatalities and left victims missing. Such incidents include the 2001 Near Coast of Peru tsunami on June 23, 2001 (UTC 20:33:14, $M_w = 8.4$), known as the 2001 Peru tsunami; the 2004 Sumatra, Indonesia, tsunami on Dec. 26, 2004 (UTC 00:58:53, $M_w = 9.1$) known as the 2004 Indian Ocean tsunami; the 2006 South of Java, Indonesia, tsunami on July 17, 2006 (UTC 08:19:28, $M_w = 7.7$) known as the 2006 Java tsunami; the 2009 Samoa Islands tsunami on Sept. 29, 2009 (UTC 17:48:10, $M_w = 8.1$) known as the 2009 Samoa tsunami; the 2010 Maule, Chile, tsunami on Feb. 27, 2010 (UTC 06:34:14, $M_w = 8.8$) known as the 2010 Chile tsunami; and the Great East Japan earthquake and tsunami on March 11, 2011 (UTC 05:46:24, $M_w = 9.0$) known as the 2011 Japan Tohoku tsunami.

One of the results that these catastrophes occurred is that houses located within a few kilometers of the coastline were severely damaged by tsunami waves. It is necessary to clarify the mechanism of tsunami wave load acting on structural housing components based on the tsunami damage assessment of damaged houses.

Matsutomi and Izuka [1] proposed a simple formulation to derive tsunami fluid velocity in front and the rear of a house based on hydraulic experiment results. Matsutomi et al. [2] clarified the dependence of tsunami fluid force acting on a house upon hydraulic quantity of tsunami fluid such as drag coefficient. Asakura et al. [3] also proposed the following formula based on an analysis of their experimental results (hereinafter, Asakura's formula) to evaluate tsunami wave pressure distribution on structural components located on land behind on-shore structures:

$$p_x(z) = \rho g\,(a\eta_{\max} - z) \quad \dots\dots\dots\dots \quad (1)$$

$p_x(z)$ is the horizontal x-axis wave pressure on a structure, $\eta_{\max}$ is the maximum run-up height, ρ is the density of the sea-water mass in a unit volume, and z is the height above the ground level. a is defined as the horizontal wave pressure index, which means the magnification factor of hydrodynamic pressure on a rigid body due to a tsunami wave as compared to hydrostatic pressure with $\eta_{\max}$. Asakura's formula indicates $a = 3.0$ for the structure, located on land behind on-shore structures and subjected to a nonbreaking wave for which Froude number F_r becomes more than or equal to 1.5. Asakura's formula is used for designing tsunami evacuation buildings [4], and it must be verified for explaining recent tsunami damage to houses. Nakano [5, 6] showed validity of Asakura's formula based on damage assessment for damaged houses in Sri Lanka and Thailand in the 2004 Indian Ocean tsunami.

Shoji et al. [7] used the same approach as Nakano for assessing damage to houses from Pangandaran to the east part of Cilacap on Java Island in the 2006 Java tsunami.

In researching the development of tsunami damage functions for structures by using empirical damage data, Matsutomi and Shuto [8] demonstrated the relationship between inundation depth and velocity and the damage rank for houses damaged in the 1993 Hokkaido-Nanseioki tsunami. Koshimura et al. [9] demonstrated methodology for developing tsunami damage functions by using tsunami damage data from remote sensing, field surveys, and numerical analysis. To enhance accuracy in predicting structural damage to houses by using the tsunami damage functions proposed above, the association of the formula describing tsunami wave pressure on a structural component, such as that used in Asakura's formula, as this is related to tsunami damage functions, is needed. The formula must also be further validated for recent tsunami house damage based on empirical data.

From the reasons above, we analyzed tsunami damage data on confined-masonry-brick and concrete-block houses damaged by the 2001 Peru tsunami, the 2009 Samoa tsunami, and the 2010 Chile tsunami. Based on Asakura's formula, we identify the values of horizontal wave pressure index a for the damaged walls of selected houses and describe tsunami wave pressure distribution on a wall by using the tsunami wave load. We also discuss the boundary value of a at which a wall shows structural tsunami damage such as that seen in collapse and cracking-failure modes.

