Survey Report:

Damage Related to the 2011 Tohoku Earthquake in and Around Kamaishi City – Beyond the Tsunami Disaster –

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Widespread damage was caused in eastern Japan as a result of the earthquake and tsunami which occurred in 2011 off the Pacific coast of Tohoku (hereinafter, the 2011 Tohoku Earthquake). A large tsunami struck the coastal area of eastern Japan and caused damage to buildings, breakwaters, tide embankments and river levees. The joint reconnaissance team of the Tohoku and Kyushu branches of the Japanese Geotechnical Society investigated the geotechnical damage in the south-central coastal area of Iwate Prefecture from the beginning of April to September 2011. This report summarizes the geotechnical hazards and the damage to port structures, roads, railways, river levees, and buildings caused by the earthquake motion and tsunami in the 2011 Tohoku Earthquake in the south-central coastal area of Iwate Prefecture. Major investigation areas are Kamaishi City (Koshirahama Port, Touni-Chou), the coastal area of Ofunato City (Sanriku-Chou Yoshihama, Sanriku-Chou Okirai), and Rikuzentakata City. In the 2011 Tohoku Earthquake, many people could not or did not evacuate from the tsunami. However, students at junior high and elementary schools started tsunami evacuation quickly, resulting in what is known as the "Kamaishi Miracle." This study focused on the tsunami evacuation of children in Unosumai district, Kamaishi City.

Keywords: 2011 Tohoku Earthquake, tsunami, Kamaishi, tsunami evacuation, Kamaishi miracle

1. Introduction

Japan has experienced several huge disaster events in the last decade, including the Tohoku Earthquake, which occurred on March 11, 2011. This report considers this event and the damage resulting from it according to the following questions: could a lesson of previous disasters be utilized? Why couldn't sustained for the housings moved uphill in Touni? What is success of the housings moved uphill in Yoshihama? How was it possible to save the life of the senior persons in Okirai? In Koshirahama port, the coastal levee was built at a total cost of 1042 million yen. However, the information plate at the port is enlightening; it states that "there is no defense superior to evacuation." In the 2011 Tohoku Earthquake, many people could not or did not evacuate from the tsunami. However, students at junior high and elementary schools evacuated promptly and voluntarily, in accordance with their experiences of evacuation drills. The students decided to evacuate further to higher ground based on their own observation of the situation. This is known as the "Kamaishi Miracle." This study focuses on the tsunami evacuation of children in Unosumai district, Kamaishi City. This study simulates and discusses the effect of their prompt tsunami evacuation on surrounding areas.

Fig. 1. Map of surveyed areas (GSI Web Map used).

2. Field Investigation for the 2011 Tohoku Earthquake

2.1. Surveyed Area

The surveyed area is shown in **Fig. 1**. Major surveyed areas are Kamaishi City (Koshirahama Port, Touni-Chou), the coastal area of Ofunato City (Sanriku-Chou Yoshihama, Sanriku-Chou Ryori), and Rikuzentakata City. These areas were heavily damaged by the tsunami.

2.2. Characteristics of Earthquake Ground Motion in Surveyed Area

Previous studies have proposed several kinds of rupture processes for the main shock. Some were estimated using teleseismic waveforms, and others were obtained by measuring strong motions. Although they focused on different frequencies or used different methods, every rupture model shows complex rupture propagations (Suzuki et al.) [1] (**Fig. 2**). This area has recorded seismic waves of the main shock and its aftershocks.

Dense recordings from the K-NET strong ground motion network for the 2011 Tohoku Earthquake indicate the occurrence of strong ground motion inside and outside of the surveyed areas. **Fig. 3** shows a comparison of the K-NET spectrum (NS) of the north and south direction inside and outside of the surveyed areas.

At the three northern sites (K-NET: OHFUNATO (IWT 008), K-NET: KESENNUMA (MYG 001), K-NET: TSUKIDATE (MYG 004)), the acceleration spectrum (NS) shows dominant frequencies around 3–10 Hz (**Fig. 3**). However, the acceleration spectrum (NS) at the two southern sites ((K-NET SENDAI (MYG 013), K-NET HARAMACHI (FKS 005)) shows dominant frequencies around 0.6–2 Hz (**Fig. 3**). It can be seen that a shift was recorded, with wavelength increasing from the north to the south. The acceleration observation waveform and the Fourier spectrum (NS) of each phase of K-NET: KAMAISHI (IWT 007) and K-NET: OHFUNATO (IWT 008) are shown in **Figs. 4** and **5**, respectively. The maximum acceleration appears in the first phase, the spectrum dominant short-period components, and the spectrum shapes are almost equal. However, in the observation record (NS) at the inland observation site K-NET: TONO (IWT 013), the high frequency component of 2 Hz is dominant (**Fig. 6**).

Furumura et al. [2] determined the main shock rupture process of the 2011 Tohoku Earthquake using the acceleration record obtained from K-NET and KiK-net (K-NET, 2011). According to their study, the first rupture occurred off Miyagi prefecture, and strong seismic waves were released all over Tohoku (first phase). After several tens of seconds, another massive rupture occurred, and strong seismic waves were released (second phase). The third rupture occurred offshore near northern Ibaraki, and strong seismic waves were radiated towards Ibaraki prefecture (third phase). **Fig. 4** shows the acceleration records of the main shock recorded at K-NET IWT 007 station (at Kamaishi), which recorded a maximum acceleration of 741.6 Gal. **Fig. 5** shows the acceleration records of the main shock recorded at K-NET IWT 008 station (at Ofunato), which recorded a maximum acceleration of 387.0 Gal. In both instances, the continuation time was over 220 s.

The Tohoku area recorded many seismic waveforms of the 2011 Tohoku Earthquake and its aftershocks. Several kinds of rupture processes of the main shock have been proposed using teleseismic waveforms (e.g., Ide et al. [3], Ammon et al. [4]) or strong motions (e.g., Furumura et al. [2], Kurahashi and Irikura [5]). It is common that every rupture model shows complex rupture propagation though the results vary according to the focused frequencies or the analysis methods.

2.3. Damage in the South-Central Coastal Area of Iwate Prefecture

Site investigations and laboratory soil investigations were performed on two geotechnical structures (a damaged river dike and an undamaged tire retaining wall), that were located in the central and southern part of Iwate prefecture. The investigation results showed that subsidence-related failure probably had taken place in the dike body with low penetration resistance. However, in the case of the retaining wall made of tires, the flexibility and resiliency of the tires prevented any damage to the wall from scouring by the tsunami.

2.3.1. Touni-Chou (Koshirahama Port and Hongo District)

In Koshirahama port (Touni-Chou in Kamaishi-City), the tsunami washed away a residential area following the collapse of the tide breakwater, causing serious damage. However, houses located higher than the embankment of T.P.; Tokyo Peil + 17.5 m were less affected by the earthquake motion and the tsunami, as shown in **Fig. 7**. The conditions at the site before and after the disaster are shown in **Figs. 8(a)** and **(b)**. According to interviews with residents, "the tremor caused by the earthquake continued for about 2 min, and the small first wave of the tsunami hit immediately. The third wave was a tide from the breakwater to the offshore, it exceeded the breakwater and the tide ridge."

At Touni Elementary School, located about 300 m from the coast, watermarks from the tsunami were confirmed up to the 3rd floor, where the elevation was 17.09 m according to the RTK-GPS measurement.

In Koshirahama port, a section of the culvert-type coastal levee (height T.P. + 11.3 m) partially collapsed, and houses above the inundation area were damaged (**Fig. 9**). The tsunami run-up height was 18.2 m according to GPS (VRS method RTK-GPS: **Fig. 10**). **Fig. 11** depicts the side of a house showing the tsunami run-up height from the coastal levee. Tsunami height permeated the lintel (Kamoi) and reached the houses further up the hill. The house had been moved after the Meiji Sanriku tsunami in 1896.

