Structural Durability Assessment of Stilt Houses to Flash Flooding: Case Study of Flash Flood-Affected Sites in Thailand

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ABSTRACT

The 'stilt house' is found in many flood-prone areas and represents local wisdom regarding building construction to coexist with floodwaters. Most academic research projects have studied stilt houses based on two types of flood: inundation and coastal flooding. The study of pillar houses in flash floods is very limited. This research investigated whether the main structure of a stilt house could withstand strong water current to determine the suitability of the stilt house for flash flood sites. The study explored the physical appearance of stilt houses in five flash flood areas in Thailand. The styles of stilt houses in each area were simplified to generate models and to then test their tolerance toward moving water. The main findings were: 1) the main structure of the stilt house can resist flood loads at 1.00 m depth with a waterflow speed at 3.05 m/s; 2) the most vulnerable points on the main structure if struck by more rapid, deeper flows of water are the base of the column and the joint between the column and beams; and 3) the horizontal or diagonal bracing members perpendicular to the flow and not above the flood level become water blockades that increase the reactive force to the main structure.

1. INTRODUCTION

In recent years, the technology of flood control has been questioned due to devastating consequences since, despite the extensive implementation of flood control measures to prevent flooding, human settlements around the world remain vulnerable to flood hazards (Andersen and Shepherd, 2013). Flood control infrastructure cannot cope with extreme flows that exceed its design capacity and it can fail unexpectedly with smaller flows. The recognition that flooding cannot be completely prevented gave rise to integrated flood risk management that incorporates non-structural measures (Parker, 2000). The ideology that flooding should be prevented in the first place or the 'flood control paradigm' remains unchallenged (Liao, 2014). With increasing flood risks associated with climate change, relying solely on flood control would make many areas more vulnerable (Liao et al., 2016). For this reason, searching for new methods of flood management and 'living with floods' has been mentioned as a new alternative strategy. It is a flood adaptation paradigm which is concerned with preventing damage when flooding happens. This strategy is different from flood control; it does not try to change the flood regime but attempts to integrate with the actual or expected flood (Liao et al., 2016). Coexistence with floodwaters has always been a part of rural life in developing countries (Laituri, 2000), whereas people in urban areas continue to rely greatly on flood control mechanisms. Although the living-with-floods lifestyle is vastly dissimilar to modern urbanism, it has enlightened flood management discourses (Thaitakoo et al., 2013; Zevenbergen et al., 2011). The flood adaptation paradigm is most expressed in the built environment, particularly in buildings. Houses on stilts are commonly found in flood-prone locations and are likely to become a unique housing style in flood risk areas. During the flood season, these houses are above the flood water since the downstairs area such houses is almost empty, so the floodwaters can pass underneath through the gaps between the supporting columns. During the dry season, there is an additional shaded

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and dry space under the house for various activities (Kusar and Ut, 2014).

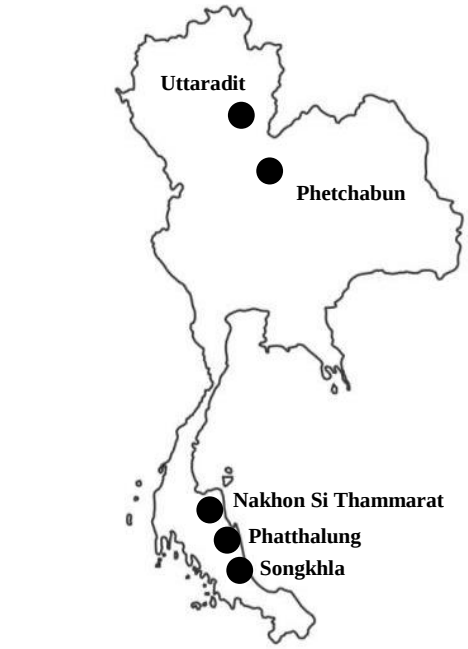
Many research projects have studied houses on stilts with various objectives. Mongkonkerd et al. (2013) studied the monetary damage of the big flood in 2011 to a pillar house in the Chao Phraya River Basin, Thailand. Ramasoot and Nimsamur (2014) estimated damages to a stilt house and the cost to repair or replace components due to flood inundation in a riparian community in the Chao Phraya River Basin. Liao et al. (2016) studied the physical appearance of stilt houses and how this influenced their coping capacity to seasonal flooding and utilization of ground level in dry season and explored ways to reinforce such stilt houses. They selected two hamlets in the Vietnamese Mekong Delta as study sites. Tikul and Thongdee (2015) estimated the coping capacity of pillar houses in three low-income communities of upper Northern Thailand to flood inundation. Kusar and Ut (2014) studied the structure and building materials of a modern house on columns built to coexist with flood inundation in the marshland of Ljubljana, Slovenia. Sastrawati (2009) examined the characteristics of stilt houses in a coastal area of Makassar, Indonesia, especially in terms of safety and security aspects, with the study focusing on the resistance of building construction to coastal flooding. Hryczyszyn and Neil (2014) studied stilt houses over inundating floodwaters in the Mekong Delta region of Southern Vietnam. They determined spatial characteristics and the importance of stilt houses and analyzed their distribution pattern in the area. From the above, it can be seen that these research studies were all concerned with stilt houses in events of inundation and coastal flooding. In fact, another type of flooding is flash flooding, which has generated severe damage to buildings and losses to people in various regions of the world. The above literature study revealed scarce attention has been paid to stilt houses in flash flood-prone areas. The current study aimed to fulfill such a conspicuous gap by exploring the physical characteristics of stilt houses in flash flooding locations and examined their structural durability to moving water. It was also expected that the research results would identify the vulnerable points of the pillar structure when struck by a flash flood and lead to the improvement and reinforcement of the house to better cope with this type of flood in the future. The completeness of the methodology, processes, and results of the structural durability assessment of a stilt house in this paper was accomplished by referring to some parts of a previous study (Charoenchai, 2018).