2. Structural Components Being Analyzed

We use survey data on concrete-block houses damaged by the 2001 Peru tsunami [10–12], called Peru data; that on confined-masonry-brick houses damaged by the 2009 Samoa tsunami [13, 14], called Samoa data; and that on confined-masonry-brick houses damaged by the 2010 Chile tsunami [15], called Chile data.

Thirteen walls in ten damaged houses were analyzed. **Table 1** and **Fig. 1** show height H, width B and thickness w of a wall thus analyzed. **Table 1** also shows observed inundation depth h and associated references. Height H, width B, and thickness w of a wall are basically from all three types of survey data. When parameters in data are lacking, we analyzed digital pictures for walls such as those shown in **Fig. 2**.

From among all survey data, we analyzed houses that were single-storey and located near the coastline but were not damaged by floating debris or by seismic excitations. **Fig. 3** shows locations of selected houses. What this means is that houses had no cracks at joints of beams or columns or in structural components such as beams, columns and walls before the tsunami damaged a house. Put another way, the houses selected had been damaged predominantly due to tsunami wave load.

3. Calculation of Wall Tsunami Strength

3.1. Calculation of Tsunami Strength

As shown in **Fig. 4(a)**, we classify the wall failure mode as type 1, i.e., ty1 when shear cracks occur in paired walls that are at right angles to the coastline. The shear strength of ty1 wall V_1 is calculated based on the following equation by setting $W = W/2$ when adopting Asakura's formula in Eq. (1):

$$V_1 = \tau_1 A \quad \text{(2)}$$

A is the cumulative surface area of bricks and concrete blocks with shear cracks, because a wall is made by bonding bricks and concrete blocks with mortar. In Eq. (2), τ_1 is shear stress. We set the value of τ_1 based on the procedure below by referring the value of 0.4 N/mm^2 taken from previous research [5, 6]. To deal with Peru data (concrete blocks), τ_1 is assumed to be 0.2 N/mm^2, which is 1/10 of the compression strength of a concrete block used for a non-proof-strengthening wall [16]. To deal with Chile data (masonry bricks), τ_1 is assumed to be 0.35 N/mm^2, which is a conservative value and is 1/20 of the compression strength of a brick used for a prism wall specimen [17].

As shown in **Fig. 4(b)**, when tensile and shear failures occur in a wall along the coastline, we classify the wall failure mode 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 these – mechanism 2, i.e., ty2-m2.

We calculate tensile strength T_2 and shear strength V_2 by using the following equations, i.e., by setting $W = B$ when adopting Asakura's formula in Eq. (1):

$$T_2 = 2(B+H)w\sigma_2 \quad \text{(3a)}$$

$$V_2 = 2(B+H)w\tau_2 \quad \text{(3b)}$$

σ_2 is the tensile stress between bricks and concrete blocks bonded with a frame by mortar. We use the value of $\sigma_2 = 0.24$ N/mm^2 by referring to Architectural Institute of Japan Standard Specifications for Concrete-Block Structures [18]. τ_2 is the shear stress between bricks and concrete blocks bonded with a frame by mortar – a value assumed to be 0.09 N/mm^2 from research by Sanada et al. [19].

3.2. Tsunami Strength

Table 2 shows results for ty1 shear strength V_1, ty2 tensile strength T_2 and ty2 shear strength V_2. Parameters related to tsunami wave pressure on an analyzed wall as mentioned later.

Wall p1 failure mode is assumed to be ty2 because wall p1 failed in the direction of tsunami flow. Based on ty2-m1, $T_2 = 2 \times (2,350\text{ mm} + 3,500\text{ mm}) \times 160\text{ mm} \times 0.24\text{ N/mm}^2 = 449.28$ kN, while based on ty2-m2, $V_2 = 2 \times (2,350\text{ mm} + 3,500\text{ mm}) \times 160\text{ mm} \times 0.09\text{ N/mm}^2 = 168.48$ kN. Similarly, wall p21 failure mode is assumed

Table 1. Height H, width B, and thickness w of the wall being analyzed and observed inundation depth h. ‘p’ denotes Peru, ‘s’ denotes Samoa, and ‘c’ denotes Chile.

