

DAMAGE AND EFFECTS CAUSED BY TSUNAMI FIRES: FIRE SPREAD, FIRE FIGHTING AND EVACUATION

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ABSTRACT: The Great East Japan Earthquake triggered fire outbreaks in many structures and buildings including hazardous-material facilities. The tsunami induced by the Earthquake also produced a huge impact under which various tank and gas-cylinder facilities, automobiles, etc. were damaged and caused to leak hazardous materials, such as gas and gasoline. In addition, the tsunami swept away numerous objects, causing collisions between objects and sparks from broken electric cables. Under such situations, fires broke out at various points in the affected region, some escalating to large-scale urban fires or forest fires. Many of the people that had been evacuated from the tsunami-affected zone had to be evacuated a second time to escape from the spreading and escalating fires.

Key Words: Great East Japan earthquake, Tsunami Fire, Fire Spread, Fire Fighting, Evacuation

INTRODUCTION

For the fire investigation, it is better to come to the fire sites as soon as possible because of the untouched evidences of fires. But this time, it is only two weeks after the earthquake and tsunami fires as the first responses and restoration activities are taking places in the affected places and it was difficult to travel to the affected places. It was also difficult for the fire stations to conduct fire investigation because of rescue activities.

The fire spread area was so wide, it is commonly recognized among researchers of universities and research institutes that cooperation is necessary to share information of earthquake fires and tsunami fires. This paper is mainly based on an interim report of this kind of cooperation organized by the Japan Association for Fire Science and Engineering (2011).

STATUS OF FIRE BRAEAKOUT

According to the Fire and Disaster Management Agency, the number of related fires was 286; the number of fires in Iwate, Miyagi, and Fukushima Prefectures was 169, of which 144 occurred in

coastal municipalities. In the region seriously damaged by the tsunami, firefighting services were not able to conduct their full capability, and many fires were not even counted in the fire statistics.

Fig. 1 shows fires which had simultaneous occurred in each houses after the shock of the tsunami in Natori City. In Otsuchi Town, official record of fires are just one, but at least seven tsunami fires could be counted through videos and photographs taken by the local people and cameramen of self-defense force, governmental bureau and mass media. Fig. 2 shows one fire site in Otsuchi Town at 16:00 about forty minutes after the tsunami. As this site is covered with six meters high water, the fire did not spread so much and this fire was not officially recorded.



Fig. 1 Video taken from an airplane on 11th March 2011 at a coastal lines of Natori city, Miyagi prefecture offered by the Tohoku Regional Developing Bureau of Ministry of Land, Infrastructure, Transport and Tourism (TBC,2011)



Fig. 2 Tsunami fire at 16:00 11th March 2011 in Ando district of Otsuchi town, Iwate prefecture (offered by Mr.Toru Suzuki, a volunteer fire fighter of Otsuchi town volunteer fire company)

Table 1 shows that number of tsunami fires are dominant in Iwate and Miyagi Prefectures. Besides these tsunami fires there are many small fires which is not recorded as the fire of Fig. 2 because there are scarce evidence of fire remained afterwards. For the estimation of tsunami fire occurrence and countermeasure of these fires, it is necessary to collect data of these fire occurrences through videos and photographs and interviews to local people who were at the fire sites.

Table 1 Number of tsunami fires and earthquake fires

Prefecture	unified by JAFSE(2011) and Kindai-Syobo-Sya(2012)				Official Record (N of Fires)
	Tsunami Fire	Earthquake Fire	Unknown	Total	
Aomori	6 (46%)	7	0	13	5
Iwate	27 (63%)	13	3	43	34
Miyagi	81 (60%)	45	9	135	135
Fukushima	4 (17%)	19	0	23	11
Ibaragi	6 (19%)	19	6	31	31
Akita	0	1	0	1	1
Gunma	0	2	0	2	2
Chiba	0	10	6	16	16
Saitama	0	12	0	12	12
Tokyo	0	33	0	33	33
Kanagawa	0	6	0	6	6
Total	124(39%)	167	24	315	286

Investigation: Japan Association for Fire Science and Engineering (2011), Kindai-Syobo(2012)
Official record: FDMA (2011)

TSUNAMI-INDUCED FIRE BREAKOUT PATTERNS

Most of the fires related to tsunami broke out in either of the following patterns:

- 1) valves and gas-pressure regulator of propane tanks at home were destroyed in the rolling wooden one or two story houses which were hit by tsunami, and then leaked propane gas caused fires in a room of floating houses or sometimes rolling propane tanks floating in the water with flame jet ignite a fire at reaching buildings or materials of collapsed wooden houses. There were also some cases that rolling propane tanks drifted in the water ejecting white smoke of flammable gas with no flame and reached to edge of flooded area and afterward exploded;



Fig.3 Rolling houses which were hit by tsunami at Otsuchi Town with sand smoke (video taken by Akihiro Sato(2011))

- 2) fuel tank and vehicle fuel filler pipe were destroyed when automobiles swept away by the tsunami were smashed against buildings, and leaked gasoline caused fires;



Fig.4 Automobiles were smashed into a gymnasium of Kesen elementary school in Rikuzen Takada city and caught fires.

- 3) Oil-storage tanks etc. of industrial plants handling flammable liquid in harbors, ships and fish boats were destroyed by the tsunami, and the leaked oil being absorbed to timber and other materials from collapsed buildings etc. caused fires like wick combustion.



Fig. 5 Floating Oil-storage tanks which were destroyed by the tsunami in Kesenuma Harbor.
(video offered by Japan Coast Guard)

Some people who remained in the wooden houses until the tsunami reached their home noticed the cases of pattern-1 fire at nearby houses, and then they survived after a great struggle. Some people noticed rolling propane tanks with flame jet drifting on the water and causing fires at buildings or materials of collapsed wooden houses.

Fig. 6 shows one case of this pattern-1 without direct eyewitness. Mr. Toru Suzuki a volunteer fire fighter of Otsuchi Town volunteer fire company took this photograph at 15:26 (six minutes after the hit of the tsunami) 11th March 2011 in Ando District of Otsuchi Town. He passed through this point before the tsunami and did not notice a fire around here and heard the sound of propane gas tank explosion after the hit of tsunami before he reached this viewpoint. He noticed that materials of collapsed building were burning.

There are some possibilities of fire caused by gasoline leaked from automobiles or fish boats, but it may have taken some more time for propagation of gasoline fire to building materials. So the cause of this fire may be leaking propane gas tank. The tank may have been pushed into a house and there may have been an explosion inside of the house. This estimation meets the size of fire of Fig.6. The situation of this fire at 16:00 is shown at Fig.2. The location of Ando District is upper left side of Fig.3 where the district was covered with dust smoke and this means the impact of the tsunami was devastating.