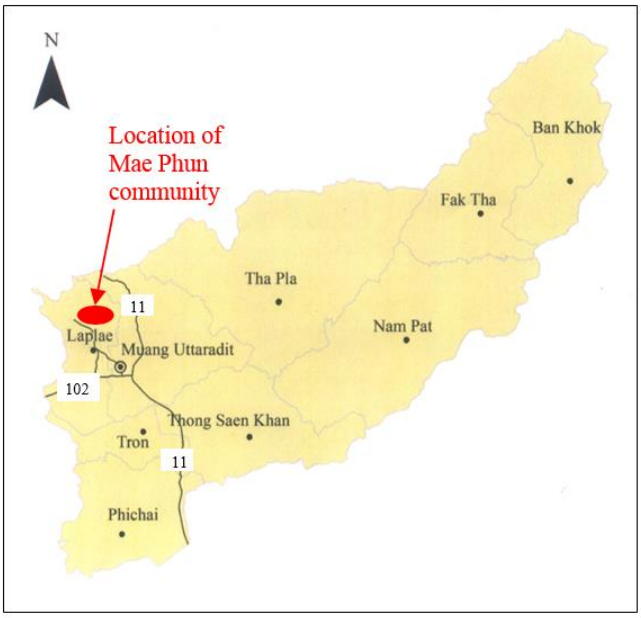
2. METHODOLOGY

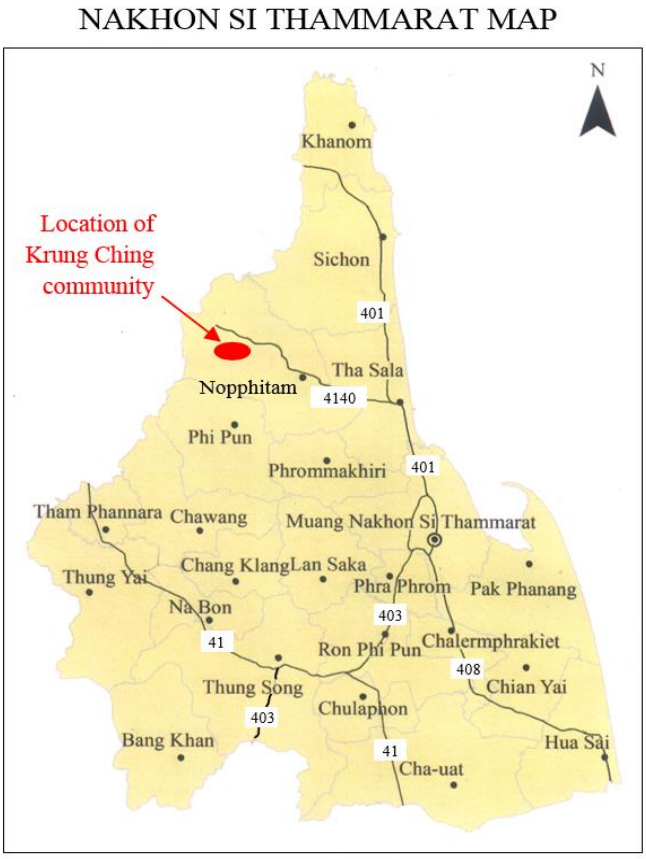
2.1 Study areas

Five communities were selected as study areas because they had been struck by flash flooding almost every year or had experienced severe flash flooding in the past. The study areas were: Mae Phun community in Uttaradit Province, Nam Kor community in Phetchabun Province (these two communities are located in the lower Northern Thailand), Krung Ching community in Nakhon Si Thammarat Province, Tamot community in Phatthalung Province and Prig community in Songkhla Province (these three communities are located in the Southern (east coast) Thailand) as shown in Figure 1. To live with serious damage from flash flooding various adaptation strategies are required, including house modifications. The stilt house is one important solution and this type of house is commonly found in the five communities above.

Mae Phun community is located in Mae Phun Sub-district, Lap Lae District, Uttaradit Province. It is in the Nan Sector IV Basin (a branch of the Nan Basin) (Hydro and Agro Informatics Institute, 2012a). It covers 116 km^2 and consists of 11 villages, 3,685 households, and a population of 9,338. Mae Phun is settled in a valley surrounded by forests and mountains. The overall topography is plains between mountains. Many important waterways that flow through this community include: Mae Prong canal; Mae Phun creek; Kum Bi (Ban Di) Creek; Mae Bok creek; and Tai creek (Department of Mineral Resources, 2013). Mae Phun has experienced seasonal flash flooding almost every year, which frequently takes place from June to August. The average depth of floodwaters is 1.50 m and remains in the community from 4 h to 2 days. In 2006 and 2009 devastating flooding caused widespread damage. The flooding in 2006 was the most extreme, with a large number of houses and farming areas entirely destroyed and many fatalities (Nation Multimedia Group, 2006; Editorial Department of Komchadluek Newspaper, 2008).







Legend:

Location of the community

Figure 1. Location of five study sites

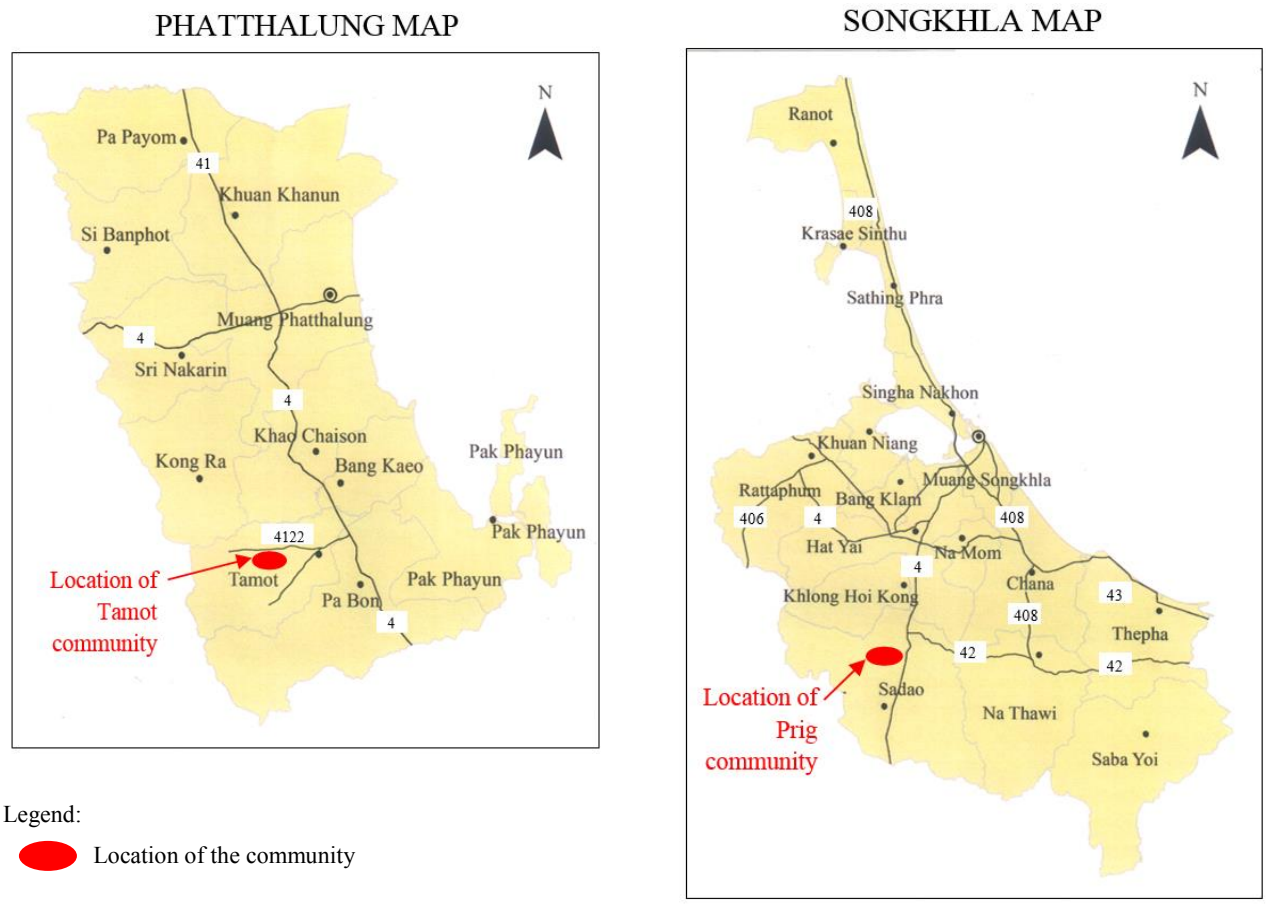


Figure 1. Location of five study sites (cont.)