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]	Reference for inundation depth
p1	p1	S16°39′19.6″	W72°40′35.1″	2.35	3.50	0.16	2.60	Reference [12]
p2	p21	S16°39′31.8″	W72°38′45.3″	2.60	3.20	0.16	2.60	Reference [12]
	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	References [10] and [11]
p4	p4	S16°39′35.9″	W72°37′59.9″	2.20	3.30	0.16	2.13	References [10] and [11]
p5	p5	S16°39′35.8″	W72°37′57.2″	2.50	2.80	0.16	2.28	Reference [12]
s1	s11	S14°15′06.7″	W170°33′53.5	2.00	2.53	0.15	2.55	References [13] and [14]
	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	References [13] and [14]
	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	Reference [15]
c2	c2	S36°32′14.89″	W72°57′32.42″	2.07	1.35	0.15	0.81	Reference [15]
c3	c3	S36°44′48.72″	W73°5′3.57″	2.67	2.90	0.15	1.00	Reference [15]

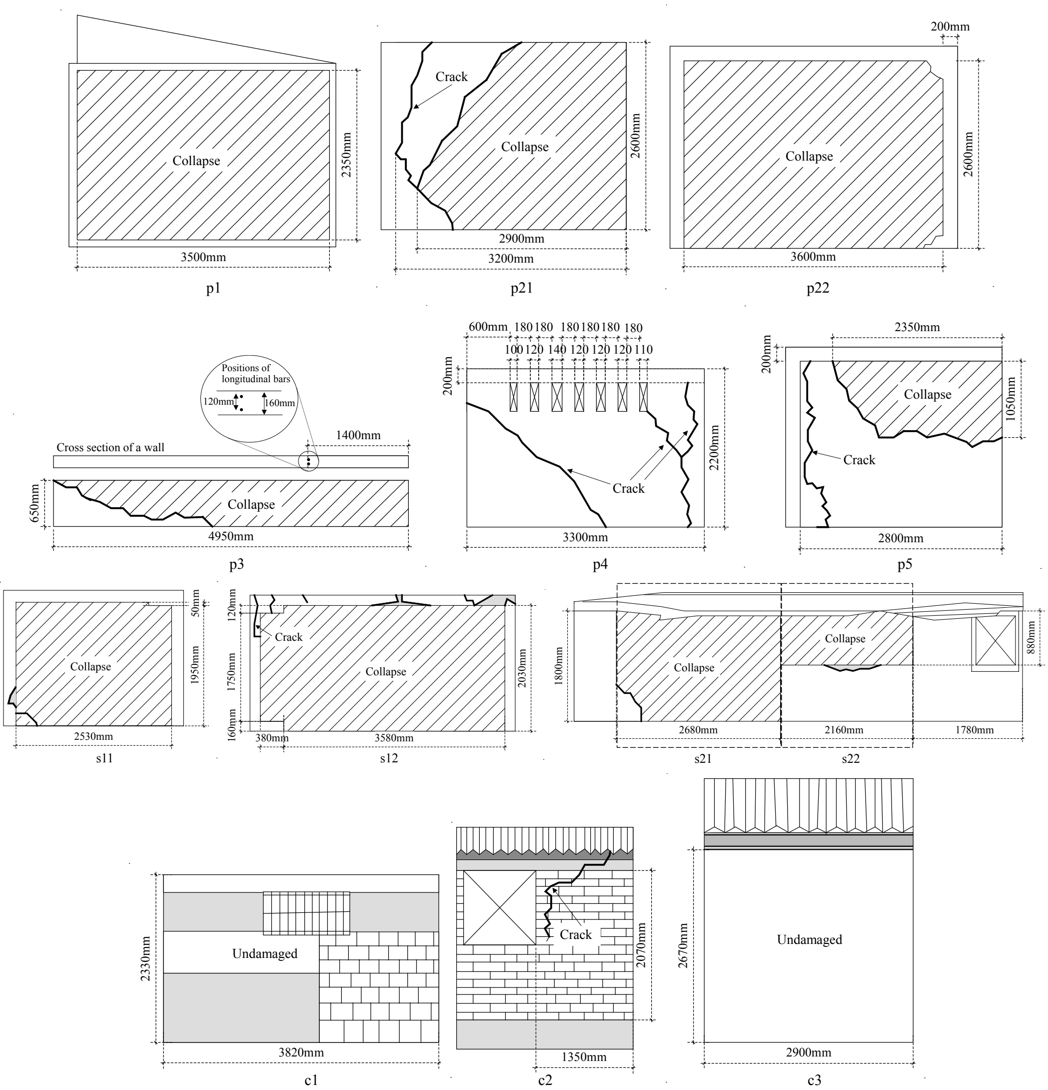

Fig. 1. Walls being analyzed.

Fig. 2. The 13 walls thus analyzed. The red dotted frame line in photographs denotes area analysis.

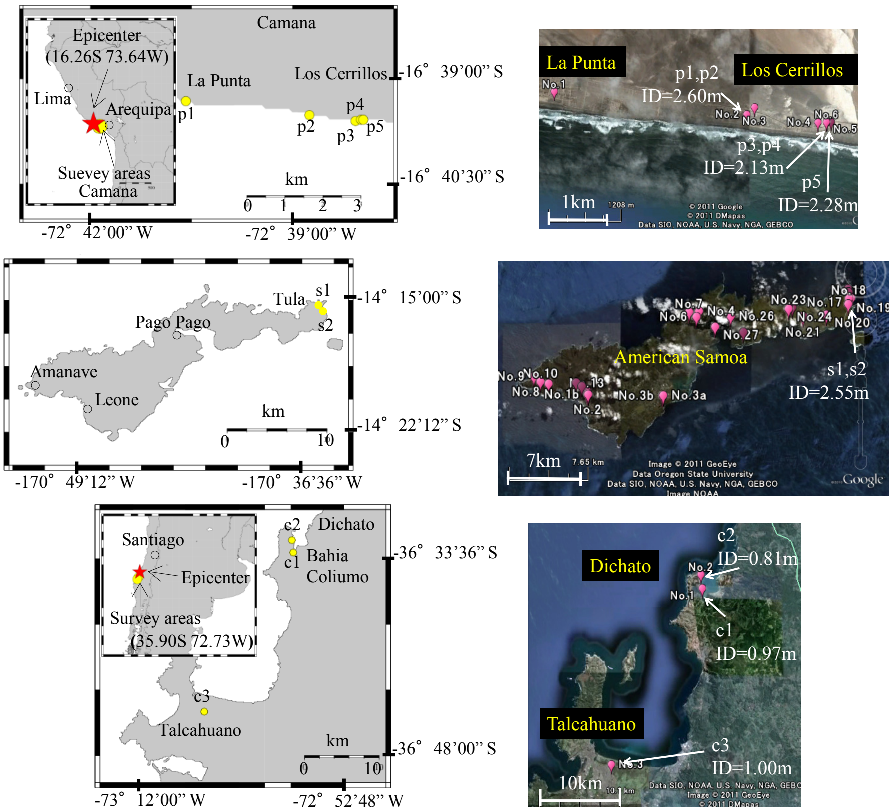

Fig. 3. Locations of 10 houses. 'ID' denotes observed inundation depth h. 'No.' in each right-column figure denotes the original number used for field survey data. The distance of individual houses from the coastline is not described in references of [10] to [15].