Figure 12 shows the Koshirahama port information plate, which is located in Touni. A summary of the construction of the Culvert-type coastal levee is shown on this plaque.

The coastal levee was built at a total cost of 1042 million yen. The construction took place between 1979 and 1990. This board states that the important thing is "there is no defense superior to evacuation."

The tsunami passed through Touni Sakura tunnel (opened 2006), which linked the Hongo district to the

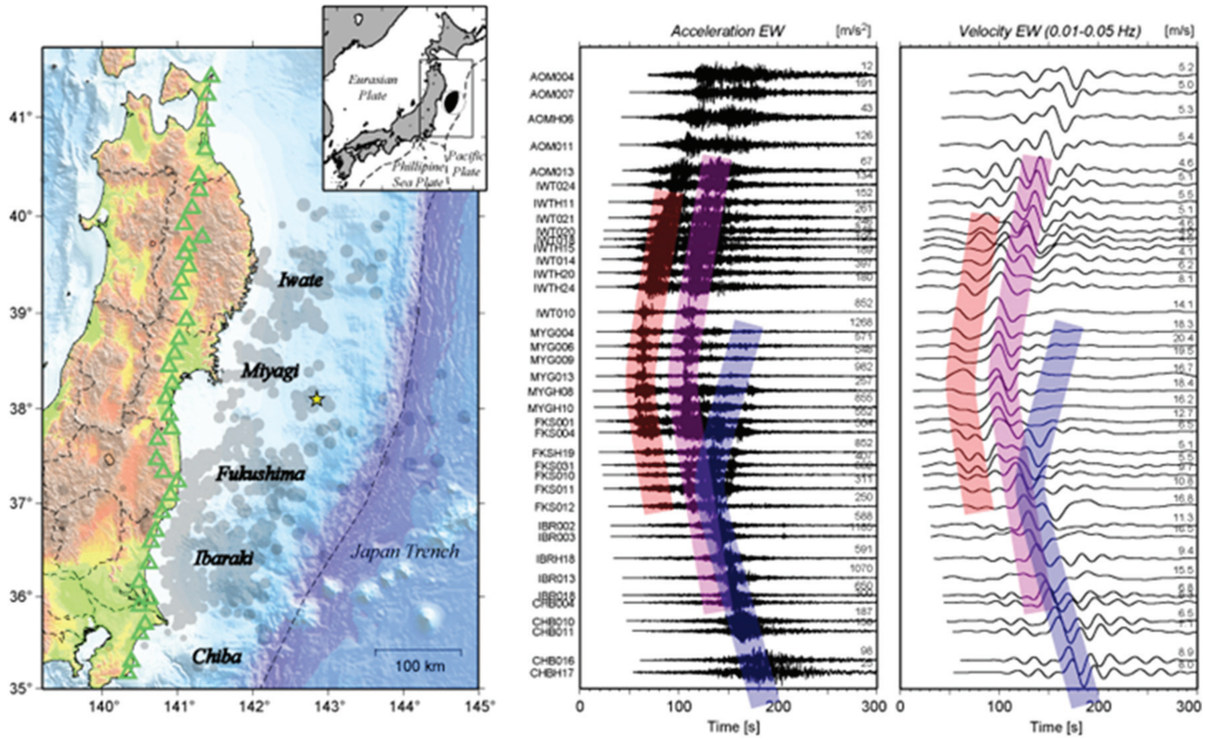


Fig. 2. Rupture process: Several kinds of rupture processes of the main shock have been proposed in previous studies. Some of them were estimated by teleseismic waveforms, and others were obtained by strong motions (courtesy of Wataru Suzuki).

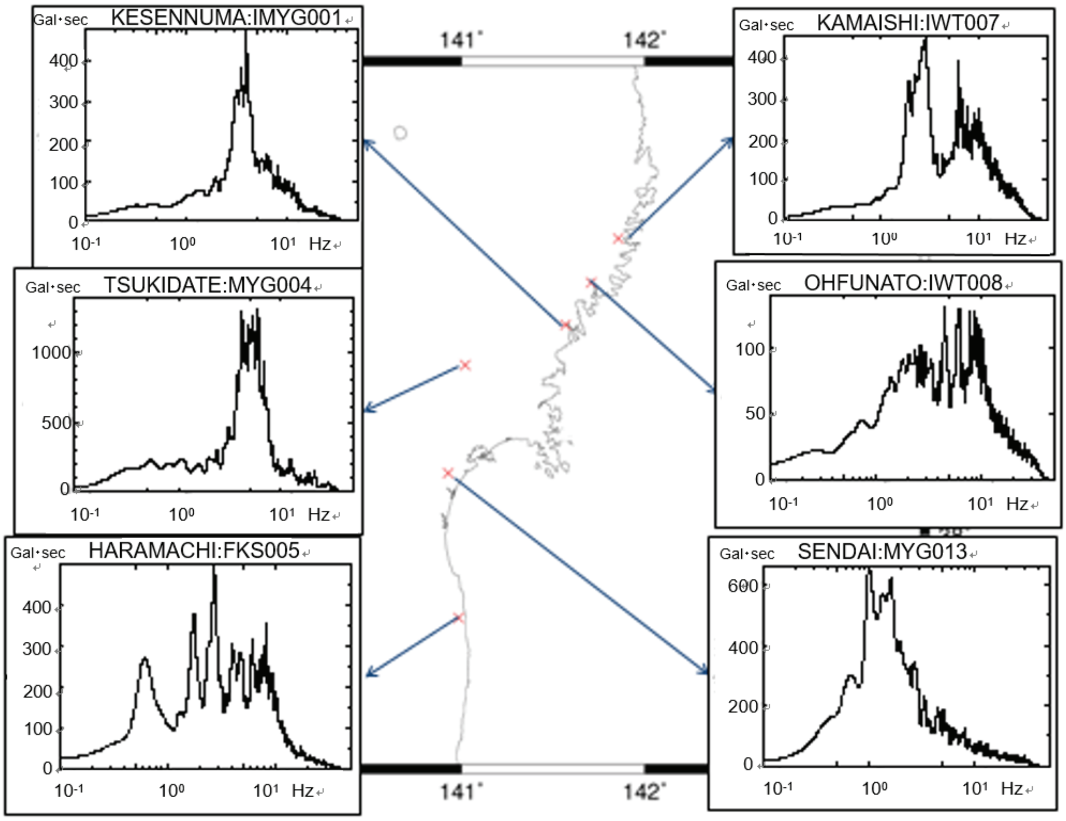


Fig. 3. Comparison of the K-NET spectrum (NS) of the north and south direction inside and outside the surveyed areas.

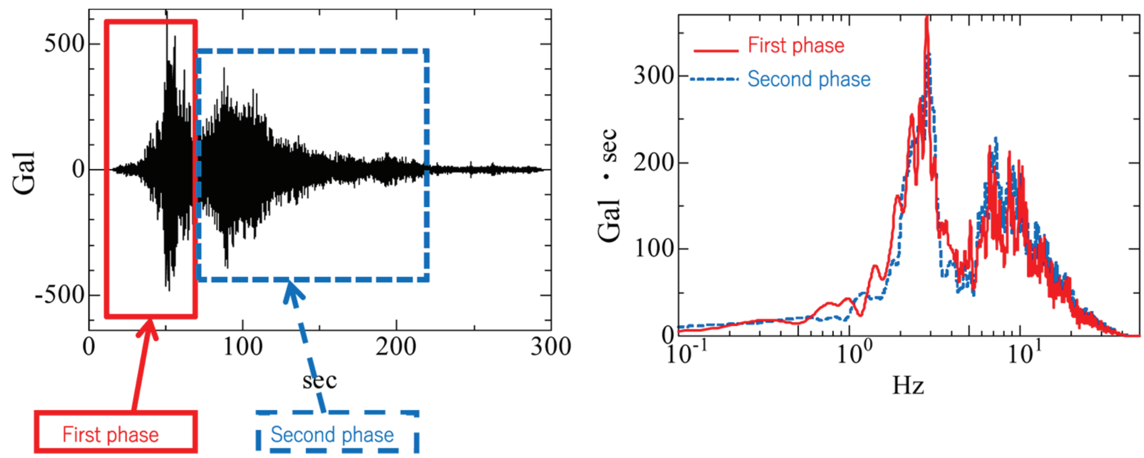


Fig. 4. The acceleration observation waveform and the Fourier spectrum (NS) of each phase of K-NET: KAMAISHI (IWT 007).