Fig. 6 Fire situation at 15:26 (six minutes after the hit of the tsunami) 11th March 2011.

One case of Pattern-1 at Ando district in Otsuchi town, Iwate Prefecture.

(offered by Mr.Toru Suzuki, a volunteer fire fighter of Otsuchi town volunteer fire company)

In many cases of pattern-2 fire, a number of automobiles parked in front of a building were washed up by the tsunami and crashed against the building, bursting into flames near the wall of the building. Fig.7 shows one typical case. After the earthquake, local people came to the ground of this elementary school with their automobiles in anticipation of tsunami. There was about thirty to forty parking automobiles in front of the gymnasium. When the tsunami reached here, about ten automobiles were pushed into the gymnasium and seven automobiles were piled up between the gymnasium and the elementary school building. A teacher at the school who have evacuated to a mountain behind the elementary school heard the sound of electric short and explosion from the gymnasium and noticed a smoke coming out of the gymnasium. Local people also heard the sound of explosion few minutes after the hit of tsunami and notice that the third of roof of the gymnasium blown off as shown in the left side photograph of Fig.7. There may have been a explosion of gasoline which were leaked from the tanks of automobiles pushed into the gymnasium by the tsunami. Fig.4 shows inside of the gymnasium.



Fig.7 Automobiles fire inside of the gymnasium at Kesen elementary school
(photograph taken and offered by local people)

The massive fire at Kesennuma Bay was a typical pattern-3 fire. Oil flowing out of the destroyed oil tanks at Kesennuma Port adsorbed to farming rafts and to the materials of collapsed wooden houses swept by the tsunami, and was ignited into flames. These blazing objects, covering some water surface, drifted from Kesennuma Bay outwards to Oshima Strait and reached the tsunami-flooded coastal area where the fire spread to ships, automobiles, factories, houses and forests. These blazing objects also drifted inwards to Shishiori District where already pattern-1 fires broke out just after the tsunami reached there as shown in Fig. 8 and Fig. 9. The people who evacuated to tsunami evacuation buildings near the pier of Shishiori were surrounded by these two types of fires until next morning.



Fig. 8 Blazing objects drifting right to left toward Shishiori (video offered by Japan Coast Guard) Fig.9 Pattern-1 fires at Shishiori district (Zerocounts(2011))

The proportion and rate of occurrence of these three patterns of tsunami induced fires are unknown because there is a lack of physical evidence and although there are some verbal evidence but not yet organized to see whole picture.

There are also other patterns of fire occurrence related to tsunami other than these three patterns of tsunami. For example, fires from oil heater in use at tsunami hit houses and electrical short fires from batteries of automobiles flooded by sea water (Hagimoto (2011)).

FIRE SPREAD AND ESCALATION

Spread of a fire depends on the distribution of Combustible materials. As the tsunami hit wooden housing area, Most of the wooden houses along the seashore were swept away and accumulated along slope of hillside or in some cases along side of banks. Some materials from the devastated houses were pulled out with backwash. Based on these formations of combustible materials, ignited fires were brought by drifting houses and ignited boats onto accumulated materials and also some fires ignited at the location of accumulated materials at slope of hillsides or side of banks.

In the pattern-1 fires in rolling houses with propane tanks, wooden houses in which a fire was burning were forced to move with tsunami. Fig. 10 and Fig. 11 show one case of this moving house fire at tsunami flooded area in Minami-Sanriku City. In this case, there is no record of fire because there was no combustible material around this burning house, so the fire didn't spread.



Fig. 10 Moving house fire on water at tsunami flooded area in Minami-Sanriku city (ZANGIEFCHAMP (2011))

Fig. 11 Moving house fire in Minami-Sanriku city (TBC(2011))

Fig. 12 shows one case of the pattern-1, a rolling propane tank floating in the water with flame jet ignite fire at broken buildings at Origasa District in Yamada Town, Iwate prefecture. Depth of tsunami was about 6 meters at the fire origin of this burnt area. It seems that the height of flooded water decreased when the burning propane tank reached the site to cause a fire as shown in Fig. 13.

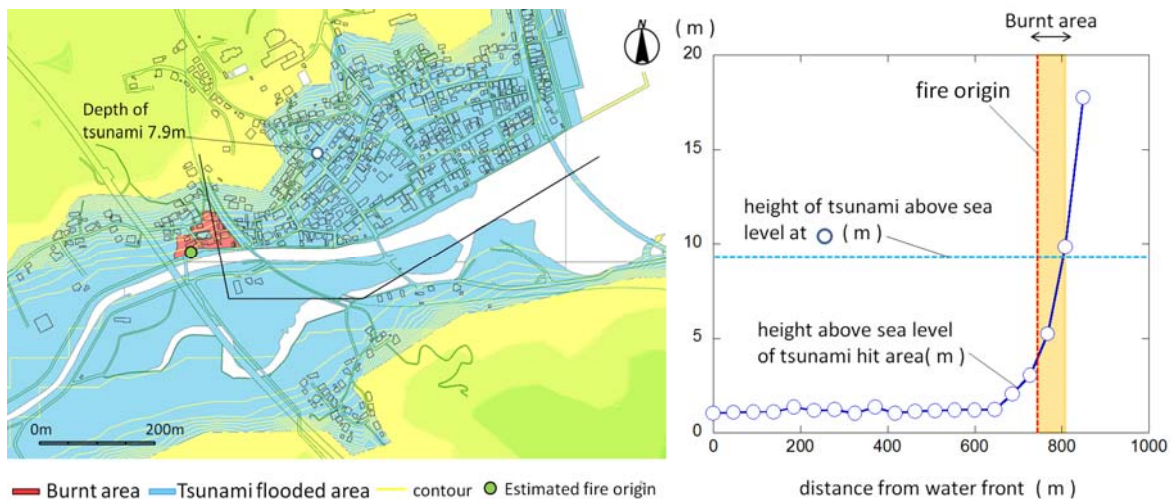


Fig. 12 Fire spread of pattern-1 fire to broken houses at the edge of tsunami flooded area (Origasa district in Yamada town, Iwate prefecture)



Fig. 13 Fire spread at Origasa district at 16:07 of 11th March 2011
(photograph taken and offered by local people)

