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Paper:

Tsunami Vertical Evacuation Buildings – Lessons for International Preparedness Following the 2011 Great East Japan Tsunami

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Tsunami vertical evacuation is an important strategy for enhancing disaster preparedness because it provides an alternative to evacuation inland or to high ground in areas at risk of local tsunami. A large number of tsunami vertical evacuation buildings provided safe refuge in the inundation zone during and immediately after the Great East Japan tsunami on March 11th 2011. This paper discusses observations of such buildings in connection with themes that arose during semi-structured interviews with local disaster prevention and emergency services officials in Iwate and Miyagi Prefectures in October 2011. The implementation of key factors in the development of tsunami vertical evacuation strategies are assessed with reference to previously published guidelines, enabling lessons to be applied in the current and future development of such strategies internationally. The most important factors for designating tsunami vertical evacuation buildings are that they be reinforced concrete construction with sufficient height in relation to inundation depth. Also important to the success of such vertical evacuation strategies are community engagement, building owner agreement, consistent and clear signage, 24-hour access and evacuee welfare.

Keywords: tsunami vertical evacuation, Great East Japan Tsunami, preparedness, community engagement, evacuee welfare, evacuation signage

1. Introduction

Tsunami vertical evacuation strategies are designed to provide safe refuge within a tsunami-inundated area by offering sufficient elevation above the maximum water level. Safe elevation may be provided by artificially-raised open ground, by towers designed specifically for evacuation or by buildings in daily use that can be used for evacuation when required. There is a need for such strategies, particularly where there is a local tsunami hazard, because many people may not be able to evacuate inland or to natural high ground (the recommended best option) due to short tsunami arrival times in the face of long evacuation distances, road congestion or damaged infrastructure.

Japan has led initiatives in vertical evacuation through the establishment of government guidelines for the construction and management of tsunami vertical evacuation buildings (TVEB) [1], although it was noted during this research that such buildings had been designated prior to the publication of these guidelines, e.g., as early as 1982 in Kesennuma City. Similar guidelines have since been published in the United States by FEMA [2, 3], in addition to numerous studies on structural requirements of evacuation structures with respect to tsunami forces, e.g., [4–7]. Although extremely important, less research has been carried out on evacuation dynamics inside TVEB [8]. In addition to structural issues, a vertical evacuation strategy requires the consideration of community engagement, building owner agreement, consistent and clear signage, 24-hour access and evacuee welfare.

The 2011 Great East Japan tsunami provided the first opportunity to assess a tsunami vertical evacuation strategy experiencing significant inundation heights in multiple locations. The use of TVEB (in Japan, called '*tsunami-hinan*' buildings) effectively mitigated loss of life in the locations visited during this research. At least 5,428 people took refuge in 37 designated TVEB and in four of the six locations the average number of people per TVEB exceeded 150 (**Table 1**). This paper discusses key factors in the success of this strategy through observations made at TVEB and the outcomes of interviews with local officials, to inform future development of tsunami vertical evacuation strategies internationally.

2. Method of Investigation

A field survey was carried out during October 2011 to investigate tsunami vertical evacuation on March 11th, 2011, in six towns and cities in Iwate and Miyagi Prefectures. Four locations – Kamaishi City, Ōfunato City, Ke-

Table 1. Summary of TVEB in locations visited during this research. Field observations were not made at all buildings listed. A full inventory of known building features is provided by Fraser et al. [10]. Not all buildings were available for observation during field investigations, but data on those buildings has been collected through interviews.

City / Town	Kamaishi City	Ōfunato City	Kesennuma City	Minami-Sanriku Town	Ishinomaki City	Natori City
Environment	Ria	Ria	Ria	Ria	Plains	Plains
Max. Tsunami Height[(a)]	30.40 m	31.99 m	23.00 m	20.54 m	25.84 m	12.96 m
Mean Tsunami Height[(a)]	14.31 m	13.13 m	10.50 m	12.63 m	6.51 m	4.36 m
First wave arrival time after EQ[(a)]	28 mins	25 mins	n/a	n/a	23 mins	63 mins
Land-use	Industrial (port & steel factory), small commercial & residential further inland	Commercial, industrial at port front, residential,	Largely industrial and commercial at port front, residential further inland	Residential and commercial	Extensive commercial & industrial at port front, residential further inland	Largely residential
No. Fatalities[(b)]	1,047	425	1,368	875	3,739	966
Fatality rate of area inundated	8%	2%	3%	6%	3%	8%
No. TVEB	3	7	16	4	3	4[(c)]
No. people saved in TVEB	50	22[(d)]	2,426	694	500	1,736[(e)]
Average no. people saved in each TVEB	17	22[(d)]	152	174	167	579[(e)]
No. built with TVEB in mind	0	0	2	1	0	0
TVEB Construction	RC, Steel Frame	RC, Steel Frame	RC, Steel Frame	RC	RC, Steel Frame	RC
Range of TVEB storeys	2 to 3	1 to 3	1 to 4	2 to 4	1	1
No. TVEB with external signage	2	0	2	1	0	0
Dedicated welfare resources	0	0	2	0	0	2