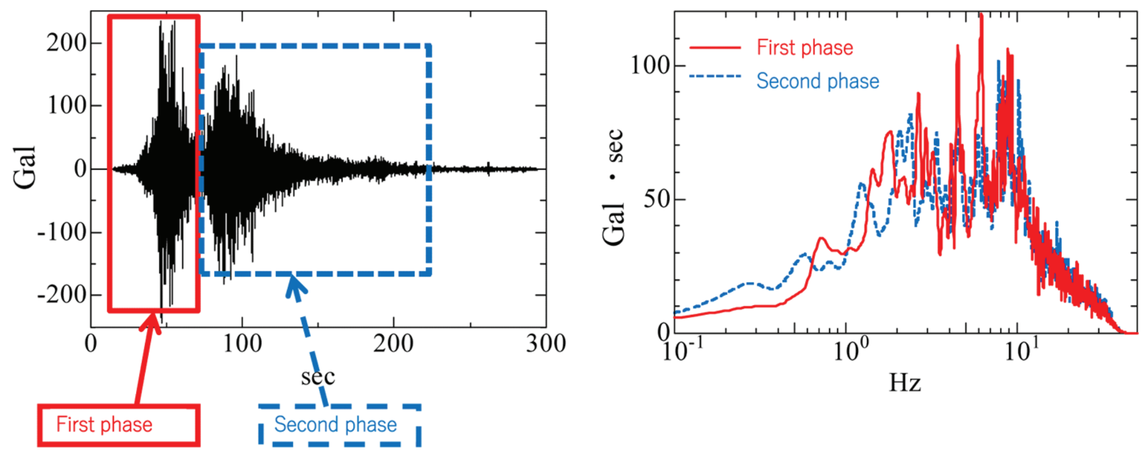


Fig. 5. The acceleration observation waveform and the Fourier spectrum (NS) of each phase of K-NET: OHFUNATO (IWT 008).

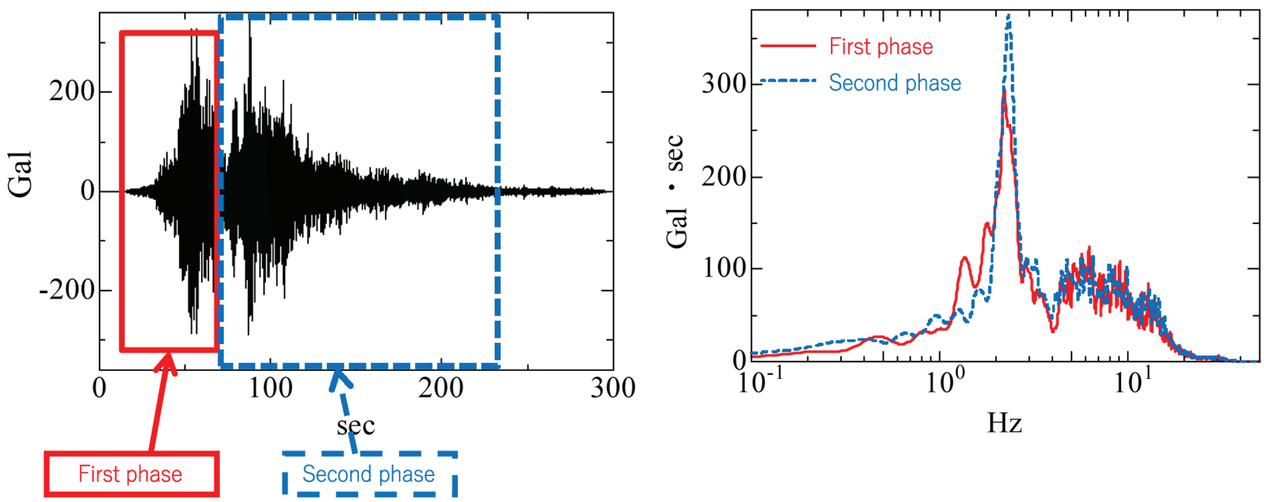


Fig. 6. The acceleration observation waveform and the Fourier spectrum (NS) of each phase of K-NET: TONO (IWT 013).

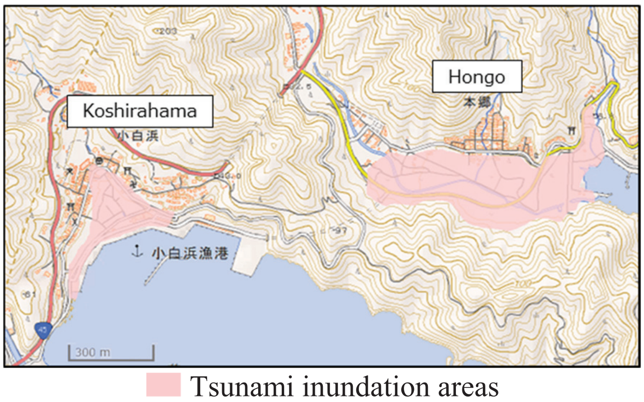


Fig. 7. Tsunami inundation in the Touni-Chou surveyed area (GSI Web Map used).

(a) Before the disaster (August 2003)

(b) After the disaster (June 2011)

Fig. 8. Before and after the disaster at Koshirahama port, Touni-Chou in Kamaishi City (photo taken by Ohsumi).

Koshirahama district, in Kamaishi City. In the Hongo district, the tsunami overtook the coastal levee and the road embankment.

The tsunami run-up height was 20 m in this district. In the village, houses above the inundation area survived intact, while everything below was destroyed by the tsunami (**Fig. 13**).

Fig. 9. Calvert-type coastal levee (height T.P. +11.3 m).

Fig. 10. GPS (VRS method RTK-GPS).

Fig. 11. Tsunami run-up height from the coastal levee.

There was a monument to the Meiji Sanriku tsunami in 1896. However, its inscription was marred by this later tsunami (**Fig. 14**).

According to tsunami history around this area (Shuto et al. [6]) (**Figs. 15** and **16**), numerous forest fires occurred and spread to housings in the low areas. These housings had been moved uphill again after the Showa Sanriku tsunami in 1933. However, stores began to open in the low-lying areas two years later, and the village had been rebuilt by 1945. In addition to a forest fire, the fol-

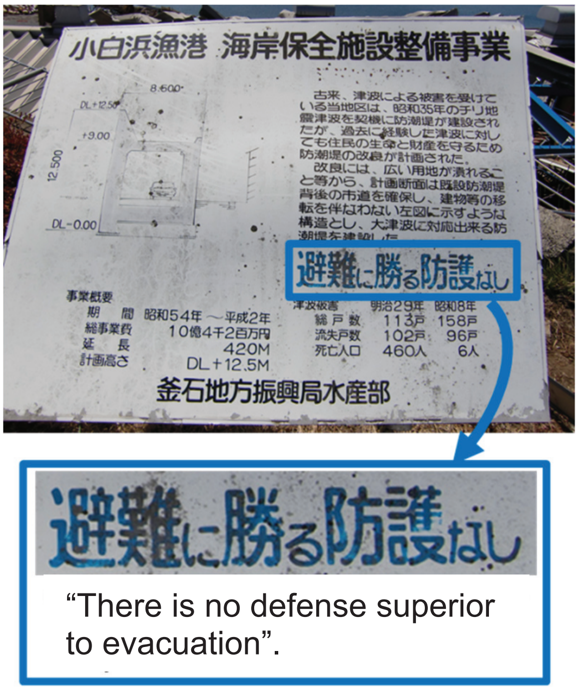


Fig. 12. Koshirahama port information plate.

