NATECH ACCIDENT INVESTIGATION DURING THE 2011 GREAT EAST JAPAN EARTHQUAKE AND RECOMMENDATIONS FOR DISASTER PREPAREDNESS BASED ON A RESIDENT SURVEY

Anirban CHAKRABORTY[1], Ahmed IBRAHIM[2] , Bohuan ZHAO[3], Kana MINAMIDE[4], Songwhan HAN[5] and Yuhan GAO[6]

[1,2,3,4,5,6] M1, Department of Urban Management, Graduate School of Engineering, Kyoto University
(Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto 615-8540, Japan)
E-mail[1]: anirban@catfish.dpri.kyoto-u.ac.jp
E-mail[2]: ahmed.farag.52x@st.kyoto-u.ac.jp
E-mail[3]: zhao.bohuan.32u@st.kyoto-u.ac.jp
E-mail[4]: minamide.kana.43u@st.kyoto-u.ac.jp
E-mail[5]: han.whan.62x@st.kyoto-u.ac.jp
E-mail[6]: gao@trans.kuciv.kyoto-u.ac.jp

Natech events are low probability but high impact events. The rarity underlines the importance to study the past events and the possibility of large scale damage stresses the application of the lessons learnt for a better preparedness against similar occurrences in the future. In this study, two natech events at JX refinery, Miyagi Prefecture and Cosmo Oil Refinery, Chiba Prefecture, Japan on the aftermath of the 2011 Great East Japan earthquake are investigated and the lessons learnt and recommendations are summarized. Results from a survey conducted at Higashinada Ward in Hyogo Prefecture, Japan to assess the preparedness against possible natech events triggered by the Nakao Trough Earthquake in the future, are also discussed based on the lessons learned from the accident investigations.

Key Words : *Natech, Sequential Timed Events Plotting, Fault Tree Analysis, Nankai Trough Earthquake,*

1. INTRODUCTION

In the last decade, *na*tural disaster triggered *tech*-nological disaster (*Natech*) events has surfaced as a new threat to the countries and their economies across the world and raised questions of preparedness against large-scale impacts even in the developed nations. The large-scale losses to the economy triggered by hurricanes Katrina and Rita (United States, 2005), disastrous fire triggered at the Tupras petroleum refinery by the Kocaeli earthquake (Turkey, 1999) and fire and explosions at Cosmo Oil refinery and JX refinery triggered by the Great East Japan earthquake (Japan, 2011) are reminders of how devastating the impacts could be, in both space and time. Natech is a relatively new challenge faced by the people involved in disaster risk management. These disasters can be particularly complicated. It generally involves situation in which (i) multiple and simultaneous release of hazardous materials becomes more likely, (ii) safety and mitigation systems may fail concurrently and (iii) conventional emergency response plans may become redundant. The high impact and low probability of these events makes it more important that past events should be well understood and the lessons learnt should be used in preparing for the future occurrences. And here lies the motivation for this paper.

The objective of the study is two-fold: (1) to investigate natech events from the past to identify and describe the actual sequence of events, the direct and root causes and most importantly, the risk reducing measures to prevent future occurrences, and (2) assess the current level of preparedness against a possible damage. Department of Energy (DOE) and Centre for Chemical Process Safety (CCPS), United States, amongst many others, provides guidelines on using different accident investigation techniques and some of these has been used for this study. In this paper, at first the natech accidents at (i) Cosmos Oil Refinery, Chiba Prefecture, Japan and (ii) JX Refinery, Miyagi Prefecture, Japan on the aftermath of the Great East Japan Earthquake, 2011, are investigated and recommendations are summarized for a better preparedness in the future. And then, a survey was done at Higashinada Ward, Hyogo prefecture, Japan to understand the level of preparedness (emergency response plans) of the local people against the possible damage from the Nankai trough earthquake in the future.

2. METHODS OF ACCIDENT INVESTIGATION

Department of Energy (DOE) and Centre for Chemical Process Safety (CCPS), United States , amongst many others, provides guidelines on using different accident investigation techniques and some of these has been used for this study. This section provides a brief overview of the various methods used.

(1) Sequential Timed Events Plotting (STEP)

STEP provides a comprehensive framework for accident investigation from the description of the accident process. The STEP is basically a matrix. The rows are the names of actors, which are the subjects of events. The column is a timeline of events. The first key concept of STEP is the multi-linear event sequence, which overcomes the limitation of single linear description of events. Secondly, an event is defined as one actor performing on action. The third feature in STEP is that the events flow logically in the process. Linking arrow in the plot shows the logical relations between events. By analyzing the STEP diagram, safety problems are identified. Identified safety problems are marked as triangles.

(2) Fault Tree Analysis (FTA)

Fault tree analysis is a method for determining the causes of an accident (or top event). The fault tree is a graphic model that displays the various combinations of normal events, equipment failures, human errors, and environmental factors that can result in an accident. A fault tree analysis may be qualitative, quantitative, or both. Possible results from the analysis may be a listing of the possible combinations of environmental factors, human errors, normal events and component failures that may result in a critical event in the system and the probability that the critical event will occur during a specified time interval. The strengths of the fault tree, as a qualitative tool, are its ability to break down an accident into root causes.

(3) Event Tree Analysis (ETA)

An event tree is used to analyze event sequences following after an initiating event. The event sequence leads to a set of possible consequences and the consequences may be considered as acceptable or unacceptable. An ETA is primarily a proactive risk analysis method used to identify possible event sequences. The event tree may be used to identify and illustrate event sequences and also to obtain a qualitative and quantitative representation and assessment.

(4) MTO Analysis

MTO analysis stands for the analysis of Man, Technology and Organization (Menneske, Teknologi og Ogranisasjon). The basis for the MTO analysis is that human, organizational, and technical factors should be focused equally in an accident investigation. This method is based on HPES (Human performance enhancement system) and it can be conducted based on three methods: structured analysis, change analysis and barrier analysis.

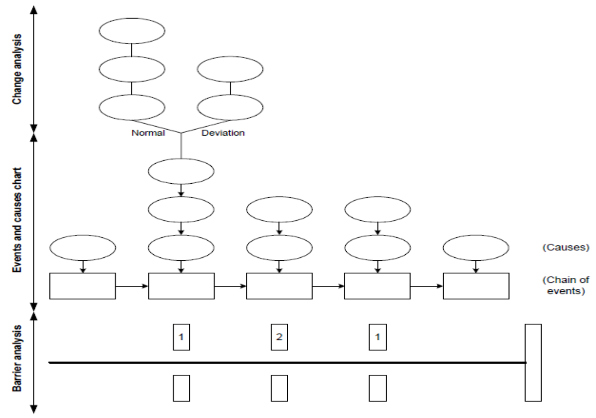

Fig 1. MTO analysis worksheet

Fig. 1 illustrates an example worksheet of MTO analysis. As we can see, the structured analysis is done by sue of an events and causes diagram while change analysis is conducted by describing how events have deviated from earlier events or common practice. Also, the barrier analysis is conducted by identifying technological and administrative barriers in which have failed or are missing.

(5) Event and Causal Factors Charting (ECFC)

It is a graphical display of the accident's sequence and is mainly used to portray the events in a chronological order. It is easy to develop and provides a clear depiction of the data. Such kind of charting is useful in identifying multiple causes and graphically depicting the critical conditions and events necessary and sufficient for the accident to occur.

(6) Barrier Analysis

Barrier Analysis is used primarily to identify hazards associated with an accident and the barriers that should have been used to prevent it. Physical barriers are easy to identify as compared to management system barriers. To understand management barriers, investigators may need to obtain information about barriers at three organizational levels; the activity, facility and institutional levels. The analysis is usually documented in a barrier analysis worksheet.