[(a)]Tsunami data from field surveys [30]; [(b)]Casualty data at February 14th 2012 [31]; [(c)]Buildings designated as refuges for multiple-hazard evacuation, not specifically as TVEB; [(d)]Numbers of people saved are available for only one TVEB in Ōfunato City; [(e)]Numbers of people saved at Sendai International Airport are not included.

sennuma City, and Minami-Sanriku Town – are located on a ria ("drowned river") coastline. Two other locations – Ishinomaki and Natori Cities – are located on flat low-lying coastal plains. All of these locations represent densely developed coastal urban environments less than 20 m above sea level with varying degrees of mixed commercial and industrial land-use around a port and dense residential housing further inland (**Table 1**). The major differentiator between locations is the physical environment and the impact of this on tsunami height: the ria coastline suffered extreme run-up [9] due to amplification of the tsunami in narrow bays, while lower maximum tsunami height but greater inland extent was typical on the plains (**Table 1**).

Planned interviews were carried out with officials from municipality government civil protection, emergency management, fire, and police departments. The aim was to gain knowledge of TVEB designation, requirements for effective use during evacuation, locations of TVEB, public awareness and use of vertical evacuation during the Great East Japan tsunami, and the nature of any post-event strategy review. Interviews provided insightful comparisons of the strategy in place on March 11th 2011, regarding recommendations in government guidelines [1]. Written questions were translated into Japanese and provided to interviewees in advance of interviews, which were carried out in Japanese using a semi-structured format [10]. Several local residents were also interviewed during field investigations. Simultaneous spoken translation between Japanese and English was provided during all interviews by the Japanese authors and a professional translator.

Due to the timing of fieldwork seven months after the tsunami, interviews drew upon information obtained by local researchers and collated by municipal governments. Observations made by the authors in the field contribute to the discussion of damage sustained by TVEB and building features such as signage and access routes. These ob-

Fig. 1. Map and images of TVEB in Minami-Sanriku Town, including numbers of people saved and tsunami inundation marked in yellow [29]. (A) Matsubara apartment block; (B) Takano-Kaikan conference venue; (C) Shizugawa Hospital; (D) Fishing Cooperative.

servations are drawn from the present field survey and a previous investigation in June 2011 in which the authors participated [11, 12].

3. Key Features of TVEB

3.1. Tsunami-Resistant Construction

For a building to be officially designated as a TVEB in Japan, it must meet several construction requirements specified in government guidelines [1]. These dictate that a building must be of reinforced concrete (RC) or composite steel-reinforced concrete construction and conform to 1981 building code seismic standards, while also being able to withstand tsunami loading appropriate to the expected inundation depth. The building must satisfy minimum height requirements according to estimated maximum inundation depth: where expected maximum inundation depth is less than one metre, the building must be two storeys or higher; three storeys or higher for less than two metres in depth; and four storeys or higher where inundation depth of three metres or more is expected. Of TVEB observed during this research, 80% were of RC construction and 20% were steel frame, 31% were three-storey and 34% were four-storey or greater.

Post-tsunami building damage surveys from Tōhoku underline previous field observations (e.g., [13, 14]) that RC is the construction type most resistant to tsunami wave loading and debris impact. There were many cases of RC structures failing in Tōhoku: overturning was observed in Onagawa Town [11, 12] and Otsuchi [15] where tsunami height exceeded 16 m. In Minami-Sanriku Town, scour of foundations caused building collapse and debris strike caused the collapse of upper storeys of some RC buildings [11]. Damage to designated TVEB, however, was generally limited to broken glazing, damaged fixtures and fittings, and debris impact to external cladding, stairwells, railings or balconies, even at flow depths of up to 20 m, as in Minami-Sanriku. No observed TVEB sustained sufficient earthquake damage to prevent its use during the subsequent tsunami evacuation.

The extent of foundation scour sustained during the tsunami reportedly resulted in some TVEB requiring demolition, but these buildings fulfilled their immediate vertical evacuation function. The Matsubara apartments at the harbour front in Minami-Sanriku (A in **Fig. 1**) were scoured at all corners of the building to at least two metres below previous ground level, exposing numerous piles that then were submerged by encroaching sea water. The welfare centre and prefectural government offices in Kesennuma (F and H, **Fig. 2**) suffered less extensive scour, but exhibited scour holes of significant depth at one or two locations at each building [11]. The occurrence of significant foundation scour highlights the continuing need for resistance against foundation scour of TVEB, although the buildings in question maintained life-safety in this event and could, with further detailed investigation, provide good models for future TVEB.