Fig. 13. Tsunami run-up height and houses above the inundation area in Hongo district.

lowing items are pointed out (Koshimura [7]); the relocated places were too far from the sea ; there was a shortage of drinking water at the relocation village; the road was inconvenient; many relocated residents were preoccupied with their ancestral land; there was opportunity for good fishing at the beach, which led to temporary cabins becoming permanent housing; a large-scale fire occurred and the housing was destroyed, and many families that had never experienced a tsunami were migrating from the mountain area.

In the Hongo district, the housings were moved uphill after the Showa Sanriku tsunami in 1933. This area was not damaged. There is a significant difference in the amount of damage to the housings in the Koshirahama area that were moved uphill, from those in the Hongo district that were not.

Fig. 14. Inscription of the monument in Monument to the Meiji Sanriku tsunami in 1896.

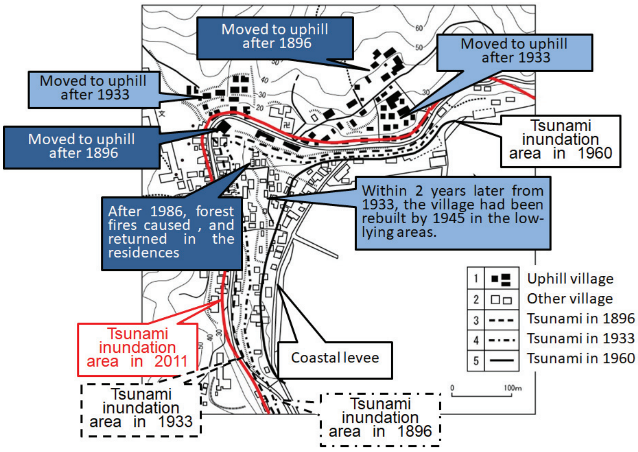


Fig. 15. Housings moved uphill after the Meiji Sanriku tsunami in 1896 and the Showa Sanriku tsunami in 1933 (Shuto et al. [6]).

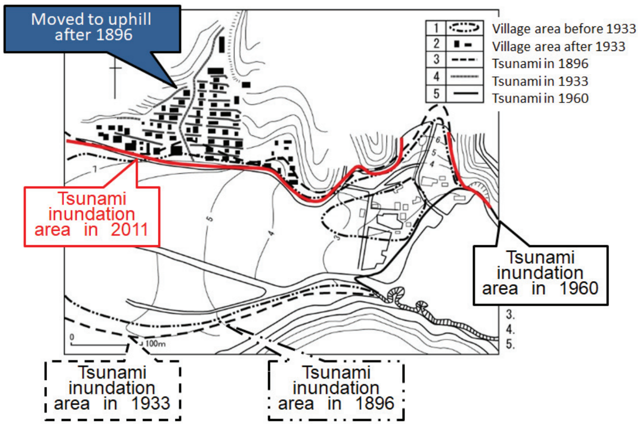


Fig. 16. The difference in house damage to the housings that were moved uphill in the Koshirahama area and those that were not in the Hongo district was significant (Shuto et al. [6]).

2.3.2. Yoshihama

Yoshihama district has repeatedly suffered tsunami damage during big earthquakes in the past (Iwate Nippo,

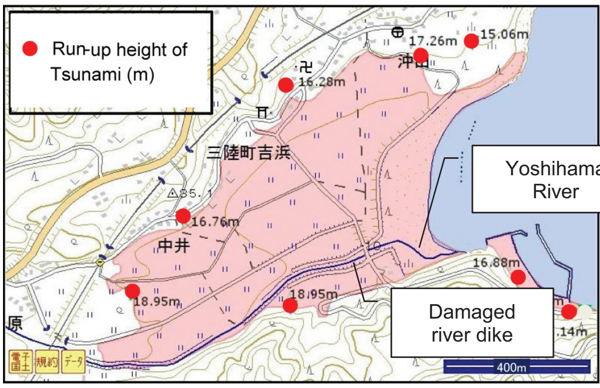


Fig. 17. Tsunami inundation in the Yoshihama surveyed area (GSI Web Map used).

Fig. 18. Houses above the inundation area in Yoshihama village survived intact, while everything below was destroyed by the tsunami.

Fig. 19. Monument to the Showa Sanriku tsunami in 1933. The Monument is located in the tsunami run-up height of Showa Sanriku tsunami (**Figs. 18–19**: photo taken by Ohsumi, May 3, 2011).

2011). Due to complete collapse of the coastal levee and the river dike, the 2011 Tohoku tsunami easily entered and inundated the plain area (**Fig. 17**). Due to strong shaking of the earthquake and the tsunami that followed, the coastal dike at the mouth of Yoshihama River was damaged over a wide range with complete collapse of the concrete slabs. In some parts, the concrete slabs were observed to have been displaced by more than 30 m. Unlike many other Tohoku-region coastal levees destroyed by the tsunami (Hara et al. [8], Hazarika et al. [9]), the damage to this dike in Yoshihama was not due to scouring or erosion. It is worth mentioning here that during the first phase of our investigation (May 3, 2011), the paddy fields behind the coastal levees were completely covered with deposited sands from the seashore, and the inundated waters extended over a wide area. Our survey indicated the crown height of non-damaged river dike was +5.2 m according to Total Station (TCR407S: Leica Geosystems).

Figure 18 shows that houses above the inundation area in Yoshihama village remained intact, while everything below was destroyed by the tsunami. There was a monument to the Meiji Sanriku tsunami in 1896 (**Fig. 19**). The monument is located at the run-up height of the Showa Sanriku tsunami.

According to tsunami history around this area (Shuto et al. [10]) (**Fig. 20**), housings were moved uphill after the Meiji Sanriku tsunami in 1896. These housings had been moved uphill again after the Showa Sanriku tsunami in 1933. These housings had been continued living uphill village. As a result, the 2011 Tohoku earthquake resulted in minimal damage (1 dead person, 2 households damaged). This area was praised as "Miracle Village" and an inscription and new monument were made, as shown in **Fig. 21**.

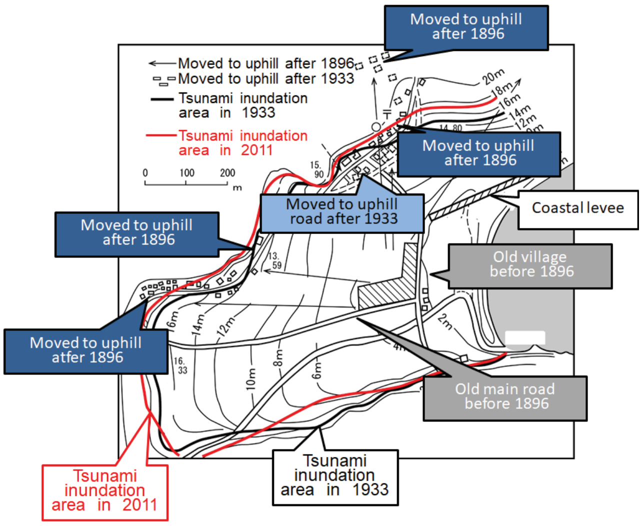


Fig. 20. Housings moved uphill after the Meiji Sanriku tsunami in 1896 and the Showa Sanriku tsunami in 1933 (Shuto et al. [10]).