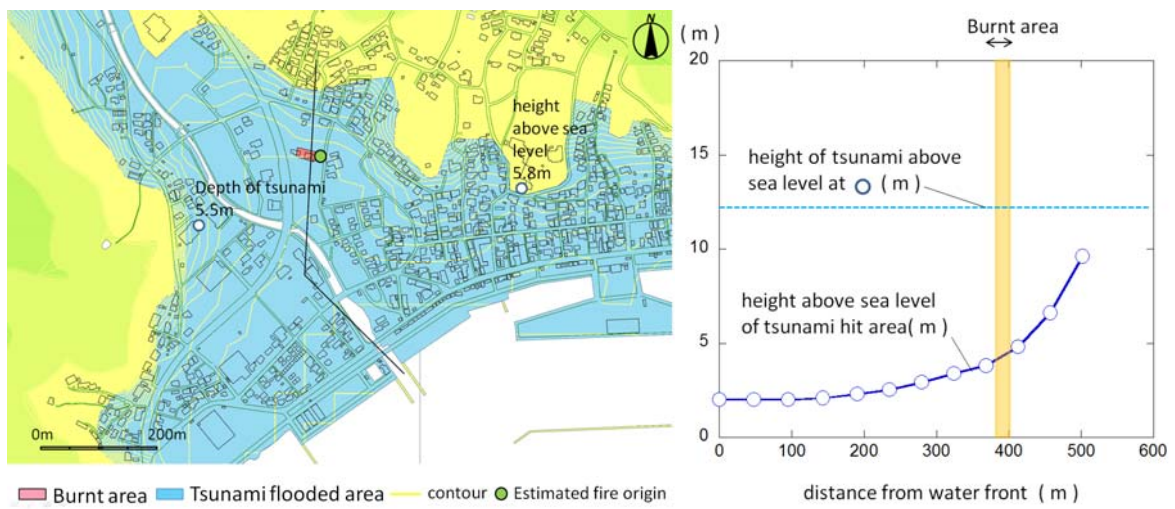


Fig. 14 Fire spread of pattern-1 fire to few houses remained at tsunami flooded area
(Osawa district in Yamada town, Iwate prefecture)

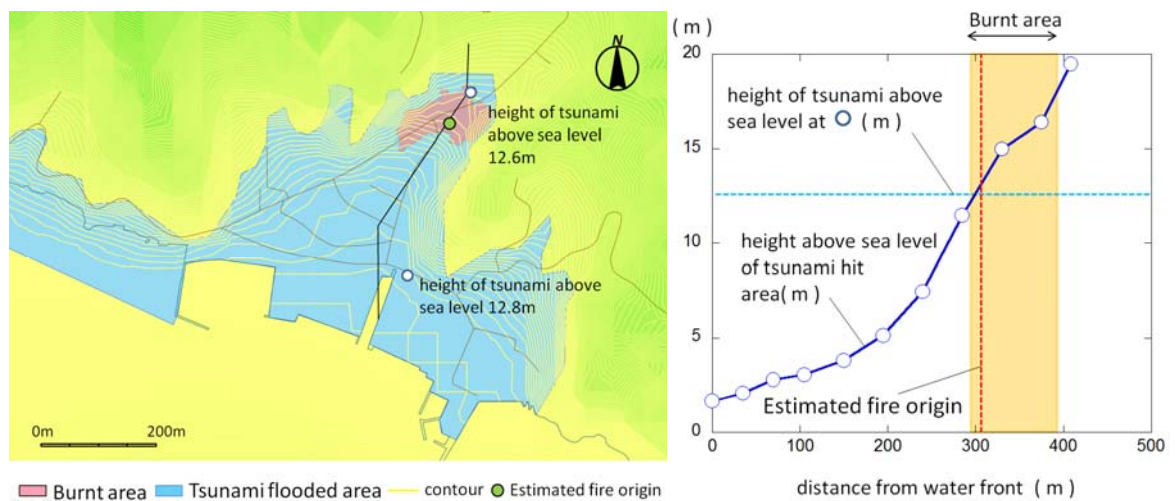


Fig. 15 Fire spread of pattern-1 fire to houses at hillslope of tsunami flooded area
(Akahama district in Otsuchi town, Iwate prefecture)



Fig. 16 . Fire situation at 15:38 (18 minutes after the hit of the tsunami) 11th March 2011. at Akahama district in Otsuchi town, Iwate prefecture (JMSDF, 2011)

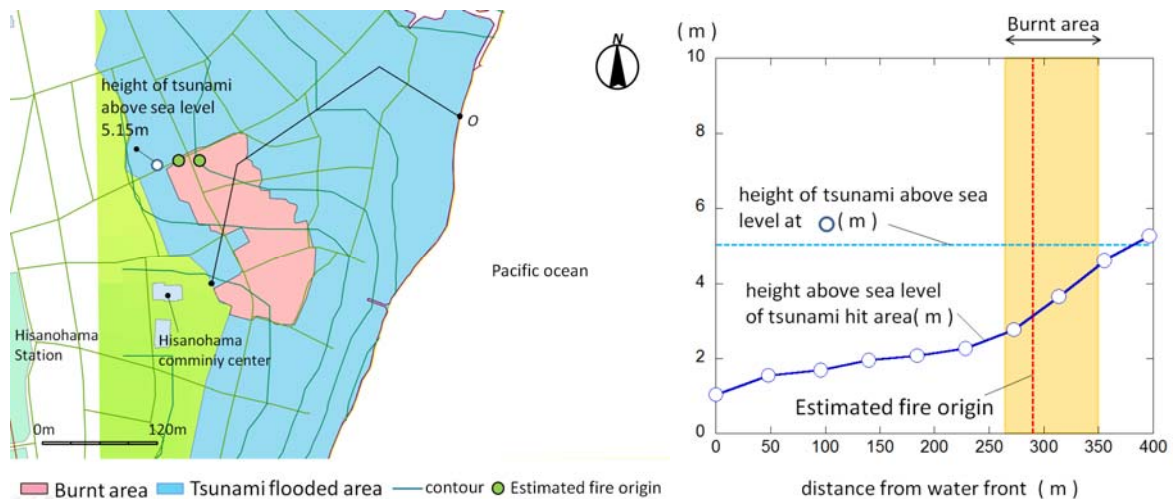


Fig. 17 Fire spread of pattern-1 fire to houses at edge of tsunami flooded area (Hisanohama district in Iwaki city, Fukushima prefecture)

Fig.14 shows one fire site where a drifting burning house reached here to spread fire to remained houses. As the number of existed houses were limited, the area of fire spread is small.

Fig.15 and Fig.17 show cases where there are testimonies that a leaking propane tank exploded to ignite a fire after the tsunami hit there. Fig.16 shows the fire situation eighteen minutes after the tsunami hit this district. As the height above sea level of this area is about 13 meters, there was no tsunami water here at this time. There were wooden houses existed around here, fire spread to these wooden houses. Four local people around here tried to block fire with hydraulic shovel and extinguished fire with home hose lines (JAFSE, 2011).

Fig.18, Fig.21, Fig.24, Fig.27 and Fig.28 show fire sites where multiple fires occurred in combustible material bed along hillslope of tsunami flooded area. This means that there is high probability of fire occurrence in this kind of beds and fires tend to spread widely around these beds.