Significant debris strike occurred at Shizugawa Hos-

Fig. 2. Map and images of nine vertical evacuation buildings in Kesennuma City, including numbers of people saved and tsunami inundation marked in yellow [29]. These comprise office buildings (A, F, G, I); a cannery (B), a retail building (C), welfare centre (D), a car parking deck (E) and a community centre (H).

pital in Minami-Sanriku (C in **Fig. 1**), where the shore-facing side of the buildings exhibited many broken RC columns at third storey balconies [11]. An office building at the inner harbour in Kesennuma (A in **Fig. 2**) sustained debris damage to external stairwells, but the stairwells appeared functional. Although TVEB generally sustained minor damage due to debris strike, it was not possible to confirm the type of debris that caused the observed damage. It is therefore not possible in this paper to explicitly evaluate the resistance of the observed TVEB to debris impact, for example to ascertain the level of damage in the case of a large ship striking the TVEB.

The performance of steel-frame buildings warrants a brief discussion here to clarify the suitability of steel-frame construction for TVEB. Numerous steel-frame structures remained standing with extensive removal of external cladding up to the level of inundation [11], suggesting that the tsunami flowed 'through' the structure once cladding and external walls were washed away. Despite this, many other steel buildings exhibited bending, buckling, twisting and fracture of structural columns or joints [16]. It is therefore possible that steel-frame buildings can provide life safety during tsunami, provided that they are of sufficient height. However, the substantial damage to cladding and high potential for failure of structural members from wave loading or debris strike makes them unsuitable for official designation as TVEB.

Observations from this event suggest that construction requirements for designating TVEB in Japan were sufficient with respect to extreme tsunami wave heights up to 20 m. Government guidelines [1] therefore provide suitable guidance for appropriate construction of TVEB internationally. Of course, Japan benefits from well-developed seismic codes and this provides a suitable basis for tsunami-resistant construction, which may not be available in all countries. Detailed structural evaluations will provide more robust analysis of the tsunami impact than the external investigations possible during this research, and are vital to inform construction requirements in the future.

3.2. Sufficient Height of Safe Storeys

The provision of safe storeys in TVEB – storeys providing refuge above the maximum tsunami height – is a vital component of a vertical evacuation strategy. Japanese government guidelines provide graded requirements for TVEB safe storeys (see 3.1), but on March 11th there was inundation of storeys considered safe in previous hazard assessments. During interviews, local officials expressed concern about the current recommended height of TVEB.

In Kesennuma, several TVEB were within one metre

of being overtopped when the tsunami arrived at low tide. The four-storey Wedding Plaza in Ōfunato, Shizugawa Hospital (four- and five-storey buildings) and Matsubara apartments (four storeys) in Minami-Sanriku were all inundated to the fourth storey, leaving only the roof as a safe refuge. At Shizugawa Hospital, 320 people survived on the roof and fifth storey of the west building, but it was not possible to move many immobile patients to a safe storey [17]. Despite being only two storeys in height, the fishing co-operative building in Minami-Sanriku (D, **Fig. 1**) was designated as a TVEB through its ownership by a public organisation looking to protect its workers. Fortunately the building was unused on March 11th as people travelled to nearby high ground; flow depth of around 12 m (twice the building height) occurred at this building.

In light of the examples above, interviewed officials in Kesennuma and Minami-Sanriku suggested that a minimum height of five storeys should be set for future designation of TVEB. Although increasing the height threshold for safe storeys appears an obvious solution, the use of a single minimum height on a national scale may rule out using suitable buildings of lesser height in areas where the maximum potential tsunami height has been robustly assessed to be lower. For example, on the coastal plains where maximum tsunami heights were lower than on the ria coastline, many single-storey and two-storey buildings in Natori and Ishinomaki provided safe refuge on March 11th, indicating the value of low-rise buildings where it is appropriate to the inundation height. Rather than construct all TVEB to achieve a single 'safe-storey threshold' at five storeys, robust probabilistic hazard assessment and site-specific analyses using maximum credible tsunami-generating earthquakes (especially local-source subduction events) could provide suitable local thresholds. This approach would allow continued use of current Japanese government guidelines in areas of lower maximum inundation height and provide greater flexibility in designating TVEB of fewer storeys.

3.3. Building Location Planning

Government guidelines [1] encourage planning of TVEB locations to provide adequate refuge capacity and distribution in areas where it is not possible to evacuate to high ground. Optimum distribution of buildings can be derived from local population estimates, evacuation routes and walking speeds, e.g., [18, 19] and [20]. Where there is reliance on existing buildings in a developed urban area, the number and distribution of TVEB may be constrained by the availability of suitable buildings or land on which to build. As a result of this and variable estimated tsunami hazard, TVEB were distributed very differently in the six locations investigated.