2.3.3. Ryori (Okirai)

Sanriku-Chou Ryori is located in the coastal area of Ofunato. The tsunami run-up height of the 1933 Tohoku Earthquake tsunami is marked by a monument, depicted in **Fig. 22**. **Fig. 23** depicts the state of tsunami inundation in the Ryori (Okirai) surveyed area. At the Yahata Shrine, the Showa Sanriku tsunami reached a run-up height of 7.80 m (**Fig. 24**). The arrow shows the road used for uphill evacuation during the 2011 Tohoku earthquake. There is the "Sanriku great king cedar" that is ca.7,000 years old in the Yahata Shrine. According to an

Fig. 21. "Miracle Village" and inscription was made as a new monument (photo taken by Ohsumi, September 18, 2014).

interview with resident Yoshinori Sugishita in May 2011, concerned about the tsunami run-up height, the residents judged the situation of the tsunami and decided to move uphill with elderly family members. The tsunami run-up height was 16.8 m according to Total Station (TCR407S: Leica Geosystems: **Fig. 25**). The residents went up as shown by the arrow on **Fig. 24** and climbed halfway up the stairs, escaping from the tsunami (**Fig. 26**). According to the residents, the tsunami advanced about six times and they were saved by staying on the stairs until nightfall.

3. Tsunami Evacuation of Children in Unosumai District, Kamaishi City

In the 2011 Tohoku Earthquake and Tsunami, many people could not or did not evacuate from the tsunami. More than 18,000 people were killed or reported missing (excluding earthquake-related deaths) (Fire and Disaster Management Agency [11]; Reconstruction Agency [12]), and more than 90% of the people were killed due to the tsunami (National Police Agency [13]). In Kamaishi City, about 1,000 people were killed or missing (excluding earthquake-related deaths) (Iwate Prefecture [14]).

On the other hand, students at junior high schools and elementary schools started tsunami evacuation quickly, and consequently, they saved not only themselves but also

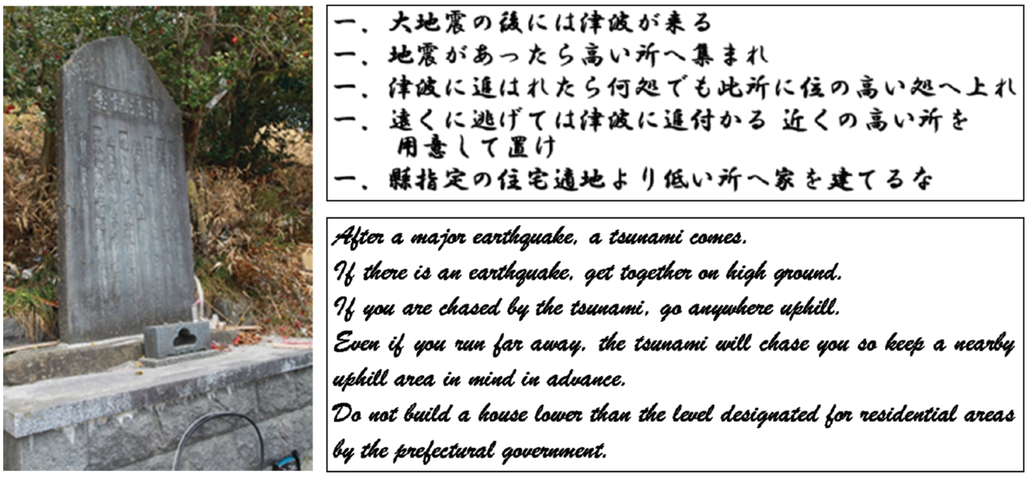


Fig. 22. Inscription of a monument in Sugishita, Okirai (photo taken by Ohsumi, May 4, 2011).

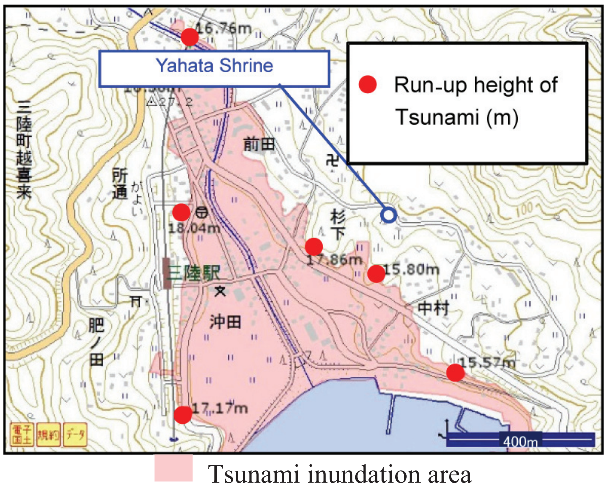


Fig. 23. State of tsunami inundation in the Ryori (Okirai) surveyed area (GSI Web Map used).

Fig. 24. Road for uphill evacuation for the Yahata Shrine (arrow).

Fig. 25. Comparison between the tsunami run-up height of the Showa Sanriku tsunami in 1933 and that of the 2011 Tohoku Earthquake.

Fig. 26. Stairs which the residents climbed halfway up for evacuating from the tsunami (**Figs. 24–26**: photo taken by Ohsumi, September 16, 2014).

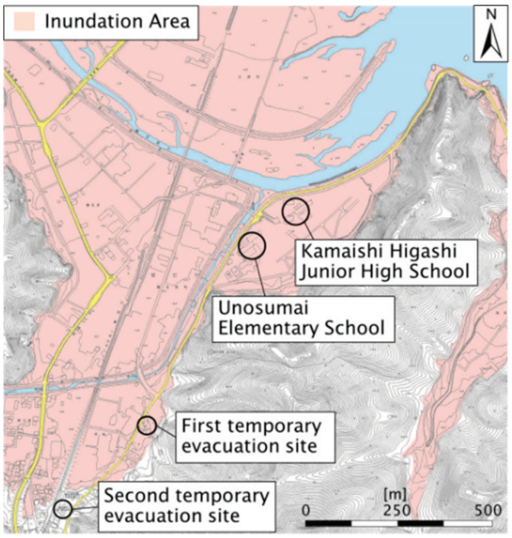


Fig. 27. Location of the schools and the temporary tsunami evacuation sites in Unosumai district (based on Kamaishi City [19]).

people around them from the tsunami in Kamaishi City. This is called the "Kamaishi Miracle" and has gained much attention as an example of the benefits of disaster prevention education (Katada and Kanai [15]; NHK [16]; Katada [17]).

Here, we focus on the tsunami evacuation of children in Unosumai district, Kamaishi City and discuss the effect of their prompt evacuation on surrounding areas.

3.1. Summary of the 2011 Tohoku Earthquake in Unosumai District

Unosumai District (7–19 and 23–29 Chiwari, Unosumai-Chou) in Kamaishi City was heavily damaged by the 2011 Tohoku Earthquake. Of the 3,276 residents in this district (February 2011), 348 people were killed or reported missing due to the tsunami (Kamaishi City [18]). **Fig. 27** shows the location of the schools and the temporary tsunami evacuation sites in the district (based on Kamaishi City [19]). Most of the area around the schools was inundated.

3.2. Summary of Tsunami Evacuation of Children in Unosumai District

We summarize the tsunami evacuation of students from Kamaishi Higashi Junior High School and Unosumai Elementary School. For more information on their tsunami evacuation, refer to Katada and Kanai [15], Katada [17], or Kamaishi City [18].

Kamaishi Higashi Junior High School was located near the sea and Unosumai Elementary School was located opposite from the junior high school (**Fig. 27**).