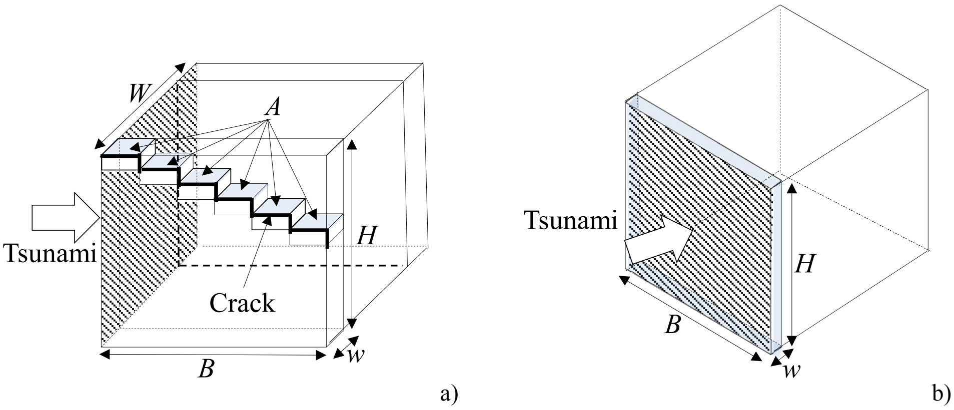

Fig. 4. Relationship between the direction of a tsunami wave and the longitudinal axis of a wall: a) paired walls at right angles to the coastline and b) wall along the coastline.

Table 2. Calculated ty1 shear strength, ty2 tensile strength, and ty2 shear strength, and parameters related to tsunami wave pressure on a wall. η' denotes $\eta' = a\eta_{\max}$.

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

to be ty2 because most of it collapsed in the same failure modes as wall p1. T_2 and V_2 are thus calculated for wall p21 as shown in **Table 2**.

In contrast, wall p22 is placed at right angles to the coastline in the same house as wall p21, so the failure mode is assumed to be ty1. Based on ty1 for wall p22 $V_1 = 0.2\ \mathrm{N/mm^2} \times 3600\ \mathrm{mm} \times 150\ \mathrm{mm} = 108.00\ \mathrm{kN}$.

We may thus assume that wall p22 failed after the tsunami flow hit wall p21. Wall p22 failure mode is thus assumed to be ty2, and associated values of T_2 and V_2 are calculated as shown in **Table 2**. Wall p3 failure mode is assumed to be ty2 because most of it collapsed similar to wall p1. By considering that upper surface and side surface of wall p3 have free boundary conditions, we calculate T_2 and V_2 by using modified Eqs. (3a) and (3b): $T_2 = (B+H)w\sigma_2$ and $V_2 = (B+H)w\tau_2$ as shown in **Table 2**. In the same way, for remaining Peru data (p4, p5), Samoa data (s11, s12, s21, s22), and Chile data (c1, c2, c3), related wall failure modes are classified into ty1 and ty2, and we calculate V_1, T_2 and V_2 as shown in **Table 2**.

4. Tsunami Wave Pressure Distribution on a Wall

4.1. Relationship Between Inundation Depth and Damage Rank

Figure 5 shows the relationship between the observed inundation depth and damage rank of an analyzed wall. We categorized wall damage into three damage ranks, i.e., completely and mostly collapsed (collapse), partially collapsed and with the occurrence of cracks (cracking), and no structural damage (no damage). Damage ranks of collapse and cracking for concrete-block houses (Peru data) are in the range of inundation depths from 2.13 m to 2.60 m. Damage ranks of no damage and cracking for masonry-brick houses (Samoa and Chile data) are at inundation depths from 0.81 m to 1.00 m and the damage rank of collapsed within an inundation depth of 2.55 m.

4.2. Evaluation of Tsunami Wave Pressure Distribution Based on Observed Inundation Depth

Tsunami wave pressure distribution on a wall is calculated by Asakura's formula as previously described in Eq. (1) with horizontal wave pressure index a of 3.0 for a structural component located on land behind on-shore structures and subjected to a nonbreaking wave. This indicates that assuming $a \geq 3.0$ is required theoretically to design a tsunami-proof structural component subjected to a nonbreaking tsunami wave. In other words, in the case of a nonbreaking tsunami wave, the horizontal wave pressure distribution of $a = 3.0$ on a structural component is