Kesennuma City had 16 officially designated TVEB relatively well distributed across the coastal areas of the city; nine are in the area shown in **Fig. 2**. With the exception of the car park deck over the fish market (E, **Fig. 2**) and the prefectural government office (F, **Fig. 2**), which were constructed with tsunami vertical evacuation as a planned function, these buildings were all existing structures that were identified as suitable TVEB because they conformed to government guidelines. These provided refuge to 2,326 people, although the number of people sheltering in each building was highly variable. For example, the car park deck in the busy dock area and fish market received 1,000 people and substantial numbers went to other TVEB in areas far from high ground (B, F, G, and H in **Fig. 2**). Buildings closer to high ground received very few people (buildings A and C in **Fig. 2** received zero and five people respectively). It is expected that the variability in number of people at each TVEB is due to the concentration of population at the time of evacuation, proximity of the TVEB to high ground, awareness of the TVEB function and variable evacuation response to natural or official tsunami warnings [10]. However, data on evacuee travel routes and TVEB choice was not available at the time of this study, so it is not possible here to robustly determine reasons for the variability.

Minami-Sanriku Town had four official TVEB (**Fig. 1**), of which only the Matsubara apartment building was constructed with prior consideration of vertical evacuation functionality. Constructed in 2007, this TVEB was intended to provide refuge to large crowds at the adjacent sports ground. There were initial public concerns about the building being used for tsunami evacuation due to its port-front location, but the local community was informed that the roof level would constitute a safe elevation. It was reported during interviews that large numbers of people taking refuge in TVEB primarily comprised people who were in the building or in the immediate vicinity at the time of the evacuation warning, suggesting that people did not travel far to TVEB. At Shizugawa Hospital, 69% of the 320 evacuees were hospital staff or patients and at the Takano Kaikan building, the majority of the 330 people saved were attending a community meeting at the building.

There were only two TVEB in Kamaishi City (Kamaishihamachō Post Office and a government office, **Fig. 3**). Relatively few people (50) took refuge in these buildings during the tsunami, perhaps owing to the 66.4% rate of immediate evacuation [21] and access to high ground within one kilometre of the port and industrial areas. The government office provided refuge to people who became stuck in vehicles due to traffic congestion. An additional building, the Hotel Horaikan at nearby Unosumai, was constructed with vertical evacuation in mind (see 3.8). Additional TVEB had been planned in the port area of Kamaishi, but they had yet to be constructed by March 11th.

In locations where minimal tsunami inundation was expected based on previous events and numerical modelling, there was little planning for vertical evacuation and therefore few designated TVEB, however, informal vertical evacuation to non-designated buildings was significant in mitigating loss of life. Around 500 people sought refuge at three designated buildings in Ishinomaki City: York Benimaru shopping centre, the Homac hardware centre,