3.2.1. Behaviors Just After the Earthquake Occurrence

The earthquake occurred at 14:46 and strong shaking hit Unosumai District. In Ofunato City, located directly south of Kamaishi City, the Japan Meteorological Agency (JMA) observed strong shaking higher than level 4 on the JMA seismic intensity scale, for a period of 160 s at Ofunato City located right south of Kamaishi City (JMA [20]).

At 14:46 at Kamaishi Higashi Junior High School, all the classes were finished and students had started club activities and were preparing for the graduation ceremony. Just after the earthquake occurrence, the vice principal tried to give students instructions to evacuate over the school's broadcasting system, but it did not work because of the blackout. The students protected themselves from danger and waited for the earthquake shaking to stop. After that, they gathered in the schoolyard on their own judgment without the instruction of teachers.

In Unosumai Elementary School, the classes were not over and the students were still inside the school building. After the earthquake shaking stopped, the teachers tried to give the students instructions to move to the third floor (higher floor).

3.2.2. Evacuation to the First Temporary Evacuation Site

In Kamaishi Higashi Junior High School, a teacher shouted, "Run away!" to the students gathered in the schoolyard. The students started to run to the first temporary evacuation site (an elderly care facility, not higher place), which was designated as the evacuation site located further inland from the school (**Fig. 27**).

In Unosumai Elementary School, the teachers and the students saw running junior high school students. This witnessing triggered the start of tsunami evacuation in the elementary school. They followed the junior high school students and moved to the first temporary evacuation site.

3.2.3. Evacuation to the Second Temporary Evacuation Site

After they reached the first temporary evacuation site safely, an old woman who had followed students and some junior high school students found the cliff behind the building was collapsing. This witness led people gathered at the first temporary evacuation site to move to the second temporary evacuation site (other elderly care facility, higher place) (**Fig. 27**).

3.2.4. Evacuation to the Third Temporary Evacuation Site

After they reached the second temporary evacuation site safely, they saw the tsunami had overflowed the seawalls. They moved to the third temporary evacuation site (the stone store, higher place).

Table 1. Main parameters and conditions in the simulation.

The number of students	573
Total time for analysis [min]	30
Time step of the Evacuee Generation Model [s]	0.10
Time step of the Evacuee Behavior Model [s]	0.05

3.3. Tsunami Evacuation Simulation

We apply the tsunami evacuation simulation tool (Dohi et al. [21]) to the tsunami evacuation of children in order to discuss the effect of their behavior on surrounding areas (see Section 4.2). This simulation tool consists of two models: Evacuee Generation Model and Evacuee Behavior Model. It can simulate not only the evacuation behaviors but also the sense of urgency (Reality of Evacuation Start: RES). For more information on the simulation tool, refer to Dohi et al. [21] or Dohi et al. [22]. We summarize the main parameters and conditions of the simulation in **Table 1**.

3.3.1. Setting the Initial Conditions

We focus on the tsunami evacuation of 212 Kamaishi Higashi Junior High School and 361 Unosumai Elementary School students from their schools to the first temporary evacuation site.

According to Kamaishi City [18], Kamaishi Higashi Junior High School had 217 students. Three of them were absent and another two of them left school early. Unosumai Elementary School had 362 students. One of them left school early and another one of them left with the family member at the first temporary evacuation site.

Regarding the start of tsunami evacuation, we set the following conditions.

- Two students went through the school gate every second and moved to the first temporary evacuation site.
- Junior high school students started tsunami evacuation after the earthquake shaking stopped.
- Elementary school students started tsunami evacuation 1 min after the leading junior high school students start tsunami evacuation.

We set the computational area around the route of the schools to the first temporary evacuation site as shown in **Fig. 28(a)** (Based on Kamaishi City [19]).

3.3.2. Setting the Parameters

(1) Evacuee Generation Model

We consider four information sources creating RES: evacuating people, strong shaking, municipal RCS (Radio Communication Systems), and TV/Radio. **Table 2** summarizes the parameters of each source.

The source of evacuating people implies that the witnessing of their behavior creates RES in the viewer. We set the effective area for evacuating people to be a circular shape around them. We set the effective areas for the other three sources to be the whole Unosumai district.

The weight assigned to an information source implies its effectiveness level and indicates which information source is more important in our society or local communities. These parameters are based on Dohi et al. [21].

To determine the radius of the circular effective area (evacuating people as the information source), we used the relationship between a visual distance D [m] and the size of an object S [m], which is defined as follows:

$$D = VS, \qquad (1)$$

where V is a vision factor. According to a visual acuity test with the use of a Landolt C, if a test subject can see the symbol (7.5 cm wide) from 5 m away, they are judged to have 20/20 vision. In this case, the vision factor V is 66.7. According to e-Stat [23], mean height of Japanese junior high school students is 1.57 m (mean height of each grade in 2011) and that of Japanese elementary school students is 1.31 m (mean height of each grade in 2011). In the case of Japanese junior high school students, using Eq. (1), $V = 66.7$, and $S = 1.57$ m, we can obtain the visual distance $D = 105$ m. Similarly, in the case of Japanese elementary school students, we obtain the visual distance $D = 87$ m, using $S = 1.31$ m. In this simulation, for the effective range (radius) of evacuating people, we use 105 m for junior high school students and 87 m for elementary school students.

(2) Evacuee Behavior Model

In this model, a human body is modelled as a double circle element with a physical radius and a psychological radius, and the interaction between people is modelled by a spring and damping. The movement of each person is determined by solving the equation of motion. For more information on the model, refer to Kiyono et al. [24].

We summarize parameters about the velocity in **Table 3** based on Okada et al. [25]. In this model, each reference velocity of the evacuee is automatically determined using the mean, maximum, and minimum velocity. Without external forces, an evacuee can move at the reference velocity. When an evacuee is subjected to external forces, solving the equation of motion, the acceleration occurs and the velocity is changed.

We set the evacuation route of students based on Katada [17] (**Fig. 28(a)**). The distances between the first temporary evacuation site and Kamaishi Higashi Junior High School or Unosumai Elementary School are $1,000 \sim 1,100$ m on this evacuation route (The linear distances are about 800 m).

3.3.3. Results

The simulation results showed the leading student reached the first temporary evacuation site 7.6 min after the start of tsunami evacuation. Half of the group (287 students) reached it within 9.8 min of the leading student reaching it.

Figure 28 shows the snapshots of RES after the leading students began tsunami evacuation. In **Fig. 28**, we consider only evacuating people as the information source in