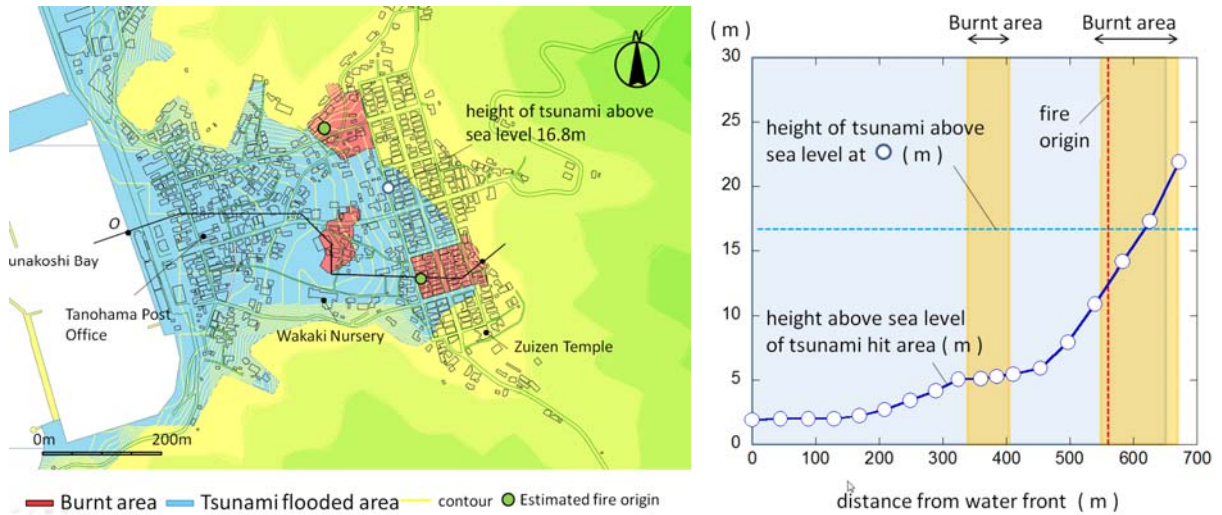


Fig. 18 Fire spread of fires to houses at hillslope of tsunami flooded area (Tanohama district in Yamada town, Iwate prefecture)



Fig.19 Fire situation at 16:15 11th March 2011 about one hour after the tsunami hit here Tanohama district in Yamada town (JGSDF, 2011)



Fig.20 Fire situation earlier time than Fig.19 still after the tsunami hit here Tanohama district in Yamada town (Lakita, 2011)

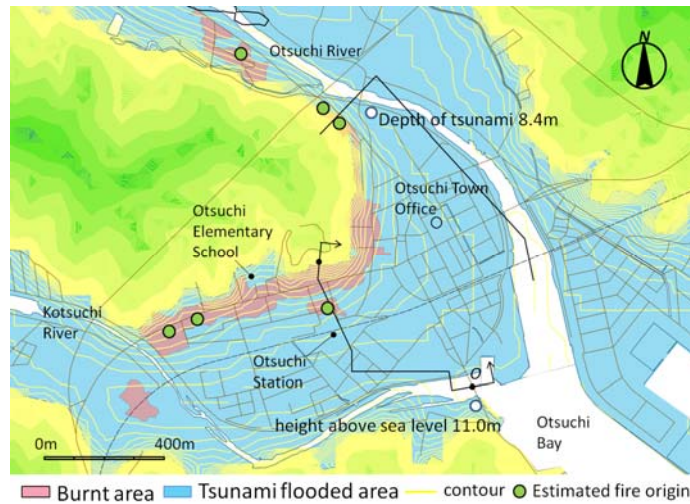


Fig. 21 Fire spread of fires to houses at hillslope of tsunami flooded area (Center district of Otsuchi town, Iwate prefecture)

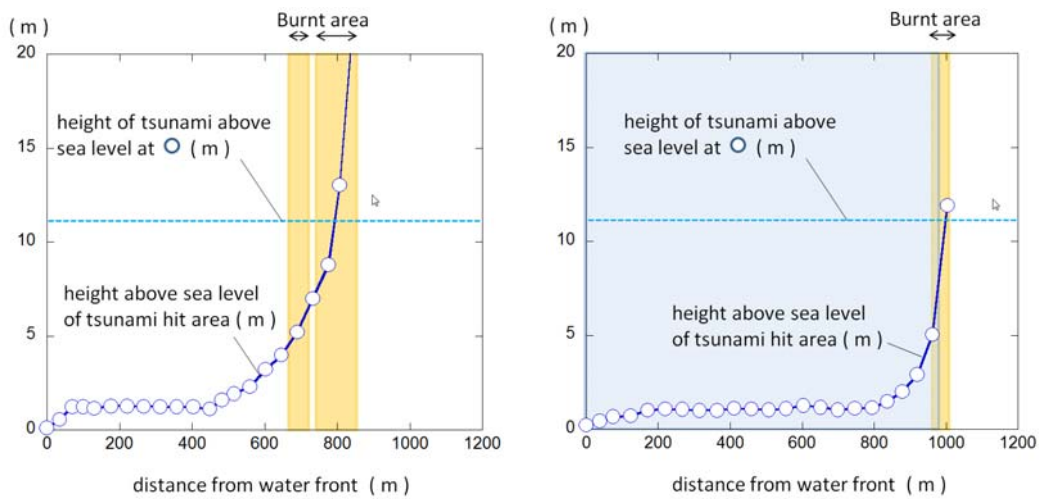


Fig. 22 Height of tsunami above sea level at fire spread area. (Center district of Otsuchi town, Iwate prefecture)



Fig. 23 Fire situation at 16:15 11th March 2011 about one hour after the tsunami hit here Center district of Otsuchi town (JGSDF, 2011)

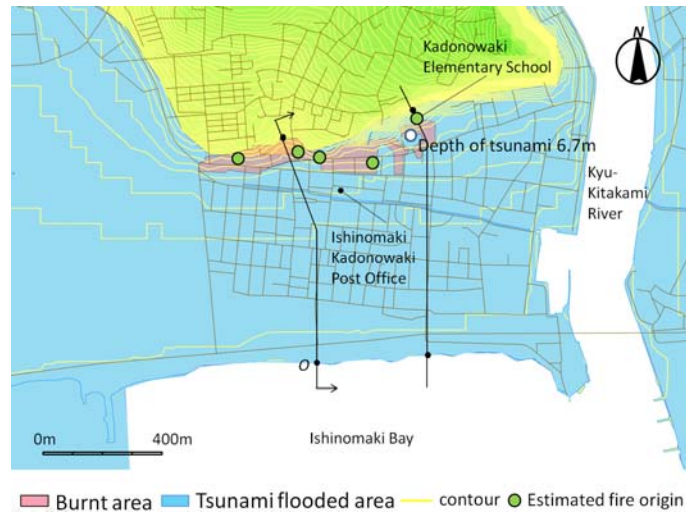


Fig. 24 Fire spread of fires to houses at hillslope of tsunami flooded area (Kadonowaki district of Ishinomaki city, Miyagi prefecture)