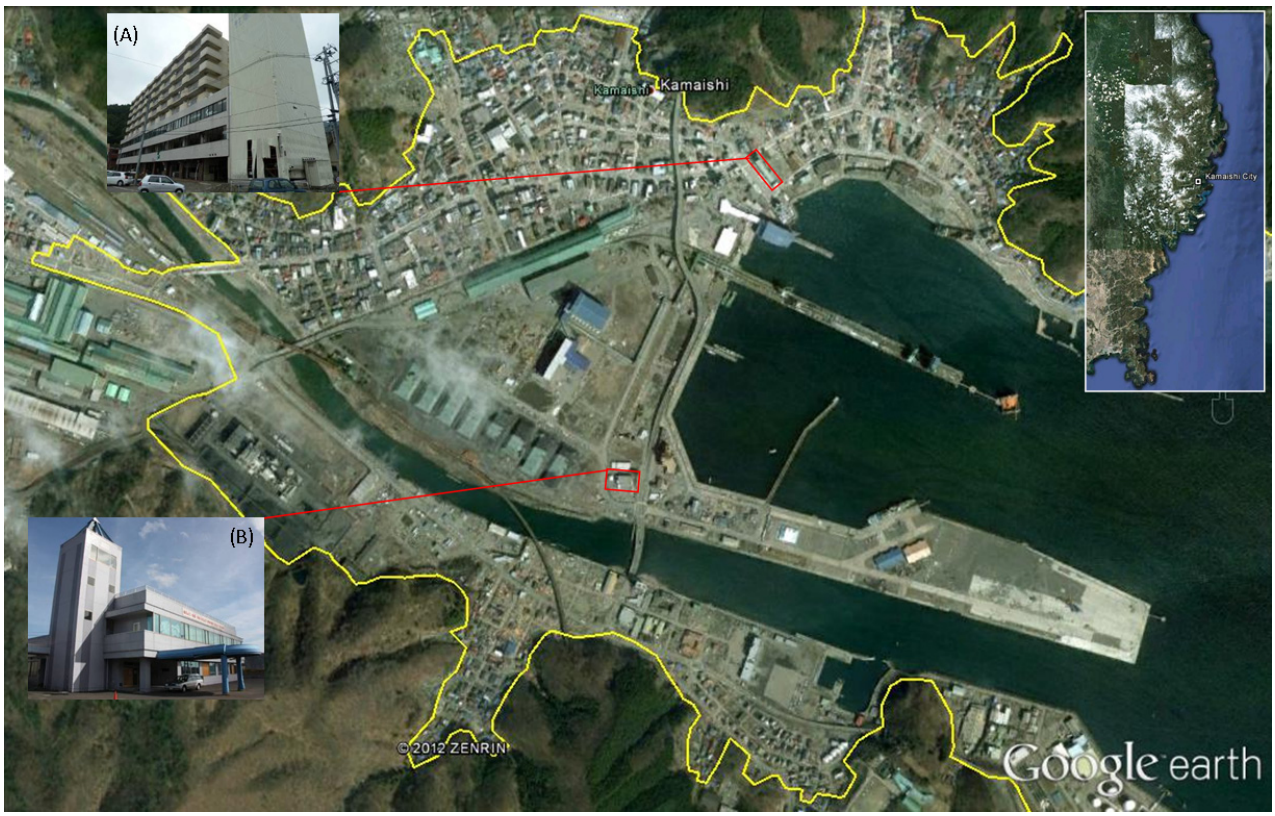

Fig. 3. Map and images of vertical evacuation buildings in Kamaishi City and tsunami inundation marked in yellow [29]. These are the Kamaishihamachō Post Office and apartment building (A) and government offices (B).

and the Hotaru funeral facility. The local interviewee reported that an additional 50,000 people took refuge in approximately 260 official earthquake and landslide evacuation buildings and other schools, temples, shopping centres and housing. Informal vertical evacuation also occurred in Kamaishi City and Ōfunato City in cases where buildings suggested by the community did not met official designation criteria (see 3.9), but the number of non-designated buildings was not available to quantify this further.

Four public buildings in Natori City had been specified by the municipality government as general hazard evacuation centres (but not specifically TVEB): Yuriage Community Centre, Yuriage Junior High School, and Yuriage Elementary School. Sendai International Airport at Kitakama was also an evacuation location. These buildings were not designated as TVEB because they were located outside of the estimated tsunami hazard zone, but proved effective for vertical evacuation in this event in further examples of informal vertical evacuation.

These observations show that vertical evacuation can be successful where the best possible distribution of TVEB cannot be achieved, and that informal vertical evacuation saved many additional lives in areas of low to moderate tsunami height. Planning TVEB in the redevelopment of tsunami-affected areas in Tōhoku is encouraged, but where there are suitable existing buildings, those buildings should also be used as effectively as possible.

3.4. Building Capacity

Any building designed as an evacuation refuge must have sufficient capacity for the estimated number of evacuees. Analysis of potential demand can be carried out using estimates of local population, evacuation routing, travel speed and distribution of safe refuges, including safe areas outside of the inundation zone and vertical evacuation structures [18–20]. Facility capacity also relies on estimates of in-refuge space required by each evacuee [1, 2].

Detailed study of building capacity or evacuees' experience while in the buildings was not carried out as part of this research. During interviews, however, there were no reported cases of buildings exceeding capacity on March 11th. The majority of designated buildings were substantial structures with a requirement for large capacity in their regular function (e.g., schools, apartments), therefore are more likely to satisfy government guideline capacity requirements [1]. It was noted in several interviews that even where TVEB existed, the recommended primary evacuation action was to go to high ground (to exit the tsunami hazard zone, rather than remain in it). This guidance may also have acted to reduce evacuee demand on TVEB where they were close to high ground (see 3.3).

Table 2. TVEB 24-hour access methods, showing numbers of buildings for each method in the locations surveyed. Data on external stairs is from field observations. Data on alternative access methods is from local interviews. Not all TVEB were accessible for observation during field investigations.

City / Town	Kamaishi City	Ōfunato City	Kesennuma City	Minami-Sanriku Town	Ishinomaki City	Natori City	All locations
Total no. of TVEB	3	7	16	4	3	4	37
Building open 24-hrs	0	1	2	1	0	0	4
Night-time residents	0	0	0	1	0	0	1
External stairs	1	1	2	1	2	2[(a)]	9
Local key-holders	1	0	0	0	0	3	4
Forced entry allowed	0	0	2	0	0	0	2
Night-time security staff	0	0	1	0	0	0	1
No external stairs, alternative access unknown	1	1	3	1	1	1	8
Access method unknown (building not observed)	0	4	6	0	0	0	10

[(a)] Schools in Natori have external stairs but staff members are also organised to open the building.

3.5. Building Access

TVEB must provide access to safe storeys at all times. The type of access (internal or external stairs, width of entrances) is a key factor in the time required to access the building and move to safe storeys [8]. External stairs are commonly installed for emergency exit from buildings in Japan, e.g., in fires or earthquakes, and offer the most efficient way to access safe storeys of an evacuation building [8]. These stairs may not always lead directly to the roof, but should enable direct access to safe storeys.