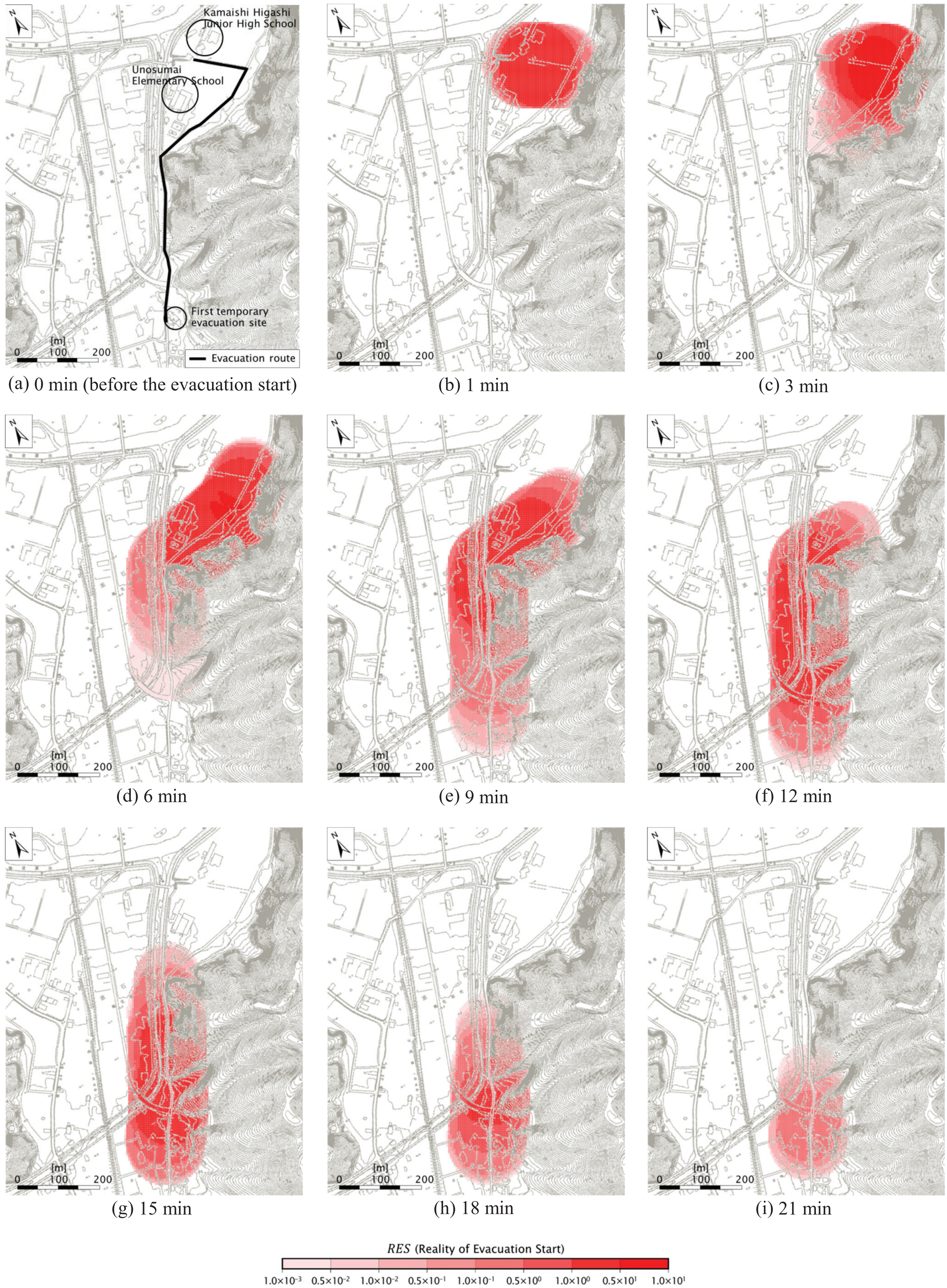


Fig. 28. Snapshots of RES after the leading student started tsunami evacuation (in the figures, we considered only evacuating people as the information source. The map is based on Kamaishi City [19] and the evacuation route of students is based on Katada [17]).

Table 2. Parameters about the information sources creating RES (the weights are set based on Dohi et al. [21]).

Information source	Evacuating people	Strong shaking	Municipal RCS	TV/Radio
Spatial characteristic (Effective area)	Around an evacuee (round shape)	Whole	Whole	Whole
Spatial characteristic (Radius of round effective area)	Junior high school students: 105 m Elementary school students: 87 m	-	-	-
Time characteristic (Effective time)	From the start of tsunami evacuation until the finish of it (From going through the school gate until reaching the first temporary evacuation site)	During strong shaking (160 s)	After the start of tsunami evacuation of the leading student	After the start of tsunami evacuation of the leading student
Weight	2.82×10^{-3}	7.66×10^{-3}	2.51×10^{-3}	2.25×10^{-3}
Total number	212 Junior high school students 361 Elementary school students	-	-	-

Table 3. Parameters about the velocity (based on Okada et al. [25]).

Mean velocity [m/s]	1.21
Standard deviation of the velocity	0.30
Minimum velocity [m/s]	0.67
Maximum velocity [m/s]	2.40

order to focus on the spatio-temporal changes of RES created by evacuating students. RES created by them moves toward the lower side in **Fig. 28** with their evacuation.

4. Discussion and Conclusion

4.1. Field Investigation and Numerical Investigations

Based on the field and numerical investigations, the following conclusions could be drawn.

The Yoshihama river dike was damaged by subsidence-related failure in the dike body with low soil density and high water table. Furthermore, the tsunami and backrush led to further reduction in levee body strength, despite the existence of concrete blocks at the back.

According to the rupture process of the main shock of the 2011 Tohoku Earthquake, using the acceleration record obtained from K-NET and KiK-net (K-NET, 2011), the first rupture occurred off Miyagi prefecture, and strong seismic waves were released all over Tohoku (first phase). After several tens of seconds, another massive rupture occurred, and strong seismic waves were released (second phase). The third rupture occurred offshore near northern Ibaraki, and strong seismic waves were radiated towards Ibaraki prefecture (third phase).

In the Touni area, residences were moved uphill after the Meiji Sanriku tsunami in 1896 and the Showa Sanriku tsunami in 1933. Numerous forest fires occurred and spread to residences in the low areas. These residences had been moved uphill again after the Showa Sanriku tsunami in 1933. However, stores began to open in the low-lying areas two years later, and the village had been rebuilt by 1945.

In Yoshihama area, residences moved uphill after the Meiji Sanriku tsunami in 1896. These residences had been moved uphill again after the Showa Sanriku tsunami in 1933. As a result, 2011 Tohoku earthquake resulted in minimal damage (only 1 dead people, 2 households damaged). This area was praised as “Miracle Village” and an inscription was made as a new monument.

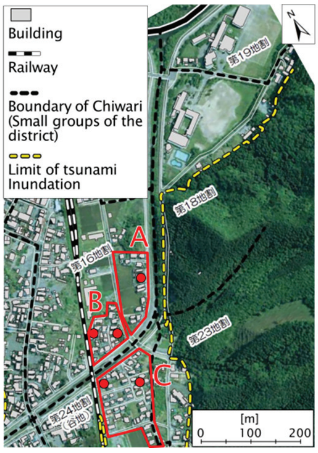
4.2. Tsunami Evacuation

We discuss spatio-temporal changes of RES by comparing RES at five sites in three residential areas around the evacuation route of students (**Figs. 29(a)** and **(b)**). In residential areas B and C (**Fig. 29(a)**), we consider sites on the far side of the evacuation route (B1 and C1) as well as on the near side of it (B2 and C2) (**Fig. 29(b)**).

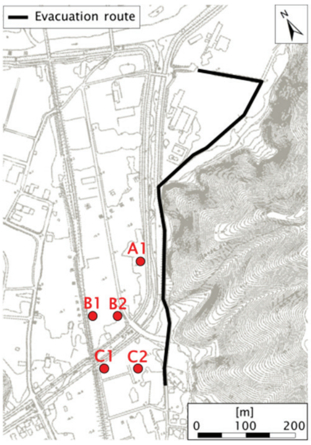
4.2.1. RES Every Second and Cumulative RES

Figures 29(c) to **(g)** show the changes of RES every second and cumulative RES at five sites. In each figure, left graphs show the per-second and cumulative RES during the 160 s of strong shaking. Right graphs show them after the leading student had begun tsunami evacuation. The right graphs (solid lines) in the figures show that strong RES was created by students on the near side of the evacuation route of students (A1, B2, and C2), 5–20 min after the leading student started tsunami evacuation. In particular, the peak of RES at A1 (around 12 min) is significantly high because a lot of students were evacuating nearby, at the peak time.