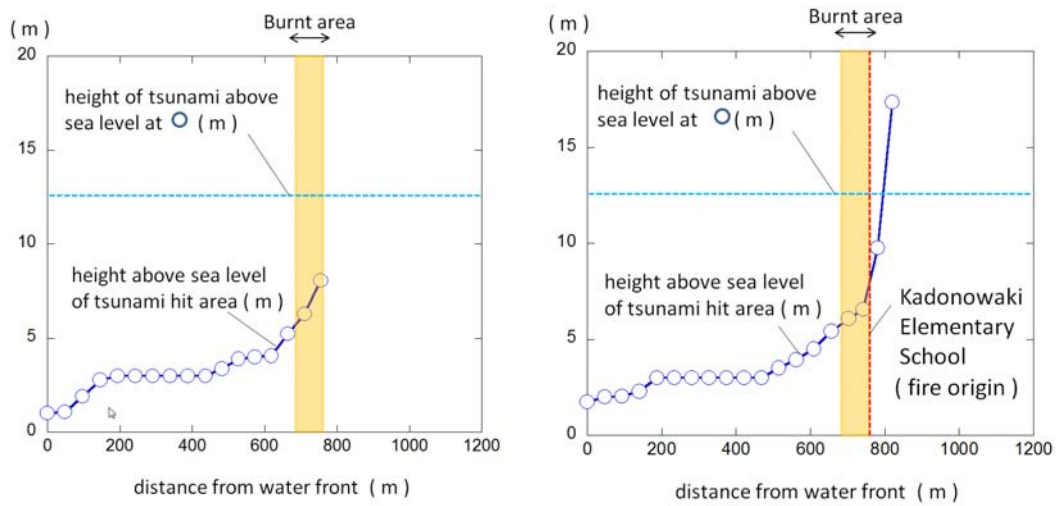


Fig. 25 Height of tsunami above sea level at fire spread area. (Kadonowaki district of Ishinomaki city, Miyagi prefecture)



Fig. 26 Fire situation at 15:53 11th March 2011 about one hour after the tsunami hit here Kadonowaki district of Ishinomaki city, Miyagi prefecture (Cocoxom ,2011)

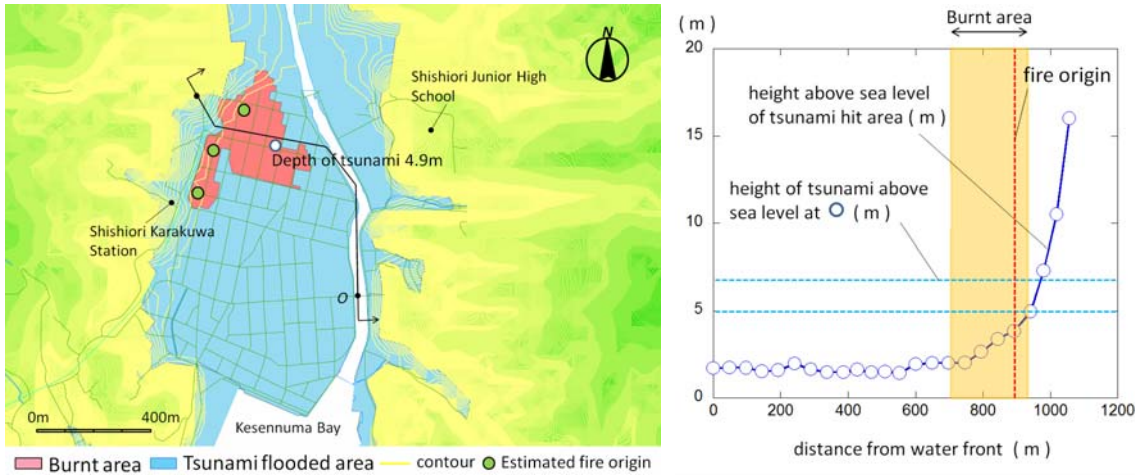


Fig. 27 Fire spread of fires to houses at slope of tsunami flooded area (Shishiori district of Kesennuma city, Miyagi prefecture)

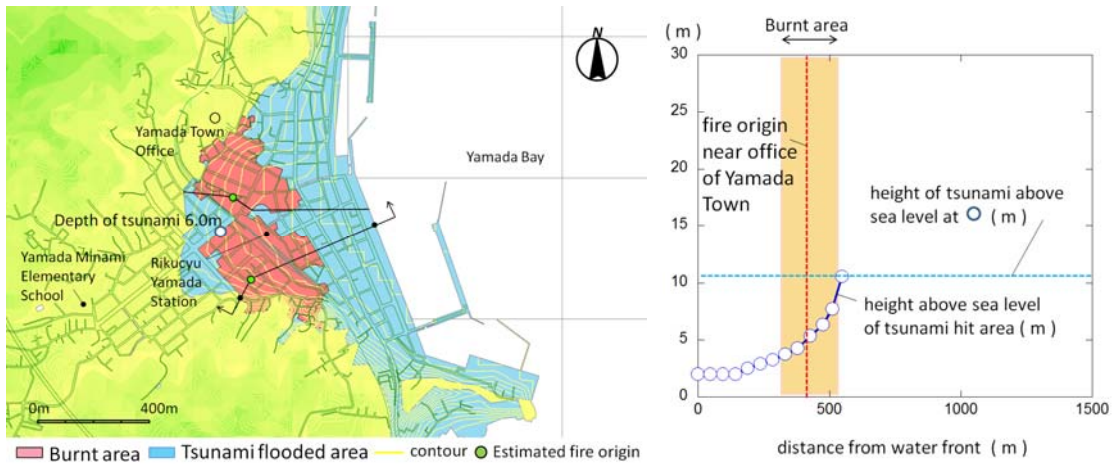


Fig. 28 Fire spread of fires to houses at slope of tsunami flooded area (Yamada district of Yamada town, Iwate prefecture)



Fig. 29 Fire situation at 16:15 11th March 2011 about one hour after the tsunami hit here Yamada district in Yamada town (JGSDF, 2011)

Slope gradients of the fire sites of Fig.27 and Fig.28 are not so steep compared with other fire sites shown in Fig.18 to Fig.26. It could be said that the burnt area tends to be wide at glacial slope. Fig.29 shows that width of combustible material bed is wide at this glacial slope.



Fig.30 Burn mark of pattern-2 automobile fires at the wall of Kadonowaki elementary school building. (Kadonowaki district in Ishinomaki city, Miyagi prefecture, photo taken on 11th April 2011)

In the pattern in which a fire was triggered by parked automobiles being washed up and smashed against buildings or in which fire was caused and spread by objects in flames drifting to built-up areas or forests, the fire broke out in many cases on the periphery of the flooded zone, where wood debris swept by the tsunami was accumulated in spaces among the wrecked houses.