External stair or vehicle ramp access was the most commonly recorded access method at TVEB investigated, available at nine (33%) of observed TVEB (**Table 2**). Where direct external access from the ground floor to safe storeys is not available, people may need to gain access by alternative methods, which are included in government guidelines [1] and were cited in our interviews (**Table 2**):

- Some private buildings have security personnel present overnight who will open doors for emergency access, e.g., the Prefectural Office in Kesennuma.
- Due to regular building function it is staffed or has residents present 24 hours a day, e.g., Shizugawa Hospital, Hotel Horaikan, the Matsubara apartments, and two other TVEB.
- Representatives of local residents act as key holders to enable access outside of office hours, e.g., two community representatives living near the government building, Kamaishi; two Yuriage schools and a community centre, where key holders are informed by telephone that they need to open the building.
- Building owners agree to the forcible breaking of doors and windows to enable emergency access, e.g., Kesennuma Junior High School and the National Office in Kesennuma.

The provision of 24-hour access may require installation or retrofitting of adequate stairs and entrances, or additional investment in structural renovation and staffing requirements. It can also affect building security and lead to concerns about crime [8]. During our interviews there were no reports of restricted building access on March 11th, because the tsunami occurred during at 14:46 (local time) when TVEB were unlocked and occupied. It was acknowledged by several interviewees that access issues may have hindered evacuation if the tsunami had occurred at night. In Natori City, interviewees noted that although two key holders were trained to go to each evacuation building in case of night-time evacuation, they had not been trained for this scale or type of evacuation. This highlights the importance of appropriate training and responsibility on the part of key holders to immediately open TVEB in the event of tsunami.

Allowing evacuees to enter TVEB by force is unlikely to be a suitable solution for buildings containing sensitive data, such as public offices or commercial premises. Satisfying access requirements of TVEB in different communities and with varying regular functions requires dialogue among evacuation planners, building owners and the community (see 3.9) on a case-by-case basis to define the most appropriate solution for each building and to ensure that the local community is aware of and trained in the correct access method.

3.6. Fire Resistance

One reason for promoting evacuation to high ground rather than into TVEB is that safety cannot be guaranteed in the event of large debris strike or fire at such buildings. Fire was a significant issue during and immediately after this tsunami; many buildings burned and some evacuation centres narrowly avoided catching fire while occupied by evacuees. In Kesennuma, over 50,000 litres of oil spilled from ruptured oil tanks and engulfed several areas around TVEB. It was reported that a government committee had

Fig. 4. Vertical evacuation signage used in Japan. (A) Sign displayed prominently on the Kamaishihamachō Post Office, (B) signage on the Matsubara apartment block in Minami-Sanriku, (C) a sign displayed above an entrance to the Kamaishihamachō Post Office (Translation: 'Evacuation building entrance (stairways)').

been set up to prevent such spillage from occurring again, and the fire-proofing of evacuation structures was raised as a consideration for the future design of such buildings. In Ishinomaki, fire spread within one hour of the earthquake to the Kadonowaki school building where people had taken refuge, but evacuees were fortunately able to relocate to high ground nearby before fire spread to the school.

Observations from Tōhoku support the need for solutions to minimise the spread of fire and to prevent fire damage to TVEB, such as fire-retardant cladding and shutters. The potential for fire damage also led to one interviewee citing the need for emergency communication links in TVEB in case of urgent need of rescue (see 3.10).

3.7. Evacuation Signage

Effective route signage is a key component of tsunami evacuation strategies, for on-going education and awareness training as well as for direction in an evacuation [22]. Signage is required inside a building to show exits and safe routes and to speed up the movement of evacuees [8]. Signage is also necessary outside a TVEB to highlight the building function and to show the most appropriate access route to safe floors, particularly for those who may be unfamiliar with a building and its vicinity, e.g., tourists and emergency responders. There has been previous recognition of the disparity in tsunami hazard awareness between resident and non-resident populations [23]; it is vital that a vertical evacuation strategy accounts for both groups, and displaying effective consistent signage is one method of achieving this. This study did not investigate the use of TVEB specifically by non-resident (transient) populations in Tōhoku because this level of data was not available. Consistent vertical evacuation signage (**Fig. 4**) for buildings is recommended in government guidelines [1] but unfortunately, prior to March 2011, the application of such signage was limited and the retrofitting of signage for existing buildings was uncommon. Only five buildings were observed during our field survey to have official signage: the Kamaishihamachō Post Office and Hotel Horaikan in Kamaishi, Matsubara apartments in Minami-Sanriku, the prefectural government office and the Yoyoi cannery, both in Kesennuma. The high numbers of evacuees taking refuge in designated buildings despite the absence of signage suggests that awareness of TVEB was high among people in the area at the time of the tsunami, although further research into evacuee behaviour should aim to identify any impact that signage may have had on destination of evacuees. In the meantime, consistent signage should be adopted and applied to all TVEB, including retrofitting of existing buildings that become designated. Signs should be clearly displayed at the top of each building and above entrances to clearly indicate the most appropriate access route to upper storeys. Signage should be nationally consistent with approved standards for style and messaging.

3.8. Building Owner Agreement

The need to gain agreement of building owners to designate their buildings as TVEB is an issue that has been raised in projects in the United States [24, 25], New Zealand [26] and Japan [1]. During our interviews, local officials indicated that owners were generally receptive to the requirement for TVEB when approached about using their building for vertical evacuation, although some owners had concerns over the access and responsibility of evacuees.