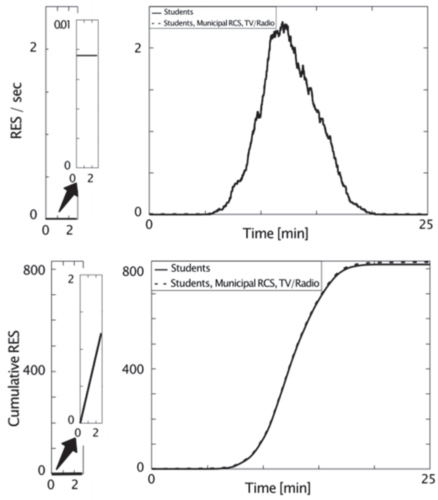
RES at B2 was lower than at A1 because B2 was always out of the effective area of RES created by evacuating elementary school students. It means the distance between B2 and the evacuation route of students is longer than that of evacuating elementary school students (87 m)



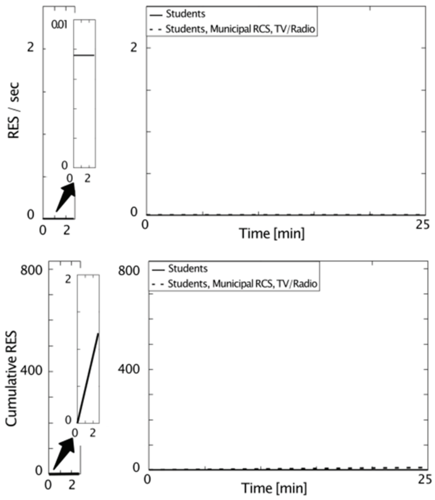
(a) Distribution of buildings near the evacuation route of the students



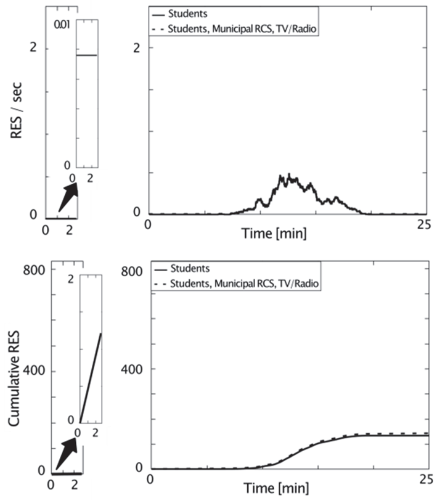
(b) Location of the target sites and the evacuation route of the students



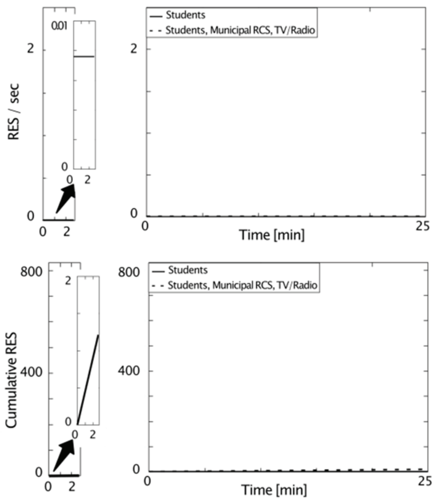
(c) Changes of RES (upper) and cumulative RES (lower) at A1



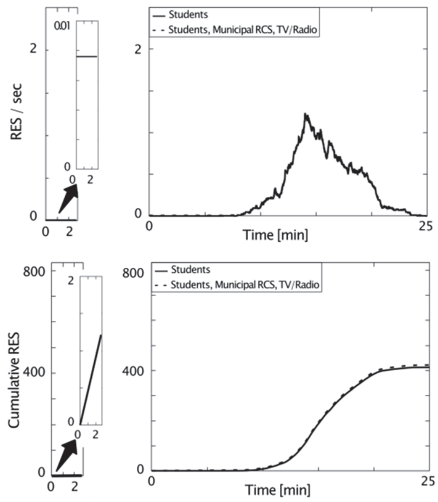
(d) Changes of RES (upper) and cumulative RES (lower) at B1



(e) Changes of RES (upper) and cumulative RES (lower) at B2



(f) Changes of RES (upper) and cumulative RES (lower) at C1



(g) Changes of RES (upper) and cumulative RES (lower) at C2

Fig. 29. Changes of RES every second and cumulative RES at five site. In (c) to (g), left graphs show the RES every second and cumulative RES during strong shaking for 160 s. Right graphs show them after the leading student start the tsunami evacuation. Two lines almost overlap in the right graphs in (c) to (g) ((a) is based on Kamaishi City [18]. In (b), the map is based on Kamaishi City [19] and the evacuation route is based on Katada [17]).

and shorter than the radius effective area of evacuating junior high school students (105 m).

RES at C2 was also lower than at A1 because the students reached the first temporary evacuation site soon after they passed near C2 and stopped acting as information sources in this simulation. This means RES at C2 was created by students for a shorter time than it at A1.

On the other hands, RES was no longer created by students on the far side of the evacuation (B1 and B2). The distance between the two sites and the evacuation route is longer than the radius of effective area of evacuating students (87 m and 105 m).

Considering the above, we can assume that the tsunami evacuation of students created strong RES in the residential areas near the evacuation route of students. In other words, it is assumed that in these areas tsunami evacuation easily began within 10 to 20 min of the leading student beginning evacuation because of the students' prompt tsunami evacuation.

4.2.2. Effects of the Students vs. Other Effects

So far, we have only discussed evacuating people (students) as the information source creating RES. Here, we compare the effects of the students with other effects.

First, we discuss the effect of strong shaking. **Table 2** summarizes the parameters of strong shaking as the information source. According to JMA (2011), strong shaking lasted for 160 s in Ofunato City. We therefore simulated RES created by strong shaking for 160 s at five sites (**Fig. 29(b)**). The left graphs in **Figs. 29(c)** to **(g)** show the RES created by it at five sites. Compared with the right graphs (solid lines) in **Figs. 29(c)** to **(g)**, which show the RES created by evacuating students, the effects of strong shaking are significantly smaller than the effects of evacuating students at A1, B2, and C2. However, in terms of RES at B1 and C1, we can assume that strong shaking was the important information source because RES was not created by students at B1 and C1 which were beyond the effect of students.

Second, we discuss the effect of municipal RCS and TV/Radio. As there was a blackout, municipal RCS could not have worked. Here, we discuss how much of a difference municipal RCS and TV/Radio could have created at the five sites. **Table 2** summarizes the parameters of them as the information source. In the simulation, we set the effective time to be after the leading student began evacuation. In the right graphs in **Figs. 29(c)** to **(g)**, the dashed lines show RES created by both evacuating students and municipal RCS and TV/Radio. Compared with the solid lines, which show RES created by evacuating students only, the effects of municipal RCS and TV/Radio are significantly small at A1, B2, and C2. However, similar to the effects of strong shaking, we can assume that municipal RCS and TV/Radio could have been important information sources at B1 and C1, which were beyond the radius of effect of students.

4.2.3. Evacuation Time

There is a possibility that more students reached the first temporary evacuation site earlier than the simulation results for the following reasons.

First, our tsunami evacuation simulation considers each evacuation behavior separately and the acceleration changes caused by physical or psychological interaction. On the other hands, the photo of the tsunami evacuation of the students showed their evacuation in line (Katada and Kanai [15]; NHK [16]). The students could have moved smoothly without physical or psychological interaction among them.

Second, the parameters about the velocity are based on the walking velocity of adults (Okada et al. [25]) in this simulation. Our simulation does not consider the following situation: according to Katada and Kanai [15] and NHK [16], the students ran to the first temporary evacuation site. In addition, they say that some Junior high school students assisted with the evacuation of nursery school children and staff who they met on the way to the first temporary evacuation site.

If the students moved more smoothly than simulation results, it is assumed that the peaks of RES were higher and peak times were shorter at A1, B2, and C2 (**Fig. 29(b)**). On the other hand, there is no change in RES at B1 and C1 between the smooth evacuation case and the simulation results, because these sites were beyond the effective area of RES created by evacuating students.

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