(7) Root Cause Analysis

Root cause analysis is any analysis that identifies underlying deficiencies in a safety management system which upon correction prevents repetition of similar accidents. One of the methods used in this paper for root cause analysis is DOE's TIER diagramming. TIER-diagramming is used to identify both the root causes of an accident and the level of management bearing the authority and responsibility to correct the accident's causal factors.

3. CASE STUDY I: JX Refinery, Miyagi Prefecture, Japan

(1) Description of the Area

JX Refinery Sendai is located in northeast of Miyagi prefecture along the Sendai pear. It produces 145,000BD with 9 crude oil tanks and 84 product tanks. This number is not that large compared to the total production in Japan (4,241,000BD), however, this refinery is essential for the lifeline of Tohoku area given that it is the only refinery in Tohoku. There are almost 300 employees and the total area of the refinery is 1.5 million m^2.The refinery can be divided into two areas (section), which is West area and East area. At the accident day, there were truck loading area, LPG tanks, asphalt plant, mega solar in the west area. On the other hands, the east area had crude oil tanks, piers, control center, processing area and power generator. In addition, there are a number of other industrial facilities around the refinery such as Sendai Gas, Tohoku Electricity and Zen-noh (agricultural products with their own oil storage) which composed of Sendai Industrial Complex. The administrative organization of the refinery was also in a complicated situation. There are three local governments, Tagajo-shi, Shichigahama-machi and Sendai-shi which manage west, east, and other areas respectively (Fig. 2). This means there is no one organization controlling JX refinery Sendai, which was one of the main problems to make the damage of the accident worse.

(2) Description of the Accident

The accident began with the earthquake. The earthquake occurred at 14:46 on 11 March with M9.0 and 2.933 gal, by which the all system of the refinery was shut down automatically. Also, the tsunami occurred by the earthquake and reached the pier at 15:40 with 2.5~3.5m of water depth. There was the first warning of the tsunami at 14:49 and the second and an evacuation order were at 15:15 and 15:30 respectively. About 100 employees who were working on the site could evacuate safely into the Shichigahama primary school located in 2 km away from the site. However, unfortunately, 4 people died who were working on a tanker because of the tsunami.

Fig 2. Damage Map of JX Refinery Sendai

When the tsunami hit, tanks were to tilt, pipes broke and oil released. In the truck loading area in the east section, ignition occurred at 21:25. Even though the causes of the ignition are still not clear, sparking from the battery of trucks or static electricity between metals might be the cause. Moreover, Asphalt and Sulphur are also released, and there are heavy oil releases, 3,900 kl from tanks floated by the tsunami and 4,400 kl from damaged pipes by direct tsunami impact.

There was onsite fire-fighting equipment (Kyodo-Bosai-Soshiki partnership) established by several facilities in Sendai industrial Complex, however, the equipment is damaged by the tsunami which was larger than expected. And, tsunami damaged containment walls and roads which make the rescue delayed. An employee who evacuated to the primary school called to Shichigahama-machi fire bureau on 11 March and requested a helicopter to investigate the site and an evacuation order for the residents in 2km radius (not only Shichigahama-machi but also Sendai-shi and Tagajo-shi) around the site through Shichigahama-machi town hall on 12 March. The helicopter from Self-Defense Forces investigated the site on 13 March. And they found there is an original valve to release the oil consistently into the fire site. The probable valves are closed on 14 March, and finally, the fire extinguished officially at 14:30 on 15 March. To analyze and investigate the accident concretely, STEP analysis, Fault tree & Event tree analysis, and MTO analysis will be used in this report. In first, STEP analysis is used in order to make clear actors and their subjects with time sequence. Secondly, Fault tree & Event tree analysis shows the flow and the sequence of the accident to the top event such as fire and also the results from the top event respectively. This methodology will help us to re-check the causes and the results of the accident. Lastly, MTO analysis contains barrier analysis and change analysis. From that, it will be possible to compare the situation of the accident with the past situation.

(3) Application of Accident Investigation Methods

a) Sequential Timed Events Plotting (STEP)

The JX refinery Sendai fire is illustrated by a STEP diagram in Fig.3 and Fig.4. Because of page limitation, we divided the diagram into 2 parts. The first half shows what happened till the ignition, and the second half shows the events flow after the fire occurred. In Fig.3, the Tagajo Office, Shichigahama Office and Sendai Office are considered as one actor named "government", because they had similar actions before ignition. In Fig.4, each of these office actors is separated since their actions are different. Also because of the limitation, actors of firefighting department only showed in Fig.4.In both figures, the timeline is on X-axis and actors are labeled on Y-axis. The events are actions by actors. In Fig.3 for example, the first yellow rectangle means that JX Company set up Emergency Headquarter on