Nam Kor community is located in Nam Kor Sub-district, Lom Sak District, Phetchabun Province. It is in the Huay Nam Phung Watershed (a branch of the Pasak Watershed) (Hydro and Agro Informatics Institute, 2012b). It covers 183 km^2, 13 villages, 2,365 households, and has a population of 6,720. The overall topography is high steep mountains and plains. The community is settled on the plains. Nam Kor creek is the only main water channel. In the rainy season every year (from June to September), Nam Kor always has flash flooding. The floodwaters have deluged the community from 2 h to 3 days with water depths of 0.20-2.00 m. In 2001, an enormous and unprecedented flash flood hit Nam Kor. This flood demolished a great number of houses, destroyed many livestock, farms, and rice paddies, and caused many injuries and deaths (Nam Kor subdistrict Administrative Organization, 2015).

Krung Ching community is in the Krung Ching Sub-district, Nopphitam District, Nakhon Si Thammarat Province. It is located in Klong Klai Basin (a branch of the Eastside South Watershed) (Hydro and Agro Informatics Institute, 2012c). It covers 364 km^2, 11 villages, 3,537 households, and has a population of 9,740. Krung Ching is settled in a valley surrounded by mountains. The overall topography is plateaus and mountains. There are many waterways flowing through the community: Lek, Wat, Nopphitam creeks, Klai, Phitam, Pien, Pong, and Phot canal (Krung Ching subdistrict Administrative Organization, 2015). Flash flooding has taken place almost every year in Krung Ching during the peak rainfall season (November to December). Floodwaters have immersed the community from 1 h to 2 days with water depths of 1.0-2.0 m. In 2010, 2011, and 2013, this community was hit by serious flash floods that the residents there had never experienced before. Roads, bridges, para-rubber and fruit plantations, and houses were destroyed (Editorial Department of Naew Na Newspaper, 2011; Sunanta, 2011; Focus News Agency, 2011).

Tamot community is in Tamot Sub-district, Tamot District, Phatthalung Province. It is located on the western side of the Songkhla Lake Basin. The overall topography is hillocks and plains. Most of the

community is settled on the plains. There are four important canals that run through the community: Tamot; Kong; Hua Chang; and Lo Chang Kra. This community covers 176.65 km^2, 12 villages, 1,879 households and has a population of 7,000 (HelpAge International, 2013). Tamot has faced flash flooding almost every year, particularly during the rainy season in November and December. The depth of floodwaters has been in the range 0.50-1.00 m with deluges lasting from 1 h to 1 day. Large flash floods were recorded in Tamot in 1970, 1998, 1999, 2010, and 2011.

Prig community is in Prig Sub-district, Sadao District, Songkhla Province. It is situated in the Songkhla Lake Watershed (Hydro and Agro Informatics Institute, 2012d). It covers 164.2 km^2, 11 villages, 5,349 households, and has a population of 16,364. Around 70% of the topography is plains and the remainder is foothill slopes. There are five important canals: U-Tapao; Prig; La Pang; Lay; and Sadao (Nopphaket, 2011; Prig Sub-district Health Plan Working Group, 2008). The basin-shaped catchment receives water from many canals, in the monsoon season during November and December, so that the canals overflow and flood the community with fast flowing water. Floodwaters have submerged Prig for around 1-3 days with a depth of 1.0-2.0 m. This community has been hit by flash flooding almost every year with notable severe flooding in 1959, 1966, 1972, 1978, 1988, 1998, 2010, and 2011 (Society and Health Institute, 2014).

2.2 Survey method

A guided field walk technique was used to explore and record the appearance of stilt houses at the five study sites. Recording involved roughly measuring some elements of each stilt house, such as size and dimension of columns, distance between columns, height from ground to stilt floor, elevation from stilt floor to roof beam, roof shape and its slope. In addition, notes and photos were used to record building materials of the house principal structure (columns and beams), roof structure, upper wall, stilt floor, and ground floor. The guided field walks were accompanied by well-known community figures to ensure households would co-operate and allow measurements to be taken. Guided field walks of the Tamot, Prig, and Krung Ching communities took place in March 2016 and surveys of the Nam Kor and Mae Phun communities occurred in July 2016.

2.3 Analysis

The assessment of structural sturdiness of stilt houses to flash flooding was conducted using software named Robot Structural Analysis Professional (Educational Version) (Autodesk, 2015). This software is an integrated program used for modeling, analyzing, and designing various types of structures. Data from the field surveys could be used to categorize the stilt houses into seven types. The physical appearance of each type was simplified and used as raw data to generate basic graphical models for testing structural durability. Flood loads were calculated and then applied to the models (Figure 2).

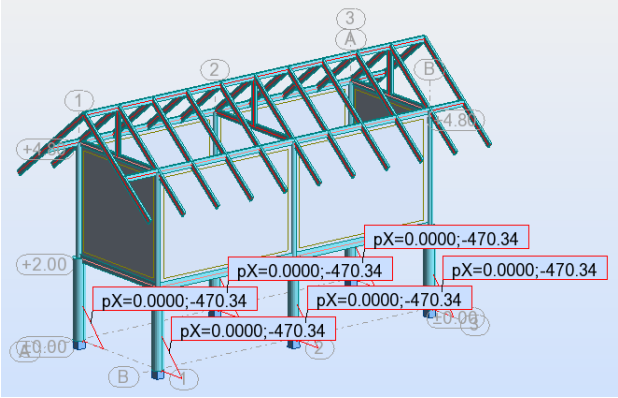


Figure 2. Example of basic graphical model of stilt house with applied flood loads on its downstairs columns.

The software processed and analyzed data and then showed the responsive stresses at any point on the main structure of the model. Such reactive stresses were compared with the ultimate strength of the material being used in the main structure. If the reactive stress is less than the ultimate strength, then the main structure of that house can resist flood loads. Conversely, if the reactive stress is higher than the ultimate strength, then the main structure is likely to be damaged by flood loads.