Fig.30 shows one example of this kind of fire site. This fire site is rightmost fire origin shown in Fig.24. The wall shown in Fig.30 has three automobile fire burn marks at the bottom of each columns. The automobiles themselves seems to be removed in Fig.30. Fig.31 shows another example of this pattern-2 automobile fire shown in Fig.4 and Fig.7. Some fires shown in Fig.27 are said to be caused by propane gas tank and automobiles on which wooden materials piled up.

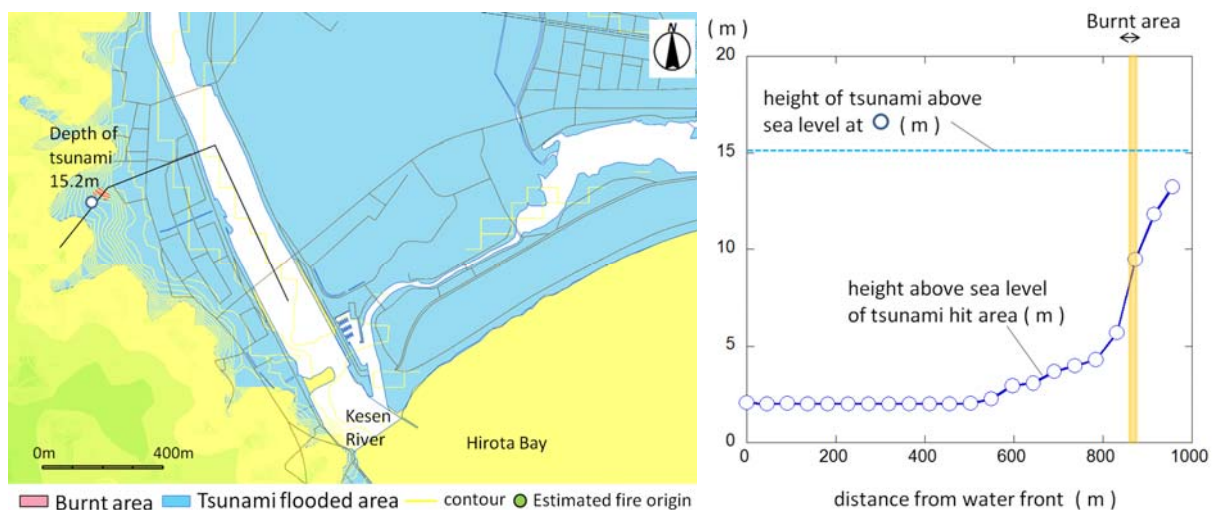
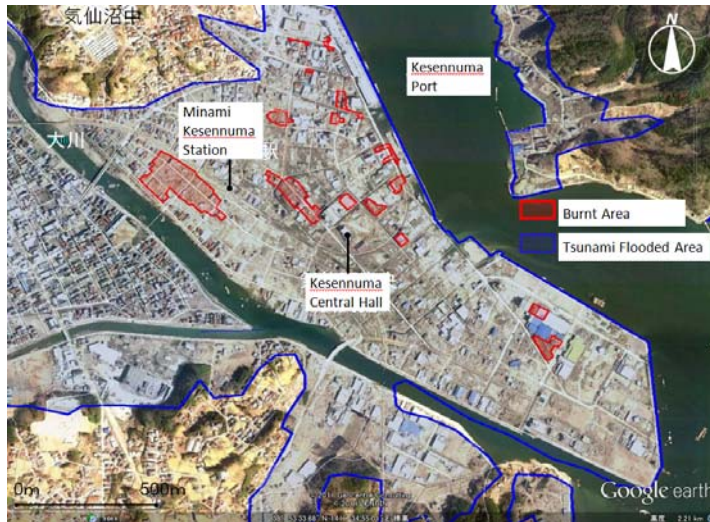


Fig. 31 Fire site of pattern-2 automobile fire at hillslope of tsunami flooded area (Kesen elementary school, Rikucyutakada city, Iwate prefecture)



(Google earth 06/04/2011)

Fig. 32 Fire site of pattern-3 leaked oil fires at Haber district Kesennuma city, Miyagi prefecture

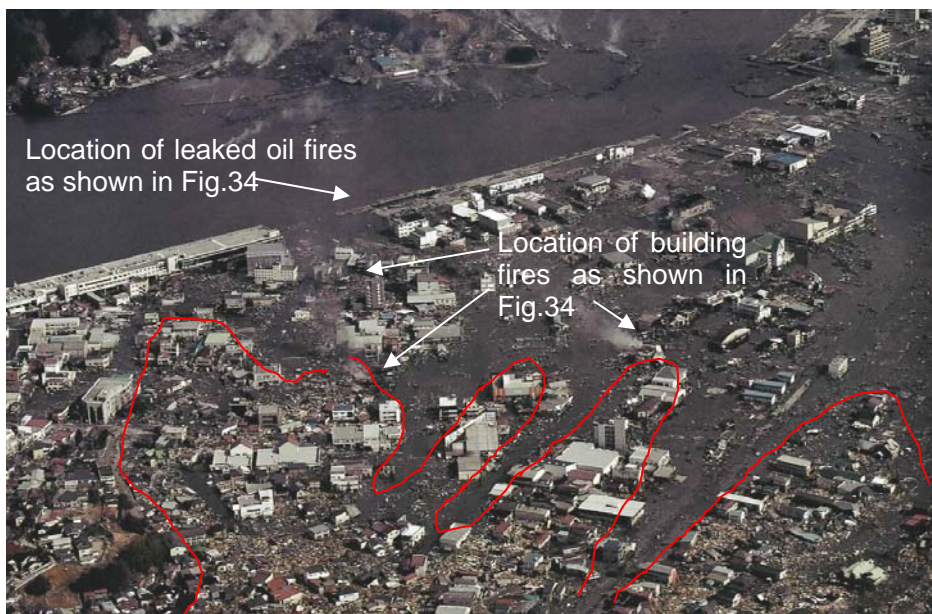


Fig. 33 Combustible material bed surrounded with red line in Haber district on 12th March 2011
The rightmost area caught fire on 14th March 2011 by unknown process (Bon Ishikawa ,2011)



Fig. 34 Flames at the rightmost are building fires ignited by drifting fires from left.
Flames at the center are oil leaked fires on the water. (NHK, 2011)

In the pattern in which fire was initiated by hazardous material leaked out of oil tanks, drifting objects in flames reached the coastal area flooded by the tsunami, resulting in the fire spreading to nearby buildings and other objects in the vicinity of the coastal and wharf area.