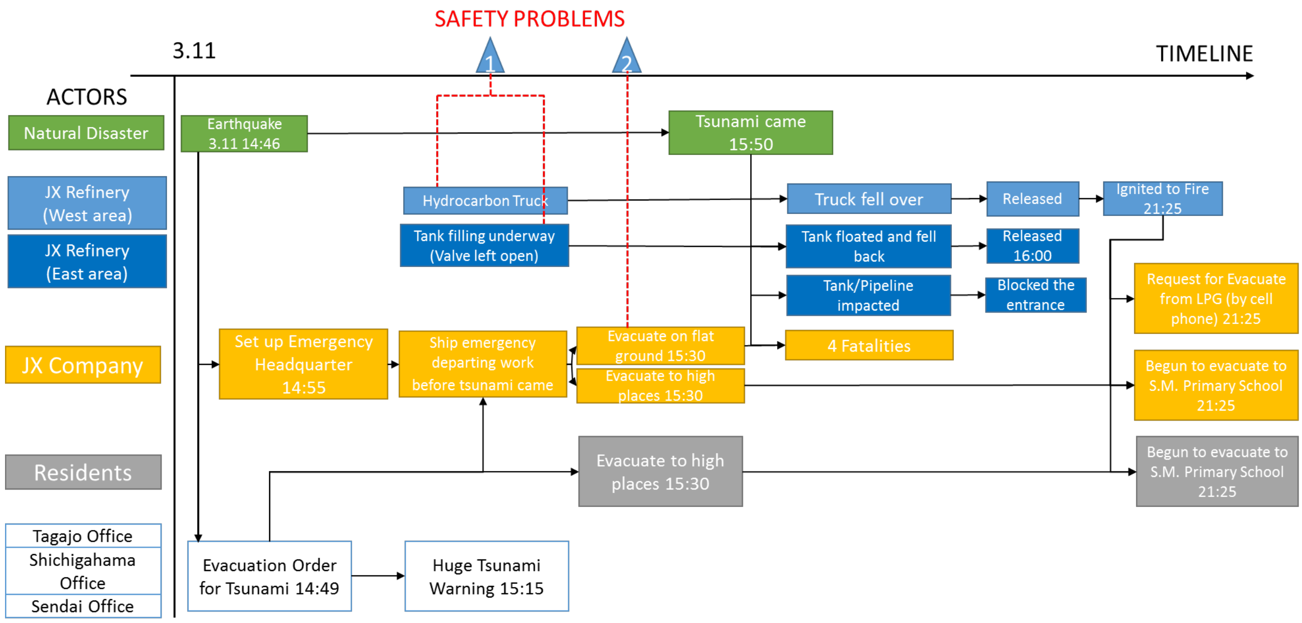

Fig. 3 1st half of STEP

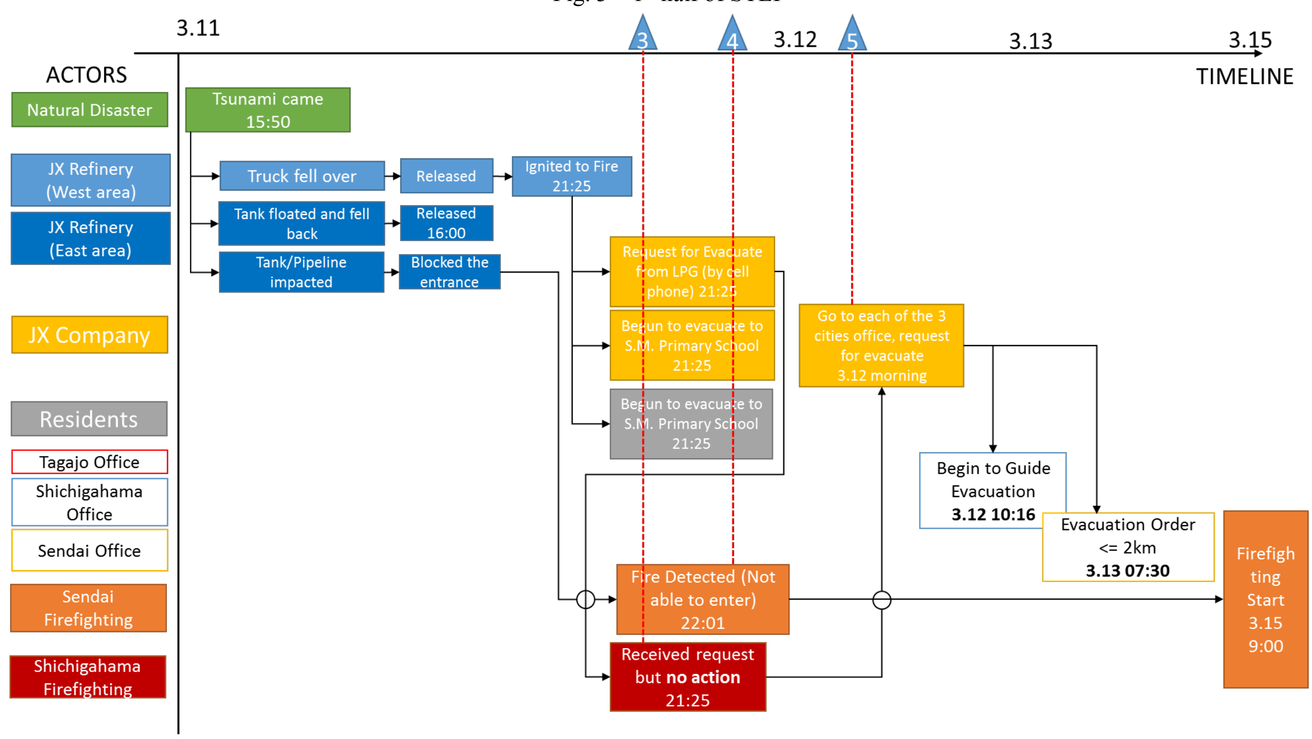

Fig. 4 2nd half of STEP

2011.3.11, 14:55. Arrows are used to link related events. Safety problems are identified during the analysis, which marked as triangles on the top. The STEP model is easy to show tractable accident clearly. However, the model only focuses on events. The STEP does not have a way to point out the interrelation or cooperation between each actor, which makes it hard to indicate the cooperation problem, such as lack of communication in Sendai case. As a result, if the investigator does not have sufficient knowledge of the specific accident, the reason for safety problems could not be recognized.

b) Fault Tree Analysis (FTA) & Event Tree Analysis (ETA)

The FTA analysis involves three steps. (1) Define the undesired event to study: There were a lot of undesired event during the JX refinery incident such as gasoline released, heavy oil released, 4 people died and fire. After putting everything in order, we finally decided to choose fire as the undesired event to study. (2) Obtain an understanding of the system: After sorting out the reference materials, we can know that there were 3 fires—2 in eastern area and the main one in the western area. Gasoline spill, as well as ignition, led to the fire. There were several reasons caused the spilling such as pipelines were broken for reasons and one of the tank roof was moved due to the earthquake and a valve remained open while tsunami came, which caused even serious spilling. Also, ignition sources can be the spark of truck's battery or metal to metal friction caused by the tsunami. (3) Construct the fault tree: After selecting fire as the undesired event and having analyzed the system so that we almost get all the causing effects to construct the fault tree. A fault tree is based on AND and OR gates which define the major characteristics of the fault tree. (Left side of Fig. 5)

An event tree analysis of JX refinery accident is performed as follows: (1) Define the system: Since we want to unify the fault tree and the event tree, so our event tree begins from the fire and end at the extinguished of fire. (2) Identify events: Here, the fire is considered as the initiating event. After the fire occurred, it spread and onsite rescue failed. The employee were evacuated and called the government for residents' evacuation request. Then, the helicopter came and firefighters from out site came to fight the fire. Finally, the opened valve was closed and the fire was put off. (3) Build the event tree diagram. The diagram is showed as the right side of Fig. 5.

c) MTO Analysis

To do an MTO analysis, the first step is to develop the event sequence longitudinally and illustrate the event sequence in a block diagram. Here, we defined the events started from the tsunami and temporarily ended at "out site rescue delayed", with an order of tsunami, gasoline/heavy oil released, fire, communication failure, onsite rescue failed, out site rescue delayed (Fig. 6). Then, analyze which technical, human or organizational barriers that have failed or was missing during the accident progress. In JX refinery accident, firstly, when the tsunami came, if there're breakwater in front of truck loading/unloading area, it may make any sense that the