3. RESULTS AND DISCUSSION

3.1 Types of stilt house

From the field surveys at the five study sites, stilt houses could be categorized into seven types based on their physical characteristics, as shown in Table 1.

Table 1. Types of stilt house.

	Physical characteristics
 Type I	Wooden roof structure, square wood columns 15 × 15 cm, wood walls, and wood floors (upstairs), round wood columns diameter 30 cm and earth ground (downstairs).
 Type II	Wooden roof structure, round wood columns diameter 15 cm, wood walls, and wood floors (upstairs), round wood columns diameter 15 cm and earth ground (downstairs).
 Type III	Wooden roof structure, square wood columns section 15 × 15 cm, wood walls, and wood floors (upstairs), square wood columns section 15 × 15 cm and earth ground (downstairs).
 Type IV	Wooden roof structure, square wood columns section 15 × 15 cm, wood walls, and wood floors (upstairs), square wood columns section 15 × 15 cm, bracing wooden bars, and earth ground (downstairs).
 Type V	Wooden roof structure, square wood columns section 15 × 15 cm, wood walls, and wood floors (upstairs), square concrete columns section 20 × 20 cm and concrete floor slabs on ground (downstairs).

Table 1. Types of stilt house (cont.)

	Physical characteristics
 Type VI	Wooden roof structure, square concrete columns section 20 × 20 cm, bricked walls, and concrete floor slabs on beams (upstairs), square concrete columns section 20 × 20 cm and concrete floor slabs on ground (downstairs).
 Type VII	Wooden roof structure, square concrete columns section 20 × 20 cm, bricked walls, and concrete floor slabs on beams (upstairs), square concrete columns section 20 × 20 cm and concrete floor slabs on beams (downstairs).

However, there were some common characteristics that were found in every type of stilt house. The distance between each column in the cross-sectional direction of the house was approximately 3.00 m while in the longitudinal direction it was approximately 4.00 m. The average height from the ground to the stilt floor was 2.00 m and from the stilt floor to the roof beam was 2.80 m. These common attributes were used as basic distances to create models of each type for subsequent durability testing.

3.2 Durability assessment of stilt house

Almost all houses in Thailand, including stilt houses, have been constructed using the post and lintel system where the main structure consists of columns and beams assembled as a frame to support other components including the roof, walls, floors, and staircases. The ability of the house to maintain its shape depends greatly on the stability of the main structure. If the main structure is damaged, other components of the house connected to the main structure will be damaged as well. For this reason, durability assessment of the stilt house to flash flooding in this research focused on evaluation of the stability of its main structure, including ground floor columns, ground floor or grade beams, stilt floor beams, stilt floor columns, and roof beams.

3.2.1 Calculation of flood loads

Flood loads are the loads on the building surface or structure induced by floodwaters. There are two basic types: hydrostatic and hydrodynamic. Hydrostatic loads are caused by water either above or below the ground surface, which results from either inundation or movement at a speed lower than 1.52 m/s. These loads are the product of the water pressure multiplied by the surface area on which the pressure acts. Hydrostatic pressure at any point is equal in all directions and acts perpendicular to the surface on which it is applied (American Society of Civil Engineers, 2014) and it can be calculated using the following equation (White, 1999):

$$p = q\,g\,h \quad (1)$$

Where: p = pressure (Pa or pascal)
q = density of water (1,000 kg/m^3)
g = acceleration of gravity (9.81 m/s^2)
h = depth in the water at which the pressure is measured (m)

Hydrodynamic loads are the loads that are induced by the flow of water moving at moderate-to-high speed above the ground. They are usually horizontal loads caused by the impact of a moving mass of water and the drag forces as the water flows around the obstruction. This type of load can be calculated using the following equation:

$$d_h = aV^2/2g \quad (2)$$

Where: d_h = surcharge depth (m)
V = average water velocity (m/s)
g = acceleration due to gravity (9.81 m/s^2)

a = coefficient of drag or shape factor (not less than 1.25)

Selection of the correct value of the drag coefficient "a" in Equation (2) depends on the shape and roughness of the object exposed to the flood flow. Generally, the smoother and more streamlined the object, the lower the drag coefficient. Drag coefficients of elements common in buildings and structures (round or square columns and rectangular shapes) will range from 1.0 to 2.0. However, the American Society of Civil Engineers (2014) recommends a minimum value of 1.25 be used. Equation (2) requires that the water velocity does not exceed 3.05 m/s. The dynamic effects of moving water should be permitted to be converted into hydrostatic pressure by increasing an equivalent surcharge depth (d_h) on the upstream side of the structure and above the ground only. Once the surcharge depth (d_h) is determined from Equation (2), it is added to the flood depth (h) in Equation (1) to calculate the resultant hydrostatic pressure. If different flow directions are considered, then each direction is an independent load case.

The calculation of both hydrostatic and hydrodynamic pressure is inevitably related to flood depth. Information on the flood depth at each study site resulted in defining the average flood depth as 1.00 m above the ground. Therefore, calculation of water pressure in this research was based on a 1.00 m depth for floodwaters. Flash flooding is an event where the mass of water moves above the ground and strikes obstructions at a certain speed, so it is absolutely related to hydrodynamic loads. In calculating the hydrodynamic pressure, the flow velocity is the key variable. In practice, it is very difficult to estimate the flow velocity precisely (American Society of Civil Engineers, 2014). From field investigations, it was found that there was no recording of flood velocity and a check with the state agencies working in water management revealed it has never been measured or recorded in small creeks or canals, only in large waterways. Each study site was located in a sub-basin having only canals as the main waterways; thus there were no data on the flood velocity for each site. Consequently, the current research used information on the average speed of flash floodwaters from other reliable sources. The American Society of Civil Engineers/Structural Engineering Institute Standard 7-05 (American Society of Civil Engineers, 2014) was used as a reference in this study. Such a standard classifies the flow of floodwaters into low velocity flow (the floodwater speed does not exceed 3.05 m/s) and high velocity flow (the water speed is greater than 3.05 m/s). Thus, 3.05 m/s is the velocity used to divide the kinds of flow and it was considered reasonable to apply this figure as the average velocity of flash floodwaters in this research.

3.2.2 Flood loads applying to each type of stilt house

Since the average height from the ground to the stilt floor of every type of stilt house in this study was 2.00 m (Table 1), for a flood depth of approximately 1.00 m, the members of the main structure directly impacted by the floodwaters are the columns at ground level. In addition to the flow velocity and the depth of floodwaters, the physical characteristics of downstairs column are another key factor influencing flood loads. The shape of the column determines the drag coefficient in Equation (2). Furthermore, it influences the value of the surcharge depth that is added to the flood depth in Equation (1) and finally, it affects the value of the hydrostatic pressure calculated using Equation (1). The size of the column determines the degree of surface area to impede floodwaters and then influences the extent of flood loads that impact each column because the flood loads are the product of the water pressure multiplied by the surface area on which the water pressure acts. Flood loads that are applied on downstairs columns of each type of stilt house were obtained using Equations (1) and (2).