Fig.32 shows one example of pattern-3 leaked oil fires. Some small burnt areas and the biggest burnt area in Fig. 32 are not related to leaked oil fires. Small burnt areas are fires occurred at factories. Hazardous materials used in the factories are seems to be ignited when the tsunami hit there. Because the factories are not wooden structure, the buildings are not swept away by the tsunami, so the fires spread only inside of the factory buildings. The biggest burnt area near Minami Kesennuma Station is a fire occurred on 14th March 2011 by unknown reason. This area before the fire is shown in Fig.33. The rightmost area was combustible materials bed which was formed by the tsunami. Because of the depth of the water after the tsunami around here might have been shallow or in chance, the drifting fires didn't reach this combustible materials bed. As this site is flat as shown in Fig.35, the shape of combustible bed was formed like pyramid. There is a robust building at the top of the pyramid. In other condition of tidal wave, the drifting fire could have been reached wider combustible material bed to spread wider area.

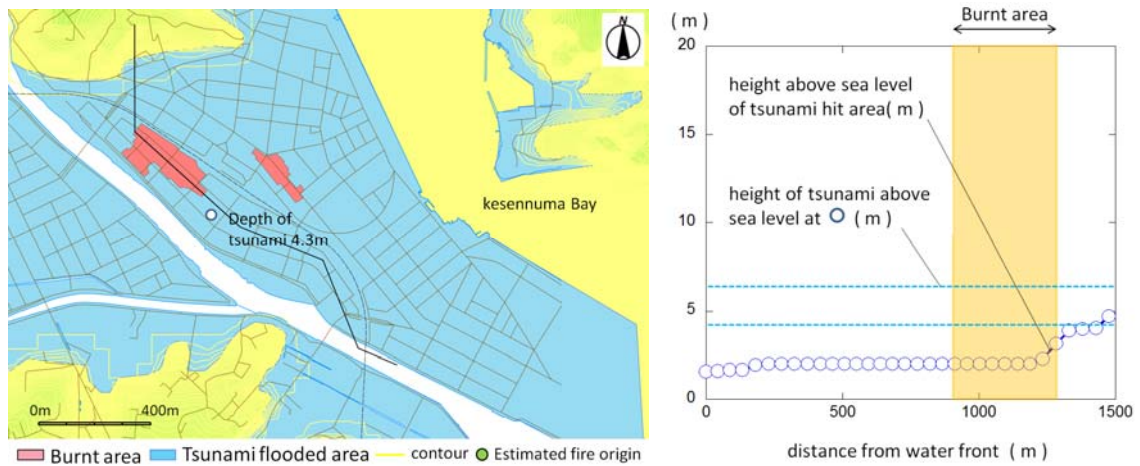


Fig. 35 Fire site of pattern-3 leaked oil fires at Haber district Kesennuma city, Miyagi prefecture

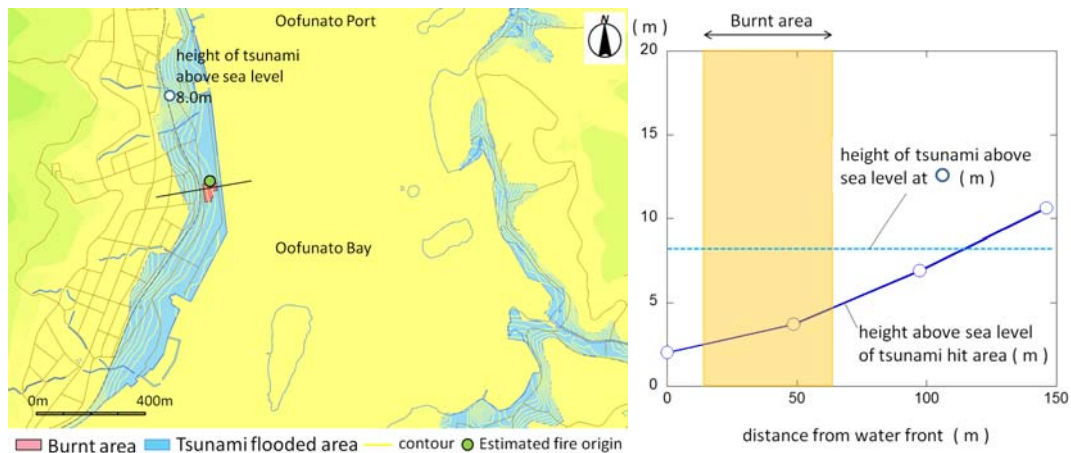


Fig. 36 Fire site of factory fire at Sunakomae district of Oofunato city, Iwate prefecture

Fig.36 shows other type of fire spread formation. In this fire site, there were some factories involved. The stream of tsunami around here was very strong from south to north, combustible materials accumulated between buildings of few factories and there propane tank fire or automobile fire might have occurred.

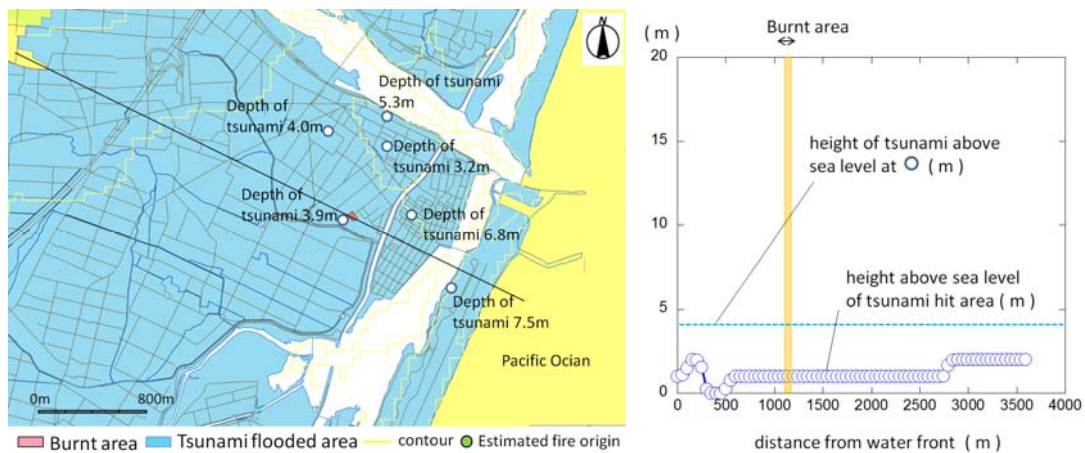


Fig. 37 Fire site in flat area, Yuriage district in Natori city, Miyagi prefecture

Fig.37 shows one example of fire spread in flat area. Burnt area depends on distribution of combustible materials and densely built up wooden housing area. There are variety of distribution of combustible materials from wooden houses hit by tsunami. Conditions of density of housing, open spaces and obstacles like railroad and highway banks make this variety. This time burnt areas in flat area were limited.