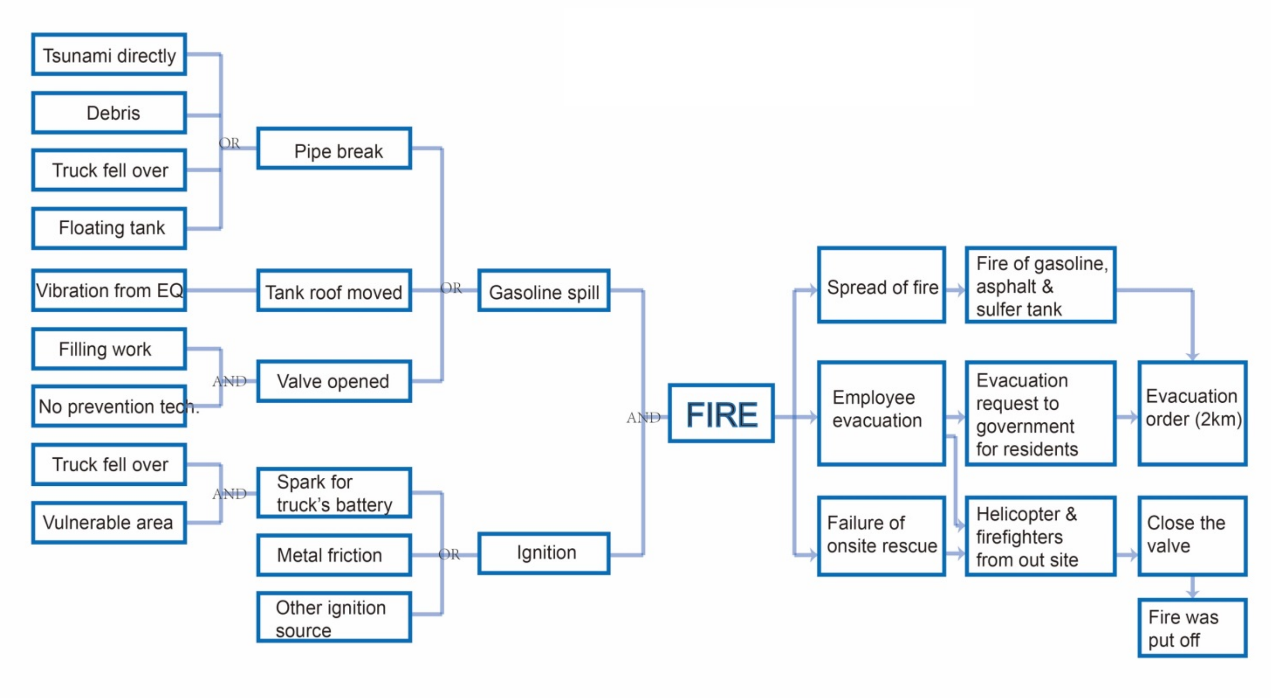

Fig. 5 Fault Tree and Event Tree Analysis

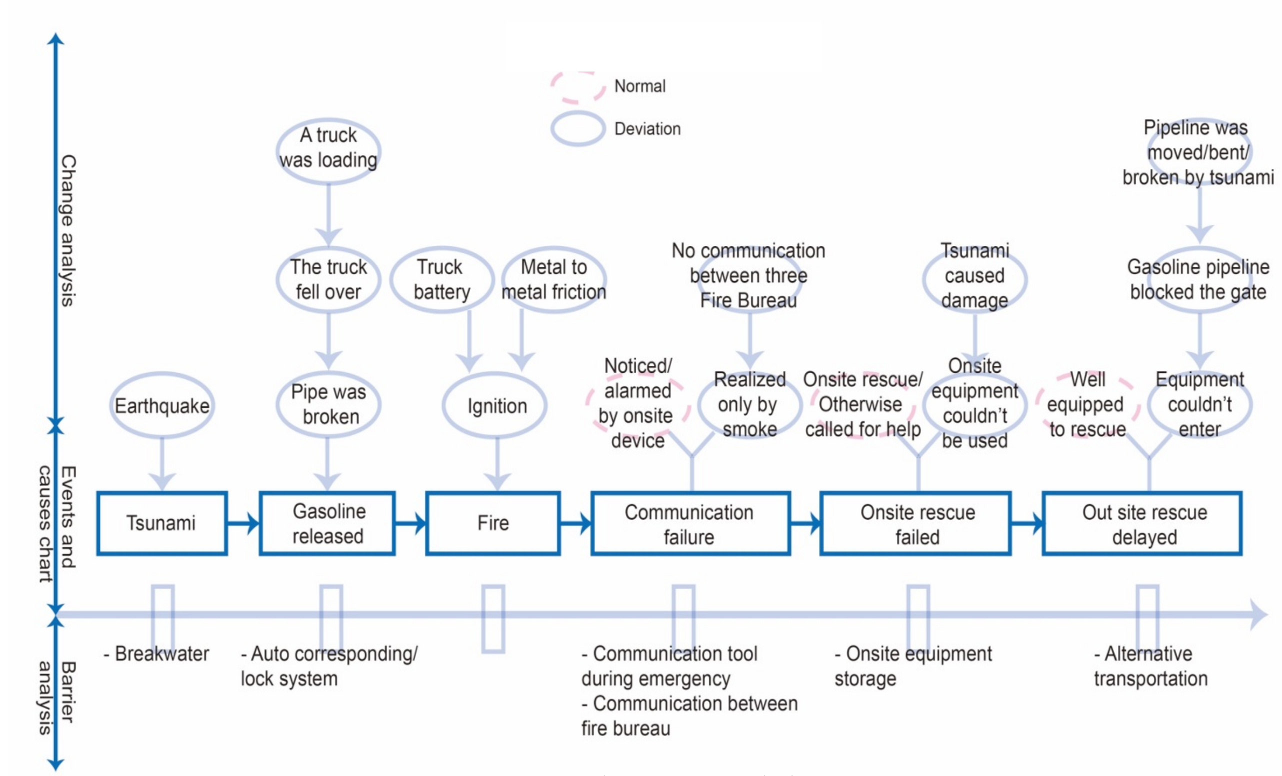

Fig. 6 MTO Analysis

truck may be just floating but not fell over, or metal friction may not happen that there would be no ignition for the fire. Secondly, during the fuel releasing happened, an automatic lock system may help towards the release problem. Also, there's a huge problem about the communication tool during emergency on site and the communication between fire bureaus as well as three local governments almost failed. What's worse, there's barriers failed of onsite equipment storage as well as fire trucks since the storage location should consider the worst condition. Finally, transportation method needs more consideration that if the rescue couldn't be conducted via land, there should have alternative transportation method. Further, we need to assess which deviations or changes in which differ the accident progress from the normal situation.

These changes are also illustrated in the diagram (shown in nominally titled circle). During the communication failure period, in common practice, the fire would be noticed or alarmed by the onsite device but actually, it was noticed only by smoke and the communication between three fire bureaus as well as three local governments were terribly delayed. Moreover, when the fire occurred, normally we will do onsite rescue firstly and call for help. However, onsite equipment was damaged by the tsunami and couldn't be used, neither do the communication tools. Additionally, after onsite rescue failed, usually the helper from other places will come but at that time the out site rescue found out that they couldn't enter the site because the gate was blocked by the broken pipeline.

(4) Lessons Learnt from JX Refinery, Sendai and Recommendations

		Disadvantages
STEP	Time sequence is described Actors and subjects are clear	No Barrier analysis Relation among actors are not clear
Fault tree & Event tree	Root cause analysis Flow and Sequence are clear	Only one accident(not suitable for multiple accidents)
MTO	Root cause analysis Barrier analysis Change analysis	Only one accident Actors are not clear

Table 1. Comparison of Methodologies

a) Comparison of Methodologies

As we can see in Table1 on the left, MTO analysis and STEP analysis are basically superior compared to Fault tree and Event tree analysis in terms of cause analysis and sequence of accidents However each methodology is not perfect and has to be redeemed with other methodologies in order to evaluate accidents precisely and concretely. Therefore, a comprehensive methodology which contains advantages of MTO and STEP is required.

b) Five safety problems are identified from the analysis.

Safety problem 1: After the tsunami warning, the tanker was still under loading/filling. The loading trucks fell over and leaked, which was the main reason of the west area fire. And the fire put the LPG tank at risk. Since it is almost impossible to do any countermeasure with the loading trucks after the tsunami warning, to choose a better location for loading area where maintain a distance away from LPG tank may be a way. On the other hand, filling tank caused a huge release in the east area of the refinery, for the valve left open after the evacuation. An auto-lock system for the whole refinery system can well solve the problem and is recommended.

Safety problem 2: After the first evacuation order for tsunami, the ship emergency departing was still at work. There were 4 fatalities during ship emergency departing work. The 4 workers who run on flat ground to escape instead of running to high place get killed by the tsunami. According to the interview, the employee said that there is no communication between JX Company headquarters and the workers because of the power failure, which may cause the workers evacuate late and in an incorrect way. If the evacuate time is clearly defined, or the workers strictly follow the evacuation order. Also, the worker should be told to evacuate to high places. For avoiding out of contact because of the power failure, an intercom is recommended in the future.

Safety problem 3: The communication problem of each firefighting department and city office is seriously insufficient. Shichigahama Firefighting Dept. received the request from JX Company for evacuating residents but did not take action immediately. Such a late action of guiding citizens to evacuate from LPG means that the government and firefighting department did not recognize the hazard level.

Safety problem 4: Although the fire was detected by Sendai Firefighting Department, they can do nothing because the main fire was in Shichigahama. Also, the firefighting equipment was damaged, firefighters were not enough, and the entrance was blocked.

Safety problem 5: After realized the LPG tanks were in danger, JX company staff had to go to each of the 3 cities' office to request for evacuating, which means that communication and management were disordered. There was no communication between the 3 cities. And the officers did not recognize the risk resulting in very slow response for the evacuation order.

4. CASE STUDY II: Cosmo Oil Refinery, Chiba Prefecture, Japan

(1) Introduction to Cosmo oil refinery fires

On 11th March, 2011 at 14:46 hrs. (Japan Standard Time) the eastern part of Japanese archipelago was hit by a magnitude 9.0 (Mw) undersea megathrust earthquake with an epicenter approximately 70 kilometers east of the Oshika Peninsula of Tohoku region and at a depth of around 30 km from the surface of the ocean. The powerful tsunami that was triggered by the earthquake reached up to heights of 40.5 meters in Iwate Prefecture and travelled up to 10 km inland. The death toll which crossed 15,000 was mainly due to the tsunami in the on shore region. The earthquake had far reaching consequences in many industrial facilities. In this report we mainly focus on the Cosmo Oil refinery located at Chiba Prefecture, Japan.