A stilt house with round columns on the ground level has a surcharge depth (d_h) of 0.57 m and a water pressure at 1.57 m depth (h (1.00 m) + d_h (0.57 m)) of 1,567.80 kg/m^2. Flood loads which act on the surface area of each round column of stilt house Type I were 470.34 kg while for Type II they were 235.17 kg because the diameter of columns for stilt house Type II is smaller than for Type I (15 cm for Type II, 30 cm for Type I), so the surface area against the water is smaller, too (0.15 m^2 for Type II, 0.3 m^2 for Type I). A pillar house with square columns on the ground has an additional depth (d_h) of 0.95 m and so the water pressure at 1.95 m depth (h (1.00 m) + d_h (0.95 m)) is 1,947.50 kg/m^2. The value of 292.13 kg is the flood load acting on the surface area of each column of stilt house Types III and IV that have square columns of section 15 × 15 cm (surface area of each column against the floodwaters is 0.15 m^2). The flood load on each square column section 20 × 20 cm of stilt house

Types V-VII is 389.50 kg (surface area of each column against floodwaters is 0.20 m^2).

3.2.3 Results of structural durability assessment

When floodwaters at 1.00 m depth strike the downstairs columns of each type of stilt house, the main structure of the house reacts by generating responsive stresses at all points of its components as shown in Figure 3. The marks "-" and "+" do not represent the numerical meaning, they just indicate the type of stress that is compressive if a negative sign and tensile if there is a positive sign.

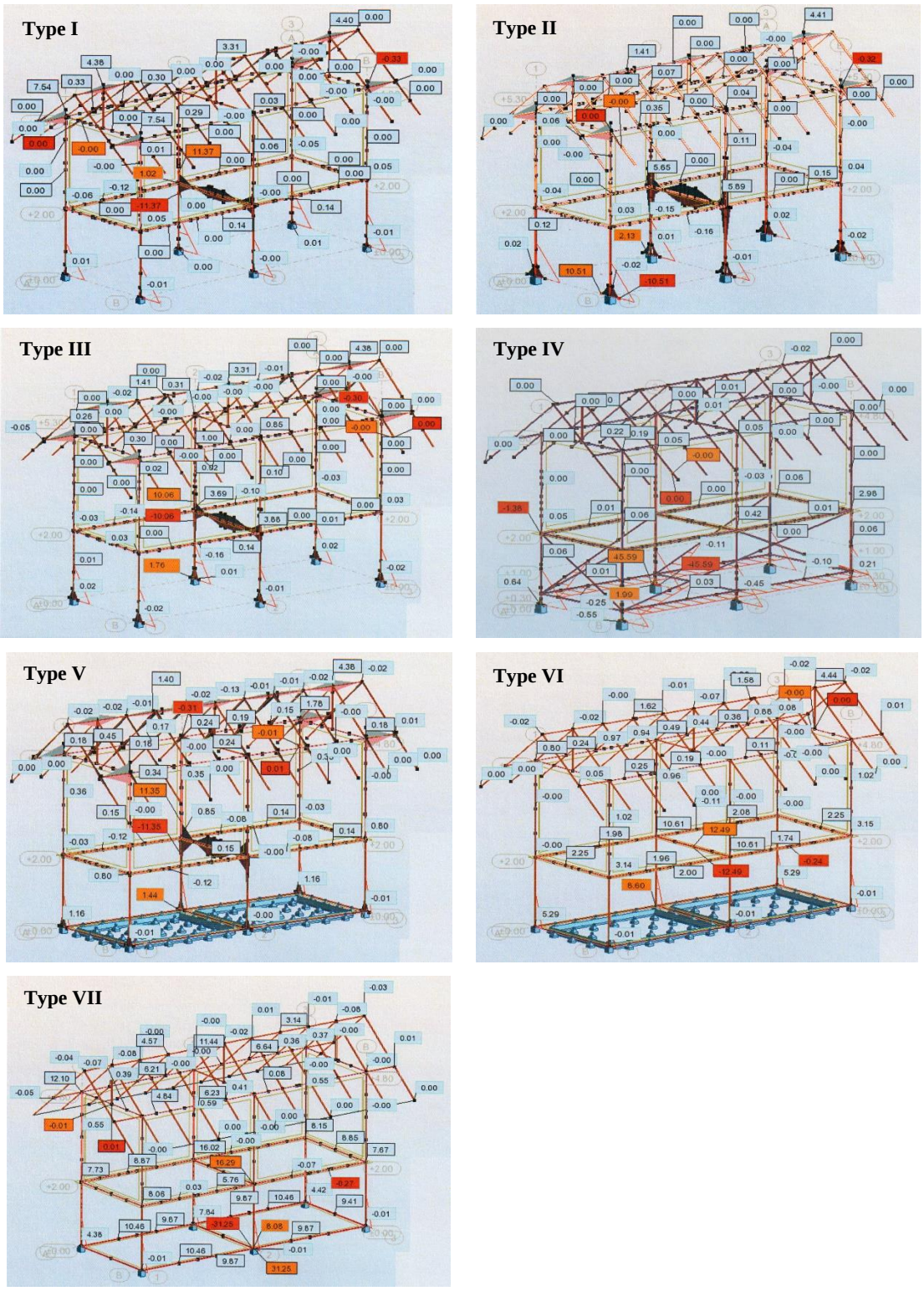


Figure 3. Reactive compressive and tensile stresses at any points of main structure of each type of stilt house, when struck by moving water at downstairs columns

Information on the mechanical properties of Thailand's timber species provided by the Royal Forest Department as cited by Chorwichien (2014) indicated the ultimate compressive and tensile strength of each kind of hardwood in the country and these strengths are divided into strength in the direction that is parallel and strength that is perpendicular to the wood grain. The current study only considered compressive and tensile strength normal to the grain because all timber columns and beams (the main structural elements) were produced with the grain parallel to the length of the component. Thus in the main frame of the house, their lateral surfaces along their length are impacted by the floodwater resulting in the flood loads acting in the direction that is perpendicular to the grain. The lowest value of ultimate compressive strength of hardwood (perpendicular to grain) is 99 kg/cm^2. The ultimate tensile strength normal to grain is approximately 10% of the tensile strength parallel to the grain (Chorwichien, 2014). The data on the mechanical properties of Thailand's timber species provided by the Royal Forest Department as referred to by Chorwichien (2014) specified the lowest ultimate tensile strength of hardwood (parallel to grain) as 806 kg/cm^2, so the lowest ultimate tensile strength that is perpendicular to grain is 80.6 kg/cm^2. For pillar house Types I-IV, for which the ground floor pillars were hardwood, their maximum compressive stresses (-11.37, -10.51, -10.06, -45.59 kg/cm^2, respectively) were not greater than 99 kg/cm^2. Similar to tension, their highest tensile stresses (+11.37, +10.51, +10.06, +45.59 kg/cm^2, respectively) were not over 80.6 kg/cm^2. The results indicated that flood loads at 1.00 m depth would not induce compressive and tensile stresses in the main structure that exceeded its ultimate strength; therefore these 4 types of stilt house could withstand the water current from a flash flood without any damage being caused to their main structures.