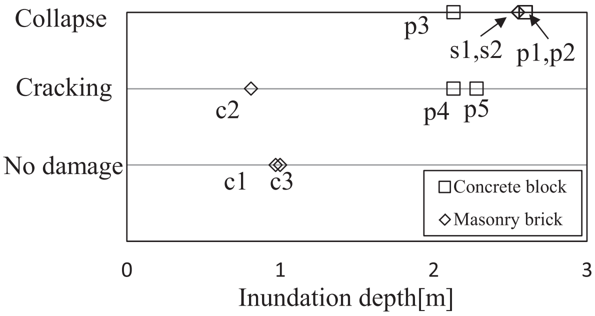

Fig. 5. Relationship between observed inundation depth h and the wall damage rank.

the limit at which a structural component presents damage due to tsunami wave load.

In this study, we first supposed ty1, ty2-m1, and ty2-m2 failure modes defined in Section 3.1 for subject walls exposed to a tsunami wave and calculated corresponding tsunami strength R, including ty1 shear strength V_1, ty2 tensile strength T_2, and ty2 shear strength V_2. We then inversely calculated the value of a as in the equations below by assuming η_{max} to be equal to observed inundation depth h as shown in **Table 1**. By comparing the value of a with tsunami damage to subject walls, we discuss validity of Asakura's formula.

$$a = \frac{1}{h}\sqrt{\frac{2R}{\rho g W}} \quad \text{(4a)}$$

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

W is the width of a wall subjected to a tsunami wave as shown in **Fig. 4**. When the value of $\eta' = a\eta_{max}$ is less than or equal to wall height H, horizontal wave pressure distribution is triangular and a is calculated by using Eq. (4a). When the value of $\eta' = a\eta_{max}$ exceeds wall height H, horizontal wave pressure distribution is trapezoidal and a is calculated by using Eq. (4b).

Table 2 shows calculated η' and a, as mentioned. **Fig. 6** shows the relationship of a to observed inundation depth h. **Fig. 7** shows results for Sri Lanka and Thailand survey data in the 2004 Indian Ocean tsunami as reported by Nakano [5, 6] and Java survey data in the 2006 Java tsunami as reported by Shoji et al. [7]. **Figs. 6** and **7** also show analytical results corresponding to ty1 and ty2 failure modes.

For Peru data, 10 cases with $a \leq 3.0$ are observed from **Fig. 6(a)**. a shows 1.07 to 2.60 for inundation depth h of 2.13 m to 2.60 m. This indicates that Asakura's formula is valid for use in these cases because these walls are classified as a damage rank of either collapsed or cracked. Two cases of Peru data with $a > 3.0$ were observed, showing collapse: $a = 3.35$ with h of 2.13 m and $a = 3.15$ with h of 2.28 m. We inferred from these cases that when a is slightly larger than 3.0, a wall has a low possibility of actually collapsing due to variations in the strength of material properties and construction conditions when a wall is fabricated.

For Samoa data, 6 cases with $a \leq 3.0$ from **Fig. 6(b)** are observed, showing $a = 1.20$ to $a = 2.97$ with h of 2.55 m. Because these walls are classified with damage rank collapsed, Asakura's formula is valid for these cases. Two cases of $a > 3.0$ are observed for Samoa data, showing $a = 3.03$ and $a = 3.29$ with h of 2.55 m. These walls collapse even though $a > 3.0$. **Fig. 6(c)** shows that Chile data has 4 cases with $a > 3.0$: $a = 3.34$ to $a = 6.77$ with h of 0.81 m to 1.00 m. We say that Asakura's formula may be valid for these because 3 cases have no damage and one shows only cracking.

When walls with a slightly larger than 3.0 for Peru and Samoa data are assumed to be damaged by ty2-m2, a becomes less than 3.0. It is quite likely that these walls would actually collapse in a failure mode of ty2-m2 rather than ty2-m1.