During the main-shock at 14:46 hrs. the peak ground acceleration at the Cosmo Oil refinery was recorded at 114 gal (cm^2/sec). One of the LPG tanks in the storage tank area of the industrial complex which was filled with water for maintenance reasons had its braces damaged by the strong ground motion. At 15:15 hrs. an aftershock measuring 99 gal was recorded. This time the legs of the tank could not survive the blow and the entire tank collapsed at around 15:20 hrs. The collapse took the neighboring pipes with it and led to the release of LPG. At around 15:47 hrs. the LPG caught fire which triggered a series of explosions which was completely extinguished on 10:10 hrs. on March 21st,2011.

(2) A Detailed Overview of the Events

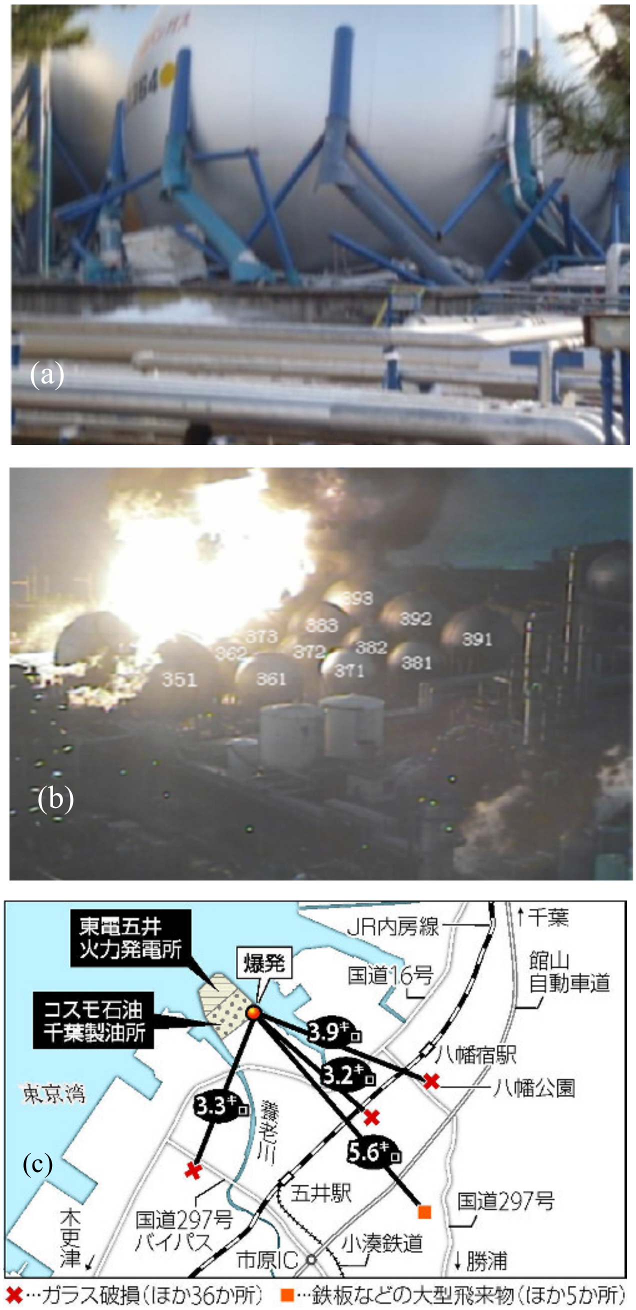

Fig. 7 (a) Collapsed Tank resulting from the damaged bracing (b) A photo just before the explosion (c) Range of flying debris projectiles

There were 17 tanks in the LPG storage farm area of the industrial complex. During maintenance inspection, the tanks are filled with water to check for possible leakage. In usual practice this is done for 2-3 days. On March 11, tank no. 364 was holding water for 12 days. Also, before the earthquake, there was a confirmed leakage of air from the pipe to which air was supplied to activate the emergency shut-off valve. As a temporary measure this valve was fixed open until the pipe was fixed. This manually switching of the emergency valve to "open" position was a violation of the "High Pressure Gas Law" by the Cosmo Oil authorities. Unfortunately, this emergency shut-off valve stayed open at the time of the earthquake too. After the first earthquake, the bracing of the LPG tank no. 364 suffered some damage. The tanks are designed for holding LPG and not for the temporary confinement of water. A mass which is 1.8 times heavier than LPG is much more viable to damage in a seismic event. The damage was not identified during the visual inspection after the main shock at 14:46 hrs. It is difficult to visually inspect a tank of 20 m diameter and 2000 kl capacity in a short period of time. At 15:15 there was the aftershock. The emergency valve was still not closed as it was wrongly assumed that the strength of the tank was not compromised. At 15:20 the legs failed and the entire tank collapsed. The collapse damaged the neighboring pipelines and triggered a release of LPG.

Overall 71 facilities in Chiba are regulated by the "Act on the prevention of disasters in petroleum industrial complexes and other petroleum facilities (Petroleum Complex Act)". The law gives instruction to the prefecture on the requirements for fire-fighting equipment and operators. The equipment should be made available and the companies can share it amongst themselves. The partnership is called Kyodo-Bosai-Soshiki Partnership. In case of an accident, the fire-fighting department of the Ichihara municipality must be informed via a hotline. The Kyodo-Bosai-Soshiki fire-fighters and those of the municipality cooperate in fighting the accident. And the prefectural (Chiba Prefecture) fire-fighting cannot get involved before the national authority gets involved. This is a basic structure of the preparedness before the accident on March 11, 2011. Upon the noticing of the LPG leakage, following the regulations the Kyodo-Bosai-Soshiki team was informed at 15:35 hrs. and the Ichihara Municipality at 15:37 hrs. At 15:47 hours an unknown source (no source was revealed from the inspection of Ichihara Municipality and Cosmo Oil) ignited the LPG and a fire was started. This fire started spreading quickly to the nearby tanks and at 15:04 the first explosion was recorded. Unfortunately, the damage did not stay confined to the LPG storage farm.