There are many factors affecting the ultimate compressive strength of concrete including: the type, quality and amount of cement, the quality, cleanness and grading of the aggregate, the quality and amount of water, the presence or lack of admixtures, the methods followed in handling and placing the concrete, the age of the concrete when placed in the forms, the temperature and curing conditions, and the age of the concrete when tested (Neville, 2015). The ultimate compressive strength of concrete is determined by casting some concrete specimens and curing them (by soaking) for 28 days, then subjecting those specimens to a specific force with a specific machine in the laboratory to determine the precise value of ultimate compressive strength of each sample. This method is extensively acknowledged as the general index to measure the ultimate compressive strength of concrete (CPAC Concrete Academy, 2000). In practice, on construction sites for general houses, no concrete specimens are used to test the ultimate compressive strength. Construction workers always mix concrete themselves and use it immediately, so there is no way to know accurately the ultimate compressive strength of that concrete. For this reason, this research had to refer to other trustworthy sources instead to obtain information on the ultimate compressive strength of concrete.

The review of the relevant literature indicated there were some sources mentioning the ultimate compressive strength of concrete. First, the ACI 318-14 standard (Section 19.2.1.1) indicated that a minimum specified ultimate compressive strength for structural concrete should be approximately 180 kg/cm^2 (American Concrete Institute, 2014). Second, Neville (2015) based on the 2015 IBC® and ACI 318-14: Concrete Quality and Field Practices specified that the ultimate compressive strength of concrete to make columns, walls, slabs, and beams should be in the range of 210-492 kg/cm^2. This research adopted the value of 180 kg/cm^2 as the ultimate compressive strength for the concrete used to build the main structures of the stilt houses at the five study sites since there was no general quality control associated with the common practice of mixing concrete on site without any strict quality control; thus, its ultimate compressive strength was not likely to be high. The figure of 180 kg/cm^2 was derived from the lowest value of the ultimate compressive strength of concrete indicated in the reference sources above.

Regarding the ultimate tensile strength of concrete, Neville (2015) mentioned that "Concrete in the structure is rarely loaded in pure tension, the tensile stresses being in connection with flexure, torsion or a combination of loadings. Research indicates that direct tension averages about 10 percent of the compressive". In addition, Al-Sahawneh (2015) stated that there is a variety of values of the ultimate tensile strength of concrete obtained from tests and measures, however, it could be concluded that the ultimate strength of concrete in tension is in the range of 7 to 11 percent of its ultimate compressive strength. Particularly, if the ultimate compressive strength of concrete was between 140 and 210 kg/cm^2, its ultimate tensile strength was approximately 10 percent of the compression. Thus,

the current study used 10 percent to calculate the ultimate tensile strength of concrete based on the ultimate compressive strength. Thus, for an ultimate compressive strength of 180 kg/cm^2, the capacity to bear maximum tensile stress would be 18 kg/cm^2.

The downstairs columns of stilt house Types V and VI were made of concrete and the testing results of structural durability revealed that the highest compressive and tensile stress in their main structure when hit by flood loads were not beyond the ultimate compressive and tensile strengths of the concrete. Stilt house Type V responded to flood loads by establishing reactive compressive and tensile stresses of -11.35 and + 11.35 kg/cm^2, respectively, at one joint of the column and stilt floor beam, whereas pillar house Type VI generated reactive compressive and tensile stresses of -12.49 and +12.49 kg/cm^2, respectively at one stilt floor beam made of concrete. Such values were not over the respective maxima of 18 kg/cm^2 and 180 kg/cm^2 indicating that the main structures in these two types of stilt house could tolerate flood loads. Similar to Types V and VI, the downstairs piles of stilt house Type VII were concrete and the highest compressive and tensile stresses (each being 31.25 kg/cm^2) occurred at the bottom of one column. Regarding compression, 31.25 kg/cm^2 is much less than the ultimate compressive strength of concrete (180 kg/cm^2), so these columns could resist compressive loads induced from floodwaters. Regarding tension, 31.25 kg/cm^2 is greater than the critical tensile bearing capacity of concrete (18 kg/cm^2), indicating that this concrete column in stilt house Type VII would likely be damaged due to the stress of tension. The field surveys revealed that in fact every column of this type of stilt house still existed without any damage. In practice, the core structure of the house was not made of pure concrete, but rather was reinforced concrete containing steel bars or rods within the concrete to increase the tensile strength of the concrete core structure. Engineers know well that concrete has a very limited capacity to bear tension, so they put reinforcing steel bars inside the concrete to absorb tensile stress instead, because of the very high ultimate tensile strength of steel.

The TIS 20-2543 standard indicated that the ultimate tensile strength of a round steel bar is 3,900 kg/cm^2 and of a deformed steel bar is 4,900 kg/cm^2 (Thai Industrial Standard Institute, 2001). The current research adopted 3,900 kg/cm^2 because most house owners in rural areas of Thailand (including the five study sites in the current research) prefer to use round steel bar to reinforce the concrete columns and beams of their houses. For stilt house Type VII, reinforced steel bars in concrete columns could bear a tensile stress of 31.25 kg/cm^2 instead of the lower value for concrete and this is the reason why every pile in this type of house was not affected by the water flow. The consequences of the structural durability assessment of the seven types of stilt house regarding flash flooding are provided in Table 2.

Table 2. Maximum reactive stress and durability assessment of main structure of each type of stilt house to flash flooding.

Type of stilt house	Maximum reactive stress	Ultimate compressive strength of main structure	Ultimate tensile strength of main structure	Percentage of maximum compressive stress to ultimate compressive strength	Percentage of maximum tensile stress to ultimate tensile strength	Durability to flash flooding
Type I (hardwood round column diameter 30 cm)	+11.37 kg/cm^2, -11.37 kg/cm^2 (at one joint between column and stilt floor beam)	99 kg/cm^2 (hardwood)	80.6 kg/cm^2 (hardwood)	11.48%	14.11%	Durable
Type II (hardwood round column diameter 15 cm)	+10.51 kg/cm^2, -10.51 kg/cm^2 (at one base of column)	99 kg/cm^2 (hardwood)	80.6 kg/cm^2 (hardwood)	10.62%	13.04%	Durable
Type III (hardwood square column 15×15 cm)	+10.06 kg/cm^2, -10.06 kg/cm^2 (at one joint between column and stilt floor beam)	99 kg/cm^2 (hardwood)	80.6 kg/cm^2 (hardwood)	10.16%	12.48%	Durable

Table 2. Maximum reactive stress and durability assessment of main structure of each type of stilt house to flash flooding (cont.).