Disaster prevention officials in Kesennuma found building owners to be extremely cooperative in the designation of buildings. The owner of the Hotel Horaikan in Kamaishi had proposed that her building be designated as an alternative to construction of defences that would block beach access. She had previously seen evacuation to buildings in the 2004 Indian Ocean tsunami and had built her hotel as a three-storey building so it could be used in tsunami evacuation. The owners of the Takano Kaikan in Minami-Sanriku (B, **Fig. 1**) were described as recognising the corporate social responsibility of agreeing to use their building for evacuation, and the Minami-Sanriku fishing cooperative encouraged the designation of its building (D, **Fig. 1**) to protect its workers. There was no disagreement from building owners in Ishinomaki when they were approached by the city; in this case, it was agreed that the city would pay compensation to building owners in the event of damage or costs incurred when people evacuate to the property, which follows government guidelines [1].

One interviewee reported initial resistance in Ōfunato City from building owners approached about the potential use of their buildings as TVEB. The owners' concerns focussed on night-time access and on who would be responsible for evacuees while in the building, but following discussions with the community the owners agreed to their buildings being used. This suggests that leveraging community interest and encouraging owners to see the provision of the building as a benefit to the community was an

effective way to gain support of building owners in Japan, and that a similar approach should be taken in implementing vertical evacuation strategies elsewhere.

3.9. Community Engagement

The use of workshops in consultation and negotiation for tsunami vertical evacuation strategies is a key component of Japanese guidelines [1], and participation of local community volunteer disaster prevention groups in building identification and evacuation mapping were common themes in our interviews. Community engagement to encourage ownership and awareness are also important components of tsunami preparedness initiatives in the United States [22, 24, 25] and New Zealand [27].

In Ōfunato City, the identification of buildings suitable for vertical evacuation was led by community groups that approached the municipal government with potential structures for designation. Some of those structures did not meet official structural requirements, so they did not become officially designated, yet these buildings were used successfully on March 11th in informal vertical evacuation (see 3.3). In Kamaishi, several community-identified structures did not meet government requirements therefore local authorities did not advise their use during tsunami evacuation. Only the building owners used these buildings on March 11th 2011 and although the lowest three storeys were damaged, the occupants survived. Community disaster prevention groups in Kesennuma reportedly approached the owners of the Yoyoi cannery in the Hamacho neighbourhood (B, **Fig. 2**) about using it for vertical evacuation, after which it became officially designated.

Engagement with the community after building designation is important for developing and maintaining awareness of the vertical evacuation strategy, and is a key component of government guidelines. The Yoyoi cannery had signage at entrances and was used in ongoing training as part of local biannual evacuation exercises. In contrast, once the use of official buildings in Ishinomaki had been agreed, the arrangement was broadcast on local news, but their function was not publicised widely and no signage was applied. In Minami-Sanriku, exercises reportedly involved evacuation to high ground only, but signs depicting past tsunami heights include directions to TVEB. It is unclear from the interviews how widespread the incorporation of TVEB into annual evacuation exercises is elsewhere in Iwate and Miyagi Prefectures, but these observations suggest a high degree of variability among municipalities.

Community engagement in the development of vertical evacuation strategies should be encouraged to foster familiarity with TVEB as part of wider preparedness and evacuation plans. TVEB should be incorporated into tsunami evacuation drills to enhance the awareness of their availability and use. Evacuation to high ground should remain the training priority and preferred option, but the use of TVEB should be practised where conditions are likely to prevent people reaching high ground during a local tsunami.

3.10. Evacuee Welfare in TVEB

Evacuees were stranded in some TVEB for up to two days during and following the Great East Japan tsunami due to standing water and debris blocking building exits. Our interviews examined the availability of welfare in TVEB, such as the provision of food and water, shelter, warm blankets and clothing, sanitation, and emergency communication links to disaster prevention officials or emergency services. It is noted that in Japan, TVEB are considered primary refuges for short-term use and that welfare provisions for medium- to long-term care are usually provided at secondary evacuation or welfare centres.

It was reported during interviews that provisions were available at the Prefectural Office in Kesennuma and at South Kesennuma Elementary School, but these were appropriate for a six-hour occupancy period only. It had been assumed that after six hours residents would be able to get to welfare centres. However, evacuees had to remain in these building until March 13th, when they were rescued after debris had been cleared. Similarly, evacuees at Yuriage Elementary and Yuriage Junior High schools were required to remain until March 12th, when they had to exit by walking through standing water. The Junior High School had very limited provisions for evacuees, and those at the community centre were on the ground level, which became inundated. There was no emergency communication equipment at either location, although this is recommended in government guidelines [1].