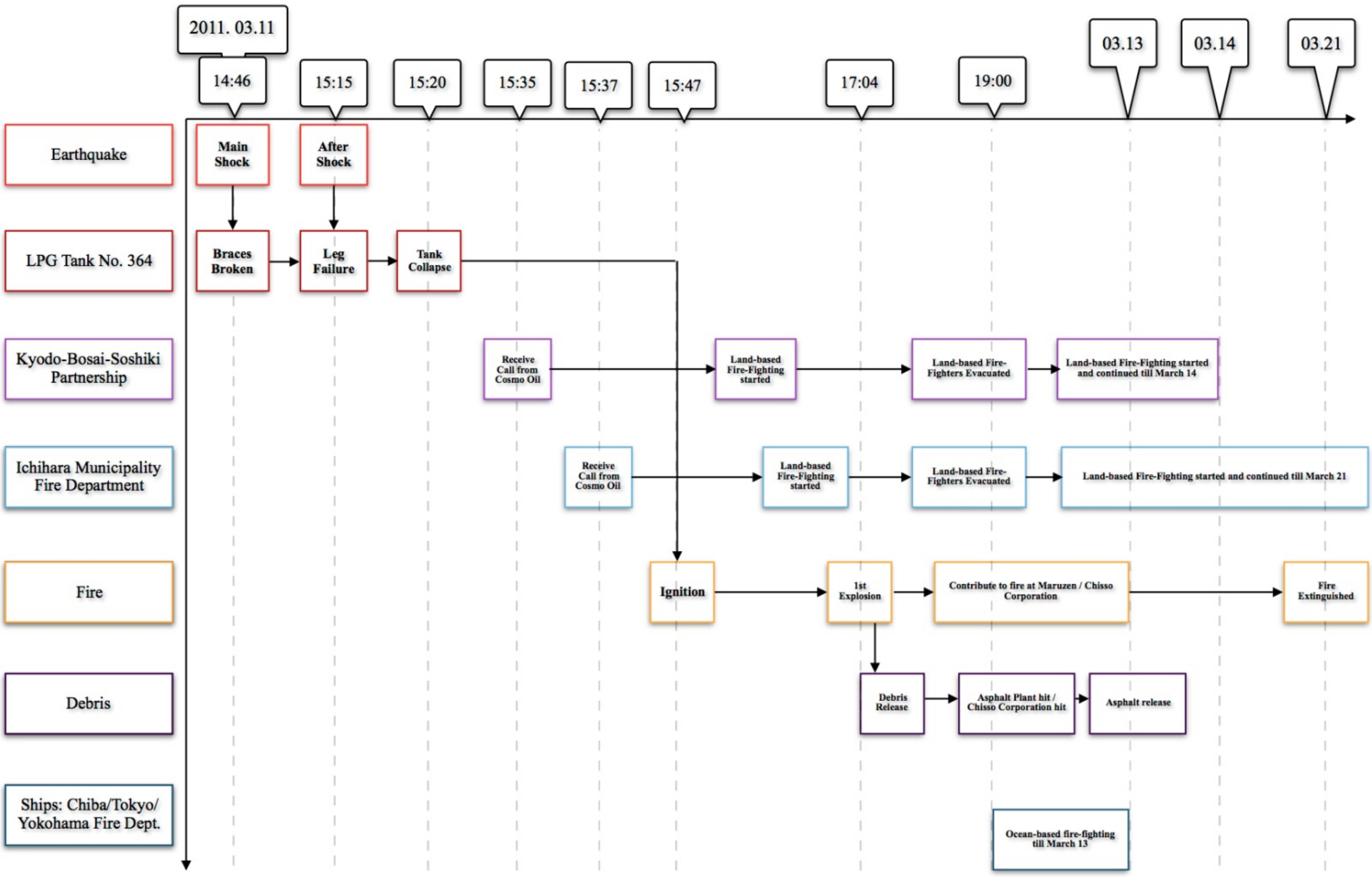

Fig. 8 STEP for the events at Cosmo Oil Refinery

Maruzen and Chisso Corporation, are the two neighboring companies. The vapor cloud from the LPG storage farm flew over to Maruzen (around 100-150 m from the LPG tank area) and triggered a fire there. A second fire was ignited and the operating room was burnt down. The radiant heat from the Cosmo Oil fire sparked a fire at Chisso Corporation and a warehouse was burnt down. The explosion of the LPG tanks led to a lot of debris release. Some of the debris was discovered at distances as far as 6.2 Km. Many residential areas in the neighborhood were affected. The nearby asphalt tanks were affected by debris from the exploding LPG tanks. The damage led to release of asphalt into the ocean. The Cosmo Oil claims that all the released asphalt has been collected and cleaned up. As reported no long term damage to the environment was caused.

The joint operation by the Kyodo-Bosai-Soshiki fire-fighters and the Ichihara Municipality cooled the nearby tanks to avoid overheating and continuity of the fire. The fires were difficult to bring under control as no foam was used during the response and there were multiple release sources. The fire was allowed to continue burn itself out. The area in radius of 700m of the burning LPG tanks was evacuated for 8 hours. They also received help from ships spraying sea water on the boring tanks. In summary, the ocean-side support lasted for 2 days, the joint land-based support continued for 3 days and the Ichihara municipality team stayed on site for 11 days. Air quality monitoring at the Ichihara municipality didn't reveal any excessive amounts of air pollutants due to the accident. No toxic materials were also released during the events. There were no injuries due to the explosion at the Cosmo Oil. Three fighters of Kyodo-Bosai-Soshiki hurt themselves during the evacuation. One of the three injuries at Maruzen corporation was serious. Chisso Corporation reported no injuries or casualties. In total, 1142 residents were evacuated due to the fires and explosions at Cosmo Oil. The personnel at other plants were not evacuated and continued to ensure the safety of their facilities.

(3) Application of Accident Investigation Methods

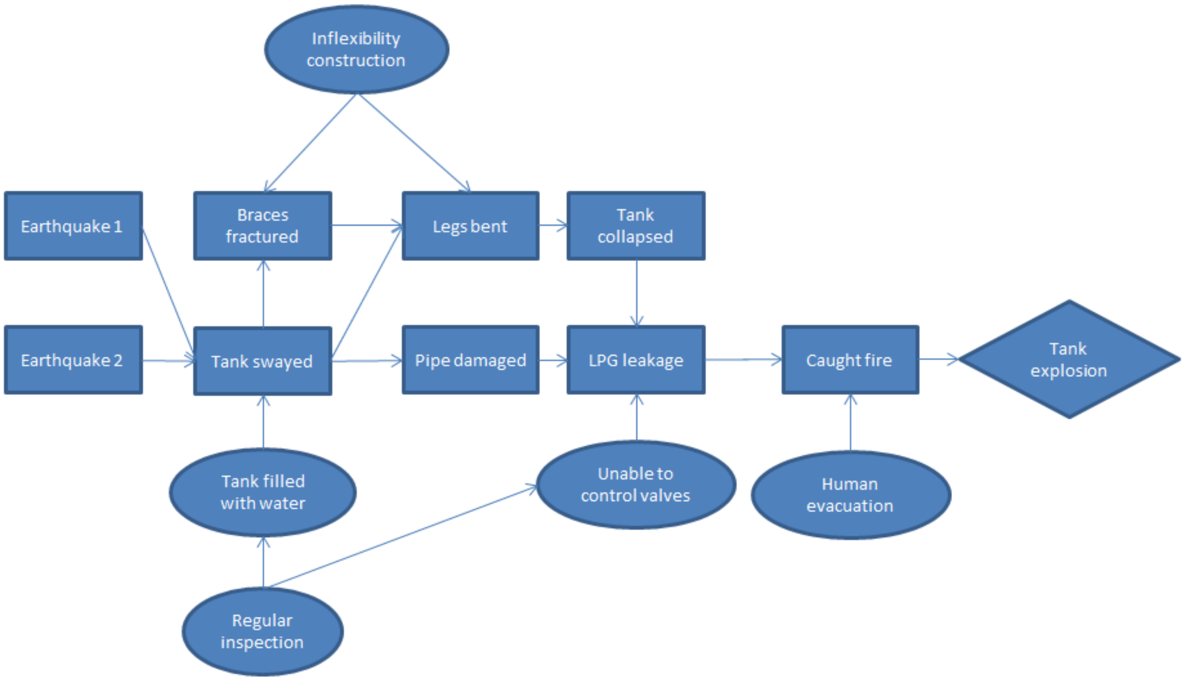

Fig. 9 Events and Causal Factor Chart for Cosmo Oil Refinery accident

In this section, we present application of some of the methodologies. Namely, Sequential event time plotting: STEP, Event and causal Factors Charting, Barrier analysis and Tier rout cause analysis. Many analysis methods give great structure for building, analyzing and digging into the root causes of accidents, However, the case with Cosmo refinery fires is quite straight forward since events are more in series than parallel, Thus, we thought that using any of the advanced analyzing methods would be quite like forcing events and incidents to fit into blanks rather making a real good use of it, a simple technique that allows us to free sketch and list out thoughts was thought to be more useful allowing a decent margin of freedom and also reduces the struggle of fitting other methods criteria. Sequential timed events plotting (STEP) is adopted as the first method. A timeline is the first step to have a basic understanding of the "events" and the "actors" involved and the flow of the events. Event and Causal Factor Charting which is useful in identifying multiple causes and graphically depicting the critical conditions and events necessary and sufficient for the accident to occur, is used as the second method. Barrier analysis is adopted as the third step. Listing all hazards and barriers that are supposed to prevent-mitigate those hazards, then listing the facts of how did those barriers perform during the accident, after this step we have listed all the possible reasons for the accident occurrence, a tier-based root-cause analysis was performed, causal factors at each tier were used to figure out what was the root cause at this level that

HAZARD 1: EARTHQUAKE			
Barriers	**How did barrier perform**	**Why did the barrier fail**	**How did the barrier affect the accident**
Structural Barrier [design and operation of the tank]	For the first earthquake the braces failed and after the aftershock the legs failed which led to a complete collapse of the tank	The tank at the time earthquake struck was filled with water for maintenance purposes as a common practice the tank legs and braces were not designed to withstand the water load in case of a seismic shock. .	The failure of the tank caused pipes damage and connections breaking.
Human Barrier [checking and inspection]	On-site workers did check the tanks visually after the first shock. Only a visual check was done and no further danger was reported.	Careful inspection and likelihood of aftershock should have been taken in consideration.	Being not aware of the tank condition after the earthquake led the explosion after one hour.