Type of stilt house	Maximum reactive stress	Ultimate compressive strength of main structure	Ultimate tensile strength of main structure	Percentage of maximum compressive stress to ultimate compressive strength	Percentage of maximum tensile stress to ultimate tensile strength	Durability to flash flooding
Type IV (hardwood square column 15×15 cm with bracing bars)	+45.59 kg/cm^2, -45.59 kg/cm^2 (at one base of column)	99 kg/cm^2 (hardwood)	80.6 kg/cm^2 (hardwood)	46.05%	56.56%	Durable
Type V (concrete square column 20×20 cm with slabs on ground)	+11.35 kg/cm^2, -11.35 kg/cm^2 (at one joint between column and stilt floor beam)	180 kg/cm^2 (concrete)	18 kg/cm^2 (concrete) 3,900 kg/cm^2 (steel bar)	6.31% (concrete)	63.06% (concrete) 0.29% (steel bar)	Durable
Type VI (concrete square column 20×20 cm with slabs on ground)	+12.49 kg/cm^2, -12.49 kg/cm^2 (at the middle of one stilt floor beam)	180 kg/cm^2 (concrete)	18 kg/cm^2 (concrete) 3,900 kg/cm^2 (steel bar)	6.94% (concrete)	69.39% (concrete) 0.32% (steel bar)	Durable
Type VII (concrete square column 20×20 cm with slabs on beams)	+31.25 kg/cm^2, -31.25 kg/cm^2 (at one base of column)	180 kg/cm^2 (concrete)	18 kg/cm^2 (concrete) 3,900 kg/cm^2 (steel bar)	17.36% (concrete)	173.61% (concrete) 0.80% (steel bar)	Durable

Remarks: + (stress value) = tensile stress
- (stress value) = compressive stress

3.2.4 Notable observations

The structural durability assessment of a stilt house to flash flooding of 1 meter-depth with a water speed of 3.05 m/s produced some noticeable findings. First, all types of stilt house considered could withstand flood loads of moving water. The highest reactive stress which occurred in the principal structure of each type of stilt house was not beyond the ultimate strength of the materials used. Thus, this type of house is safe and suitable to build in locations prone to flash flooding. This finding was consistent with several studies of stilt houses in flood risk areas. Idham (2018) reported that the elevated floor in a stilt house is the most suggested house structural system for confronting flood disaster, since such an elevated floor provides a safe place for dwellers while allowing the water to run through the structure as a first precaution against disaster vulnerability based on the environmental threat. Saharom et al. (2018) suggested that according to the condition and affordability for the house owner, the ideal house construction system was an elevated stilt house system that used lightweight material to reduce the load on unstable ground. The elevated ground floor provides protection for the house residents from flood danger compared to a non-elevated house system which is more prone to flooding. Tikul and Thongdee (2015) reported that a suitable housing style helped to reduce livelihood problems during flooding, with a one-story house with a high basement being the most suitable housing style because it lets the water flow through the basement. Ourn and Suntornvongsagul (2015) studied one community experiencing repeated flooding in Cambodia and found that the houses in the community were built on high stilts to let the floodwaters pass through, clearly reflecting a mechanism adapted to flooding.

Second, although a stilt house can resist lateral loads of moving floodwaters at 1 meter-depth with a water speed of 3.05 m/s, if the level of floodwaters is deeper than 1 meter and flow with the velocity faster than 3.05 m/s there will be increased flood loads hitting the house. Under such conditions, the most vulnerable points at high risk of damage before other parts of the house are the base of columns and the joint between columns and stilt floor beams. The maximum reactive stress at those two vulnerable points might exceed the ultimate strength of their materials resulting in serious damage to the primary structure. Considering in detail the structural durability assessment of stilt houses, where the house consists of columns which extend from ground up to the roof without any joints in them,

the most vulnerable point was the base of the column as this is the connection point between the superstructure (structural members above the ground) and substructure (structural members under the ground, namely foundations) of the house. For a house with columns having joints on them (such as where the columns meet the stilt floor beams and are clearly a change in the column size or in the column material between under and above the joint), the most vulnerable point is the joint between the column and the stilt floor beam. Such a joint is the connection point between a vertical structural member (a column) and a horizontal structural member (a beam) in the house.

The connection points between the superstructure and substructure and between vertical and horizontal structural members are always the weakest points of the post and lintel structural system of a stilt house because they are the first point that will sway and move and then get damaged when struck by a lateral force. This is consistent with Allen et al. (2010) who studied lateral load resistance capacity in a bay of framing. They remarked that a bay of framing (a post and beam system) is mainly designed to resist axis or gravity loads. If a lateral load is applied to a bay of framing with ordinary joints, the bay will deform and collapse with a twisting motion and the top of a column that connects to a beams and the foot of the column will slide from its position. Such lateral load tends to push over beams and columns and then separate them (Figure 4).

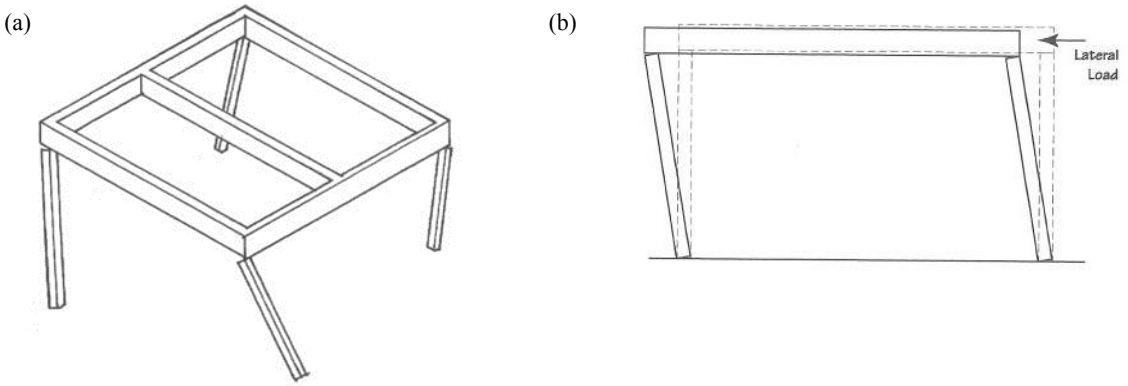


Figure 4. (a) Unbraced bay of framing will often collapse with a twisting motion; (b) lateral load tends to push over a beam and column (Allen et al, 2010)

Therefore, strengthening should be done to the base of the column and the joint between the column and the stilt floor beam in order to make the main structure of the house more resistant to any moving water force. Several studies have implied that the bottom of the post and the junction between the post and beam are the weakest points when struck by flood loads as well as remarking on how to make those weakest points more resistant to water force. Stephenson et al. (2018) indicated that the effect of lateral pressure from floodwaters is considered in relation to the resistance of the structure to being washed away. Concerning wash out, the connection of the structure to the foundation is a significant factor, since the friction action of the embedment of the post to the foundation is considered to resist flood loads and provide vulnerability reduction. Dilhani and Jayaweera (2016) found that reinforcing the superstructure of the house is one effective method to reduce flood damage. The building structure should be fixed to strong and deep foundations. The base of columns should not be free standing, but rather vertical reinforcement in columns should link foundations to the top of the superstructure walls and the roof. Zain (2016) found that the ways of making traditional houses in West Kalimantan, Indonesia to resist flood loads efficiently used posts which extended from the foundation up to the roof structure and the main columns are strengthened by roof and floor beams which go through the columns.