Comparing **Figs. 6(a)** and **(b)** to **Fig. 7(a)** shows cases with $a \leq 3.0$ having no damage for Peru and Samoa data and 4 cases with $a \leq 3.0$ showing no damage for Sri Lanka and Thailand data are observed. In contrast, Sri Lanka and Thailand data have one case with collapse regardless of $a > 3.0$ as well as Peru and Samoa data. By comparing **Fig. 6(c)** to **Fig. 7(b)**, as mentioned, one case has $a > 3.0$ showing cracking with ty1 failure mode for Chile data and two cases for Java data, in which a shows 4.19 to 5.33. It is thus possible that a wall with a of 4 to 5 beyond $a = 3.0$, meaning a wall with larger tsunami strength, suffers cracking failure mode due to a tsunami wave.

5. Conclusions

We have analyzed tsunami damage data for confined-masonry-brick and concrete-block houses damaged by the 2001 Peru tsunami, the 2009 Samoa tsunami, and the 2010 Chile tsunami. We have classified them into three failure modes for a wall subjected to a tsunami wave, i.e., shear cracks induced in paired walls at right angles to the coastline (ty1), tensile failure induced in a wall along the coastline between bricks and concrete blocks bonded with a frame by mortar (ty2 mechanism 1) and shear failure induced in a wall along the coastline between those (ty2 mechanism 2). Based on Asakura's formula [3] for evaluating tsunami wave pressure distribution on a structural component located on land behind on-shore structures, which is used for designing a tsunami evacuation building, we identified the values of horizontal wave pressure index a in Asakura's formula for 13 damaged walls of 10 selected houses, and discussed the boundary value of a at which a wall shows structural damage such as collapsed and cracking failure modes.

We deduced the following conclusions:

1) Some 16 cases with $a \leq 3.0$ showed collapse and cracking failure modes, while 3 cases with $a > 3.0$ showed no damage among 24 assumed failure modes. From these results, we concluded that Asakura's formula is valid for evaluating the tsunami strength of a wall subjected to a nonbreaking tsunami wave.