HAZARD 2 : TSUNAMI			
Barriers	**How did barrier perform**	**Why did the barrier fail**	**How did the barrier affect the accident**
Structural Barrier [seawall]	The seawall managed to prevent the tsunami wave to overtop the building and protect the facility.	----	The seawall managed to prevent extensive damage that might have increased the loss and damage.

HAZARD 3 : LPG LEAKAGE AND EXPLOSION			
Barriers	**How did barrier perform**	**Why did the barrier fail**	**How did the barrier affect the accident**
Safety valves	Safety valve was manually fixed open due to repair works that led later on to LPG leakage	The valve was fixed open not to get automatically shut by the air intruding the pipe during the repair.	The LPG leakage caused the initial explosion of tank 346 that led to further extensive damage later on.
Human barrier [safety workers]	Workers on site left the valve locked open in violation of the high pressure gas law. Despite the first shock of earthquake the valve was not shut.	Personnel were not well educated about hazards of sort. No adequate training or emergency drills for such large scale disasters had been taken.	open valve after the earthquake led to leakage of LPG making the firefighting process very difficult

Fig 10. Barrier Analysis Worksheet (I) for Cosmos Oil Refinery Accident

HAZARD 4 : CASCADING EVENTS AND FURTHER DAMAGE			
Barriers	**How did barrier perform**	**Why did the barrier fail**	**How did the barrier affect the accident**
Secure connection system	Pipes were quite rigid so they broke at the collapse of the LPG tank and gas was released	Pipes material and connection were rigid and do not allow differential movement.	LPG was released due to the pipe break and valve opening
Human barrier	Workers on site left the valve fixed open in violation of the high pressure gas law. Despite the first shock of earthquake the valve was not shut.	Personnel were not well educated about hazards of sort. No adequate training or emergency drills for such large scale disasters had been taken.	Uncontrollable LPG leakage that started the explosion
Tanks layout and spacing.	The spacing was between the adjacent units were insufficient as the fire spread to an adjacent asphalt Plant. Also units at Maruzen and Chisso were partially damaged.	The layout of the industrial complex has planning flaws. There is not provision of isolating explosion scenarios.	The cascading effect could have been controlled.
Firefighting team	Firefighting team arrived quite late due to traffic problems, they were not able to handle it alone, later on the municipal firefighting force joined and seaside firefighting as well	Lack of coordination between the site and the firefighting HQ, being under-prepared for a fire of such big magnitude and the significant distance from the fire site that caused the delay.	Fire was not well contained at first and further efforts were needed to contain the situation.

HAZARD 5 : ASPHALT RELEASE			
Barriers	**How did barrier perform**	**Why did the barrier fail**	**How did the barrier affect the accident**
Facility layout and complex and sectors isolation.	The Layout of the complex was quite tight that the rate of cascading events was quite high.	The debris hit so strong and reached quite far that even a proper layout and sectors isolating wouldn't have been very useful.	. Asphalt release to the surrounding soil and ocean happened indicating a danger of contamination.

Fig 11. Barrier Analysis Worksheet (II)
for Cosmos Oil Refinery Accident

ROOT CAUSES ON A TIER BASED SORTING		
Tier	**Causal factors**	**Root causes**
Laws and regulations	No regulations pertinent to tank filling for maintenance	No definite regulation for maintenance
Senior management	1. Safety management plan and emergency drills were not well prepared 2. Evacuation, onsite and offsite, were not well prepared 3. There was no onsite firefighting force 4. The complex is tightly places so other nearby sites can easily get affected	No definitive NATECH Response Plan
management	1. Personnel in charge were not aware of the danger due to lack of information or training. 2. Firefighting force response and coordination was quite slow 3. and leadership were not well estimated from the beginning and had to be changed	Low Quality of Regular Inspection
Supervision	1. No careful inspection or aftershock consideration have been taken 2. Valve was locked open in violation of laws 3. Water was left in the tank for long period *12 days* while the common practice is 2-3 days	
Workers actions	4. No careful inspection or aftershock consideration have been taken 5. Valve was left open despite the time workers had to shut it down after the earthquake	
Direct causes.	1. Earthquake 2. Aftershock 3. Safety valve locked open 4. Rigid pipes and connections.	

Fig 12. Root Cause Analysis on a Tier based sorting.

should have been accounted for in order to prevent the accident or any future potential ones.

Figure 8. describes the sequential event time plotting (STEP) for the events at Cosmos Oil Refinery from 3rd March, 2011 (the day the earthquake struck) till 21st March, 2011, the day on which the fire was fully extinguished. As can be clearly understood, STEP is a very simple way to understand the course of the events. The STEP is modified as new information surfaces and thus it is also useful in pointing out the grey areas where more information is necessary. Figure 9 shows the event and causal factors chart(ECFC). As can be seen the main shock (earthquake 1) and the aftershock (earthquake 2) are direct causes for the disaster. The tank filled with water swayed largely which led to the damage of braces, legs and nearby pipelines. The tank collapsed ultimately and triggered the release of LPG. The ignition source is difficult to pin point. ECFC is an elegant way to point out the underlying causes. Figures 10 and 11 are Barrier Analysis Worksheets. As mentioned before, barrier analysis is used primarily to identify hazards associated with an accident and the barriers that should have been used to prevent it. It is usually documented in the form of worksheets. The barrier analysis Worksheet (I) in figure 10 points out the importance of the safety valve in the entire process that happened after the uninterrupted release of LPG.

(4) Lessons Learnt from Cosmos Oil Refinery Accident and Recommendations

Our root cause analysis (Fig. 12) came to three major conclusions: Firstly about regulations during maintenance, this includes the structural regulations pertaining tanks design as well as the cautions and time limitations during common practice maintenance.

Second is a definitive NATECH response plan, the likelihood of such events seem small, but there proven that they can still happen anytime, luckily evacuation due to tsunami warning preceded the explosions, so evacuation plans due to NATECH were not really put into test, on the other hand the firefighters response was quite low, size of crisis exceeded their abilities and the need for support emerged, existence of an onsite firefighting team would have saved a lot of effort and lost communications.

Third is the supervision quality, no doubt about frequency of course, but still a question hanging about the quality if a violation of high pressure gas laws such as working with a manually fixed open valve is tolerated as a part maintenance routine.

One of the major events in this accident is the check valve that was fixed open during the repair works of a damaged pipe, this valve was the key to continuous fires since the LPG leakage was going on all the time making the firefighters mission nearly impossible, evacuation had to be done and a decision of letting the tanks empty as fast as possible to consume fire. In the press release of Cosmo industries about the accident issued in August that year they cleared it out with a pledge not to do this again, raising a question about the quality of regular inspection in the whole facility. At the first glance the accident seems to be a course of bad luck, the rough probability of an earthquake and aftershock while a tank is filled with water along with an open valve due to maintenance is indeed very low, but regardless the loss and injuries it is a great lesson, for those who issue regulations and also those who perform onsite that no matter how the possibilities are low there is still a chance they coincide.