In Ōfunato, provisions were said to be available at the shopping centre due to the regular function of the building, but no specific arrangements had been made to provide short-term support for occupants in the event of a tsunami. As with retail units, apartment buildings are likely to have some provisions and shelter due to their regular residential use. The official interviewed in Ōfunato highlighted the importance of providing communications links in all refuges to facilitate contact with emergency services, especially in cases requiring urgent rescue when cell phones or other radio systems are not functioning, e.g., if threatened by fire or serious illness.

Several interviewees cited cases of people leaving TVEB prematurely and being killed by subsequent tsunami arriving. Although adequate provisions may help reduce the need or urge for evacuees to leave a refuge earlier than necessary, further work is recommended to assess evacuee decision-making in this regard. With long-term tsunami preparedness in mind, Sharma and Patt [28] show that evacuees' previous experience in the quality of their stay in an evacuation shelter positively influenced their response to warnings in future. Therefore, the provision of amenities for evacuations in the short-term may yield benefits for long-term mitigation.

An important challenge recognised by the official interviewed in Minami-Sanriku and an area requiring further work is the assessment of adequate resources for a TVEB. It is difficult to say how many people will use any given building and therefore ensure adequate welfare resources, although evacuation modelling can help to estimate likely evacuee numbers once the coverage area of a TVEB is

established [1].

The upper storeys of TVEB should ideally have emergency shelter, food and water sufficient for several days' occupancy, given the potential for extended periods of isolation. Communication links to civil defence or emergency services should also be provided. Such provisions were lacking in TVEB at the locations investigated, but there were no reports of this resulting in deaths at TVEB. Therefore, availability of short-term welfare should be considered secondary to the structural requirements for providing life-safety, and the designation of suitable buildings should not be delayed or prevented because of inadequate welfare provisions.

4. Conclusions

Safe refuge was provided by many TVEB during the 2011 Great East Japan tsunami, highlighting the value of a vertical evacuation strategy in areas at risk of tsunami. These buildings are not a replacement for evacuation to high ground, but provide effective alternative options for those unable to evacuate the inundation zone prior to tsunami arrival. This research presents a reconnaissance-level view of the implementation of tsunami vertical evacuation guidelines in Japan and the performance of TVEB in an extreme event. Observations and interviews have shown that in the locations visited, there was variable adherence to published tsunami vertical evacuation guidelines and that there are some aspects in which implementation of the strategy could be improved.

The positive structural performance of TVEB with respect to wave impact, foundation scour and debris strike in extreme tsunami indicates that construction requirements for designating TVEB in Japan provide a sound basis for the future development of TVEB in Japan and internationally. Due to previous underestimation of tsunami hazard in Tōhoku, some TVEB were (or were close to being) overtopped and safe storeys inundated. Future designation of suitable TVEB height for safe storeys must be based on robust hazard assessment to ensure the height is appropriate to the estimated local maximum tsunami height. Although TVEB escaped fire damage in this event, the widespread occurrence of fire and damage, e.g., to a school that had been occupied by evacuees shows the continuing importance of minimising the spread of fire and preventing fire damage to TVEB.

All of the locations investigated in this work were developed urban areas and the vertical evacuation strategy relied largely on using existing buildings, thereby limiting planners' ability to achieve an ideal distribution of TVEB – an issue likely to occur internationally. Experience in this event shows that this is not, however, a barrier to effective vertical evacuation because loss of life was mitigated even where the best possible distribution of buildings could not be achieved.

Observations from this work provide several examples of building access methods that should be considered in the development of TVEB internationally. Although special access plans were not enacted in this event due to its day-time occurrence, concern was expressed in some interviews over the efficacy of night-time access preparations. It is therefore important that 24-hour building-appropriate access and subsequent community evacuation training are given high priority in future strategy development. The provision of access and responsibility for evacuees represent concerns for building owners when the use of their buildings as TVEB is considered. In the development of strategies internationally, this important issue will require engagement between the community and building owners, which helped to gain agreement of owners in Japan.

Two significant aspects of Japanese government guidelines that were largely absent from observed TVEB were signage and welfare provisions. More effective implementation of external signage might have helped to minimise loss of life through greater use of TVEB, particularly among transient populations unfamiliar with local evacuation planning, although further research is required to confirm this. The majority of TVEB had no dedicated welfare provisions or had provisions suitable only for several hours of building occupancy. Observations from this event show that potential occupancy period should be considered in terms of days rather than hours, and indicates a particular need for emergency communications equipment in TVEB.

In Tōhoku, the planning of optimal TVEB locations may now be possible during extensive redevelopment, and greater adherence to existing government guidelines is encouraged. Internationally, the development of vertical evacuation strategies can benefit by recognising the Japanese government guidelines and by learning from experiences in the Great East Japan tsunami.

Further study of evacuees' experiences in identifying, accessing and taking refuge in TVEB would enhance the understanding and use of TVEB. Approaches to improving the integration of TVEB in evacuation exercises and more clearly identifying welfare requirements should be explored. In addition, detailed structural analyses of specific TVEB and their performance with respect to tsunami loading, debris strike and foundation scour are expected to enhance structural resistance against tsunami.

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