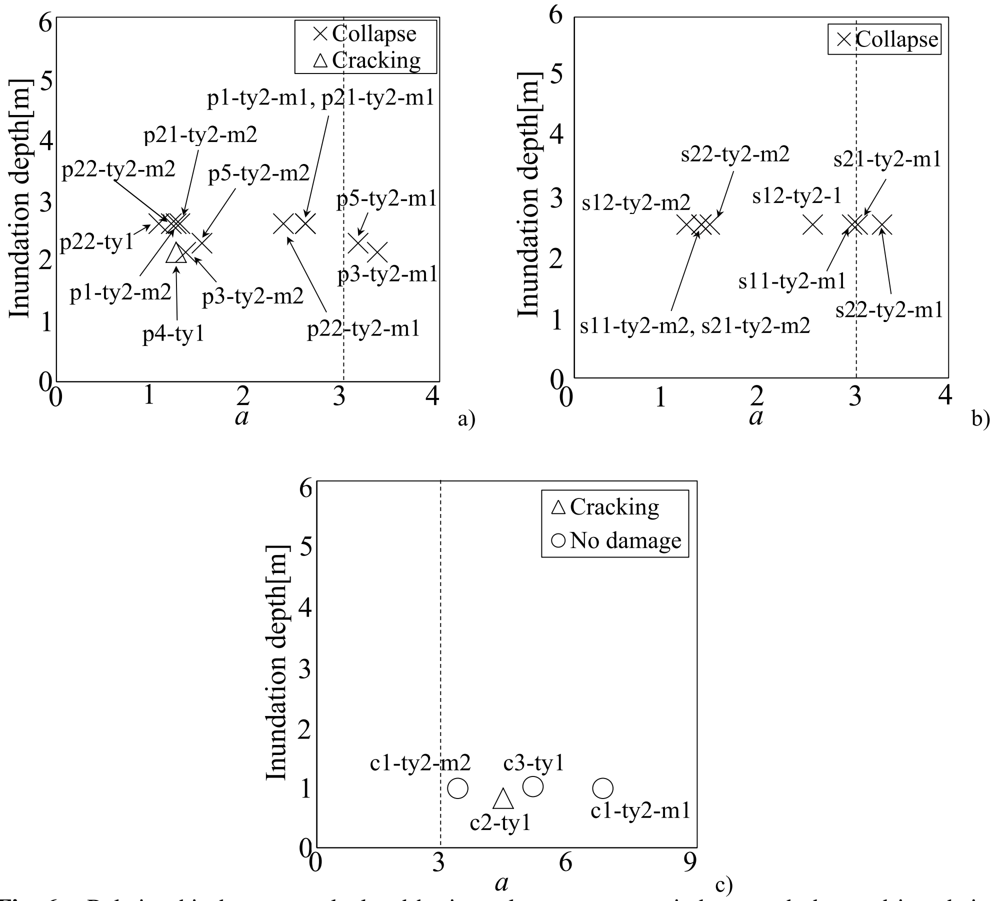

Fig. 6. Relationship between calculated horizontal wave pressure index a and observed inundation depth h for Peru, Samoa, and Chile data: a) Peru data, b) Samoa data, and c) Chile data.

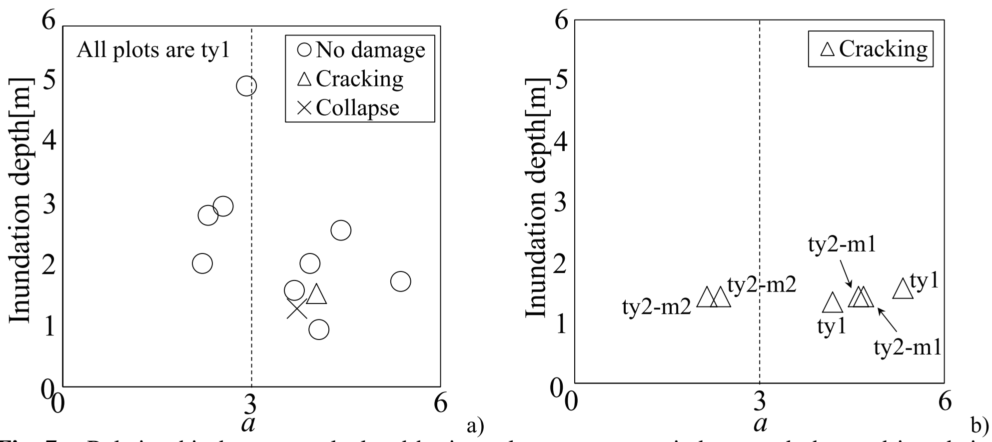

Fig. 7. Relationship between calculated horizontal wave pressure index a and observed inundation depth h for Sri Lanka and Thailand data [5, 6], and Java data [7]: a) Sri Lanka and Thailand data, and b) Java data.

2) When subject walls with a slightly larger than 3.0, e.g., 3.03 to 3.35, for Peru and Samoa data are assumed to be damaged by ty2 mechanism 2, a becomes less than 3.0. It is quite likely that these walls would actually collapse with ty2 mechanism 2 rather than failure mode ty2 mechanism 1.
3) One case with $a > 3.0$ showing cracking with ty1 failure mode for Chile data was observed and two cases for Java data, for which a showed 4.19 to 5.33. It is thus possible that a wall with a of 4 to 5 beyond $a = 3.0$ – meaning a wall with greater tsunami strength – may suffer cracking failure mode due to a tsunami wave.

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Name:
Gaku Shoji

Affiliation:
Associate Professor, Division of Engineering Mechanics and Energy, Faculty of Engineering, Information and Systems, University of Tsukuba

Address:
1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan

Brief Career:
1996- Research Associate, Tokyo Institute of Technology
2001- Assistant Professor, University of Tsukuba
2008- Associate Professor, University of Tsukuba

Selected Publications:
- "Analysis of Tsunami Flow Velocities during the March 2011 Tohoku, Japan, Tsunami," Earthquake Spectra, Vol.29, No.S1, pp. S161-S181, 2013.

Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineers (JSCE)
- Japan Association for Earthquake Engineering (JAEE)
- Institute of Social Safety Science (ISSS)