Table 2 shows burnt area of major fires. The total burned area was approximately 65 ha (hectare), excluding the extensive area of burned forests.

Table 2 Distribution of Fire Spread Area of Urban Fires occurred around boundary line of Flooding Areas from Tsunami

Prefecture	Municipality	10~20ha	5~10ha	1~5ha	0.3~1ha	~0.3ha
Iwate	Noda Village					1
	Miyako City				1	
	Yamada Town	1			4	1
	Otsuchi Town		1	2	3	
	Oofunato City				2	
	Rikuzentakada City					1
Miyagi	Kesenuma City		1	1		
	Minamisanriku Town			1		
	Ishinomaki City		1		1	1
	Sendai City				2	1
	Natori City			1		
	Watari Town					2
Fukushima	Soma City					1
	Iwaki City			1		

Only Spread fire are included. There were many unidentified small fires.

STATUS OF EVACUATION

Status of evacuation

As the spread fires in district of residence were almost limited in tsunami flooded area, most of the local people evacuated outside of tsunami flooded area. In the case of evacuation to designated tsunami evacuation building or to nearby buildings, when fires occurred the evacuees in tsunami evacuation buildings or nearby buildings had to be evacuated once again as the fire was spreading to the building, but with great difficulty since the surrounding area was submerged in tsunami water and they had to evacuate at the meantime of tsunami interval. In case of weak person, they had to hide in the safe fire compartment of the building and the supporter fought the fire.



Fig. 38 Tsunami Evacuation Buildings at Harbor district in Kesenuma (Bon Ishikawa, 2011)



(1st May 2011)

(Niji-ro-crayon 2011)

Fig. 39 Local people evacuated up to hillside after automobile fire occurred in front of Kadonowaki elementary school where they evacuated from the tsunami

CONCLUSIONS

Hazardous materials are main factor to occurrence of tsunami fires. Combustible materials from broken houses hit by tsunami determine the possibility of fire spread. Drifting materials, houses and boats contribute to fire spread.

It is difficult to evacuate from tsunami evacuation buildings and collapsed houses in case of fire, it is necessary to consider secondary evacuation routes, safe zone in buildings, fire extinguishing equipments or other strategies.

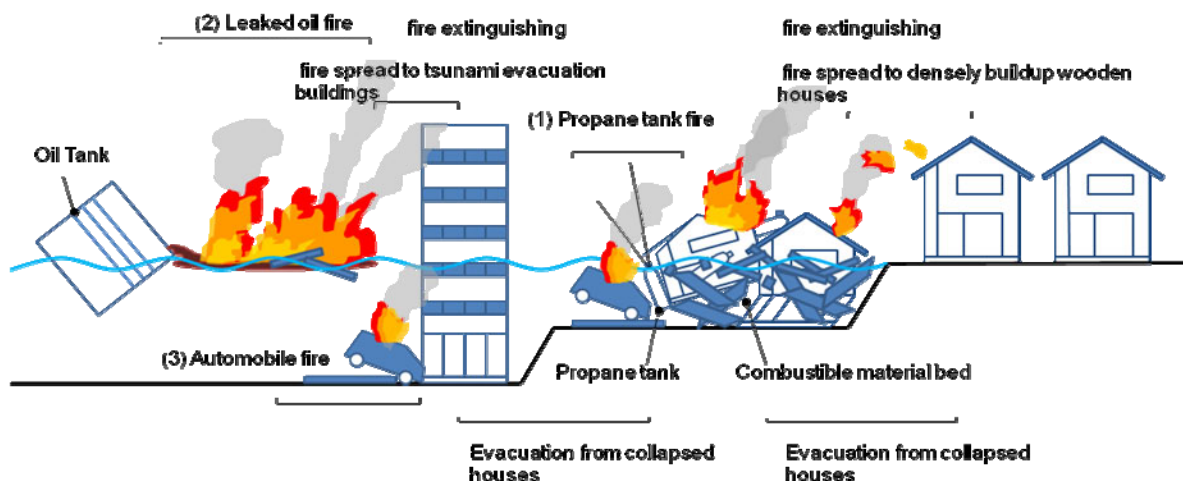


Fig. 40 Mechanism of tsunami fire and responses

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REFERENCES

- Akihiro Sato (2011). "<http://www.project-next.com/projectNext/Message.html>, last accessed at 31/01/2012"
- Bon Ishikawa (2011). "THE DAYS AFTER: Memories of the Great East Earthquake, a photography book, Asukashinsya"
- Cocoxom (2011). "<http://www.youtube.com/watch?v=RLgP3nmpaRc>, last accessed at 31/01/2012"
- FDMA (2011). "No. 142 report of the Disaster Response Headquarter of Fire and Disaster Management Agency"
- JAFSE (Japan Association for Fire Science and Engineering) (2011). "A preliminary report of Investigation on Earthquake and Tsunami Fires"
- JGSDF (Japan Ground Self-Defense Force) (2011). "The aftermath of the tsunami caused by the

- Tohoku region major earthquake off the Pacific coastline. 2011 March 11th approximately 4:15 p.m. Taken from the air above Yamadamachi Town and Ohtsuchichou Town in Iwate Prefecture. This image was taken from the second anti-tank helicopter squadron of the Japan Ground Self-Defense Force stationed in Hachinohe. <http://www.youtube.com/user/KohoHachinohe> , last accessed at 31/01/2012”
- JMSDF (Japan Maritime Self-Defense Force) (2011).”Airborne imagery over Iwate Prefecture by JMSDF just after the Earthquake, <http://www.jiji.com/jc/movie?p=top225-movie02&s=243> , last accessed at 31/01/2012”
- Hagimoto (2011). “Ignition pattern”, A preliminary report of Investigation on Earthquake and Tsunami Fires, Japan Association for Fire Science and Engineering.
- NHK ((2011). “Video taken by Tohoku Unit of Japan Ground Self-Defense Force”
- Kindai-Syobo-Sya (2012). “Occurrences and responses of Fires related to the Great East Japan Earthquake, Digest of the Great East Japan Earthquake”
- Lakita (2011). “<http://youtu.be/ZmG7QWGR7N8>, last accessed at 11/10/2011”
- Niji-ro-crayon (2011). “<http://kodomohinanjoclub.cocolog-nifty.com/blog/inochi.html>, last accessed at 28/11/2011”
- TBC(2011). “Document of the Great East Japan Earthquake - Miyagi 3.11 - , last accessed at 31/01/2012”
- Zerocounts (2011). “<http://www.youtube.com/watch?v=A-u3Xc9vQWs>, last accessed at 31/01/2012”
- ZANGIEFCHAMP (2011). “http://www.youtube.com/watch?v=GtG_e9pwWmk, last accessed at 31/01/2012”