In addition, there have been some research projects studying the structural durability of stilt houses to lateral forces that are not flood loads. They definitely confirmed that the bottom of the column and the joint between the column and beam are the points that should be strengthened to better resist lateral loads. Madeali et al. (2018) reported that in the primary structure of Bugis traditional houses in Indonesia formed using a column and beam system, the joint between the column and the beam (both roof and floor beams) should be fixed or have a rigid joint such as a mortise and tenon. With this type of joint, Bugis houses can withstand wind loads at higher levels. Wasilah (2019) stated that the success of

Ammotoan stilt houses in South Sulawesi regarding their resistance to earthquakes was the system of columns and joints. The columns used a deep pile system where the main piles of the structure are embedded about 1.00 m into the ground. Rigid joints are used to connect the pillars and beams to the floor.

Third, diagonal and horizontal bracing members, fixed among stilt columns and perpendicular to the flow direction of floodwaters, were nearly useless if they were not above the flood level. Instead of permitting floodwaters to flow through rapidly, such bracings became water obstructions which increased reactive stresses and resulted in a high risk of severe damage to the core structure of the house. This does not mean that bracings are not permitted but rather that diagonal and horizontal bracing elements should be aligned in parallel with the water flow direction and installed above flood height so they do not hinder the flow of floodwaters and can increase the strength of the main structure to resist lateral forces (flood loads) efficiently. This finding corresponded to Liao et al. (2016) who studied stilt houses in the Vietnamese Mekong Delta, especially in areas subjected to floodwaters that coincided with a storm to produce waves that could collapse the house. They found that to mitigate the flood hazard, many households in those areas reinforced their stilt houses by tying bamboo poles between the stilts. Dilhani and Jayaweera (2016) mentioned attributes of flood risk mitigation strategies in dwellings, with one being to strengthen the main structure of the house by using bracing members. They suggested bracing of the adjacent posts diagonally in order to keep the house from leaning. Parekh (2018) reported that where a building is constructed so that the lowest floor is elevated above the regulatory flood height, the stilts should be compact and free from unnecessary appendages which would tend to trap or restrict free passage of debris during a flood. Bracing, where used to provide lateral stability, should be of a type that causes the least obstruction to the flow and the least potential to trap floating debris. Chaves (2015) stated that the horizontal structural members of the building not above the flood height are considered to be obstructions that can transmit the force of water impacts to the rest of the structure.

The above observations and discussion strongly reinforce that stilt houses can be constructed in flash flood-affected areas with some specific reinforcement methods to some particular parts of the house. In the five study locations (referring to the numerical data from the field survey), the income/year/household of most local residents was approximately USD 9,000 whereas the expenses/year/household were approximately USD 7,100. Each household had savings of USD 1,900 per year, or 21% of the income which is considered high. In Thailand, the current cost of a concrete stilt house is between USD 20,000 and 23,000 and the cost of wooden stilt housing is approximately USD 25,000 to 26,000 (Thai Appraisal and Estate Agents Foundation, 2018). A comparison between the construction costs of a stilt house and the savings proportion of the household indicated that the households could take out a loan to build their stilt house and their high proportion of savings would likely enable them to meet the repayment. With this financial status, owning a stilt house should be affordable to local residents.

The stilt house is an obvious example of flood damage mitigation. This type of house is representative of a flood adaptation paradigm that does not try to control or change the flood regime but rather it attempts to coexist with flooding as well as minimizing damage. The field survey showed it was a fact that some flood risk areas that have engineering structures to control or prevent flooding still face flood events. Moreover, some locations do not have such structures. This might emphasize that flooding cannot be completely prevented. Therefore, it might be better if people in flood risk areas were self-reliant by adopting flood adaptation measures instead of depending solely on flood controls. In addition, one important thing that local residents need to learn after the flood event is that they must adapt to be able to cope with flooding properly and safely. This means not only adapting their livelihoods during flood, but that adaptation should cover adjustment of their housing style. They should observe and learn which types of house are the best for coexisting with water current and suffer the least damage and they should also look for opportunities to build such a house.

Nevertheless, the structural durability assessment of stilt houses to flash flooding in this study was undertaken based on conditions of a flood depth of 1.00 m and a water flow velocity of 3.05 m/s. Consequently, these results cannot be generalized to the structural durability of stilt houses in all locations of flash flooding. The flood depth used in this research was the average value derived from only five study sites and as such, it cannot represent water depths at all locations of flash flooding. The flood velocity used in this research was based on some reliable sources instead of actual data from the study sites because of the lack of

recording instruments. Consequently, the velocity does not necessarily represent the real speed of flow water in a real place. In fact, flood depth and speed vary depending on the topography of each area. Further research should be undertaken on sites having different flood heights from those in the current study (deeper and shallower than 1.00 m) and on sites that have accurate measurement or recordings of the speed of floodwaters. Knowing the flood depth and velocity accurately will result in more precise calculations of flood loads and more closely reflect reality, this making the assessment more valid.

4. CONCLUSION

The results from this study revealed that the main structure of both wood and concrete stilt houses can resist flood loads of moving water at 1.00 m depth with a flow speed of 3.05 m/s. However, if the house is subjected to water deeper than 1.00 m and faster than 3.05 m/s, the house might be damaged. The points having a high risk of damage are the base of the column and the joint between the column and beam; these points require some strengthening. Where a house has horizontal or diagonal bracing members fixing the main structure and these are perpendicular to the flow and not above flood level, instead of making the house structure more stable, they become water obstructions that increase the reactive force to the main structure.

It can be concluded that for a stilt house to effectively withstand flash flooding, the main structure needs to be reinforced. First, the column base should be embedded into the ground and fixed to deep and strong foundations. The friction of the embedment of the column into the foundation helps to resist flood loads. Second, the connections between the column and beam (both roof and floor beams) should be rigid or fixed joints to reduce the opportunity for twist motion at these joints when they are hit by moving water. Third, the bracing members (both diagonal and horizontal) that are fixed to the main structure should be aligned in parallel with the water flow direction and be above the flood height to avoid becoming flow obstructions that can transmit the stress of water impacts to the main structure.

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