The selected investigation methods seem to fit the nature of the accident. Important to note that listing approaches may cause confusion if the accident contains many simultaneous events, using of charting methodologies can be much more convenient in such case. Although the analysis seems to be sufficient from the point of digging into root causes and handling the givens it doesn't force the analyzer to consider a further domain of the accident, for instance, evacuation on both levels of the facility and the nearby vicinity which we think is a gap in our analysis, for a lack of information about evacuation on both sides. Also that the listing approach of the used two methodologies makes the course of events fit to the frame of the method without any further blanks to fill.

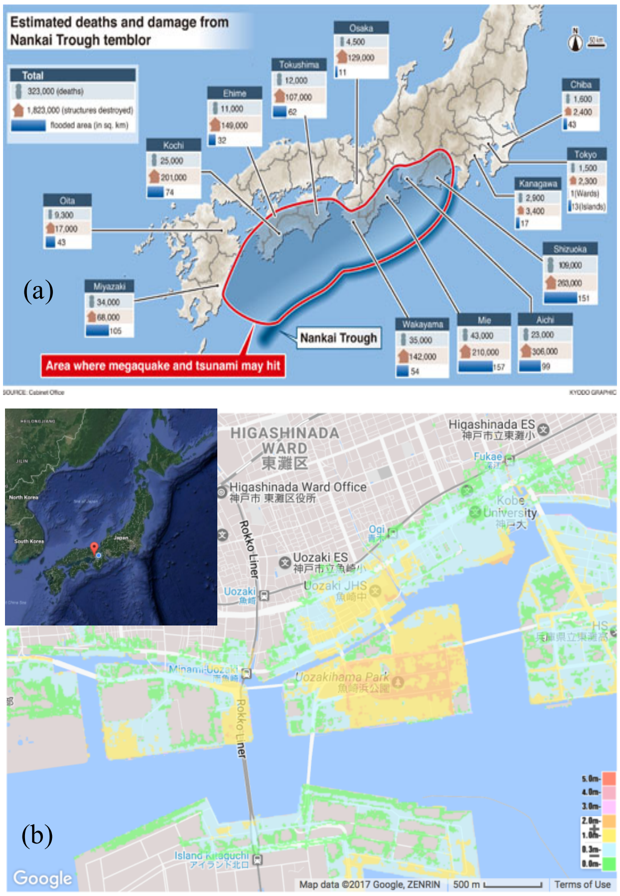

Fig. 13 (a) Estimated deaths and damage from nankai trough tremor (b) location of Higashinada ward on the map and the expected inundation level for the tsunami triggered by the nankai trough earthquake.

5. A PREPAREDNESS ASSESSMENT SURVEY

This section discusses a survey that has been conducted to assess the preparedness of people in the face of an incoming disaster. The March 2011 Great East japan earthquake was no doubt a devastating one but still the epicenter was located quite a few miles out in the ocean. Another earthquake which is supposed to be overdue already might occur in an area of the ocean called the Nankai trough. Educated assumptions are being made for the height of the wave during the tsunami triggered by the nankai trough earthquake. The height can exceed way above 1.5 meters in the coastal areas and thus flooding the low-lying areas. One of the possible areas to be affected by this event is Higashinada Ward in Kobe, Hyogo Prefecture. The area also has a few industrial complexes in the vacuity and the motivation of the survey was to understand the level of awareness of the people from the impending danger. On 18th December, 2016 we visited the locality and collected the data from them.

The survey results are discussed as follows:

(1) When asked about the biggest concern when the Nankai trough earthquake occurs, 45 % people expressed concern over the building collapse due to the earthquake and 40% fears inundation by tsunami. Only 10% of the people expressed concern in accidents in nearby industrial complex. The data could be reflective of the past experience by the people in Higashinada Ward during the 1995 Kobe earthquake. Thus building collapse occupies the concern of the majority. The people are also aware of the tsunami inundation problem but not so aware about the possible consequences from accidents in nearby industrial facilities.

(2) When asked about the evacuation destination, 56% of the people wrote about designated evacuation shelter and 20% indicated moving to the upper portion of the building. The decision to move to the upper portion of the building is indicative of the awareness of the possible inundation due to a tsunami. And the data also shows that the people are aware of the location the evacuation shelter.

(3) Upon asking why they chose the evacuation destination as such, almost 70 % of the people said because of safety and followed by 20% of them who said because it is near their house. Designated evacuation shelters are prepared for emergency. Non-designated areas may be a temporary relief but

not a good choice if someone is stuck for a long time. Thus, the results show the high level of awareness of the people.

(4) The fourth question was related to the means of transportation one would use to move to the evacuation destination. 77% of the people said they will walk. One reason might be that the evacuation destination is close to home in some cases. But walking might be the best solution in case of a disaster. As traffic jams on the road is the last thing one wants when the only thing most valuable at that moment is time. One should be able to reach the evacuation destination within the time limit. Sometimes, too many cars on the road end up creating a panicking situation. This answer might be one of the best indicatives of the level of understanding of a post disaster situation.

(5) This question dealt with the decision maker in the family. Who decides which evacuation shelter to go? 56% of the people said they decide by themselves and 25% of the people said they value the decision of their spouse. Of the people who said that they value their family advice 64% are women.

(6) The question dealt with the age and condition of the accompanying person. The survey results show that majority of the people have dependent children accompanying them to the evacuation shelter.

(7) This question dealt with knowing if anyone had any experience from Natech related events. Not many people answered to this question. Those who replied majority of them said they will go to a designated evacuation shelter.

From the survey data, it can be seen that the locals of the Higashinada Ward are aware of the direct consequences of earthquake and tsunami. The people in the locality experienced the 1995 Kobe earthquake and thus most of them might be very aware of the post disaster scenarios and the importance of an evacuation shelter and a storage of essentials. This survey particularly concentrated on the preparedness for the nankai trough earthquake. To this majority of the people seems to be aware of the chances of tsunami and the importance of moving to a high ground. But it is inconclusive as to the level of the awareness to the secondary effects of the natural disasters i.e. natech events.

6. CONCLUSION

Natech events are rare but high impact events. This makes it important to study the past events and utilize the lessons learnt for a better preparedness against similar occurrences in the future. In this paper, two past natech events at JX refinery, Miyagi Prefecture and Cosmo Oil Refinery, Chiba Prefecture, Japan were investigated. Accident investigation techniques provided by Department of Energy (DOE) and Centre for Chemical Process Safety (CCPS), United States were used as tools for the analysis. The different methods of accident investigation have been used and compared. MTO analysis and STEP analysis are found to be superior compared to Fault tree and Event tree analysis in terms of causal analysis and event sequencing. However, one methodology by itself is not perfect and has to be redeemed with other methodologies to evaluate accidents precisely and concretely. The lessons learnt from each accident and recommendations from the authors have been summarized at the end of each part of the case study. In the part for JX refinery accident, five safety problems have been identified and recommendations proposed. In the Cosmo Oil refinery fire accident, the root cause analysis identifies three important points and discusses better preparedness in case of future occurrences. In the last part a survey conducted at Higashinada ward, Hyogo prefecture has been discussed to assess the level of preparedness against large scale dangers. The results of the survey indicate a high level of awareness amongst the people of the direct consequences of earthquake and tsunami. The previous experience during the 1995 Great Hanshin earthquake played an important role in the current level of awareness. But it is difficult to conclude whether they are equally aware of the grave consequences of natech events that are a possibility in case the nankai earthquake happens as predicted.

REFERENCES

1) Sklet S. Methods for accident investigation [J]. Trondheim: Gnist Tapir, 2002.
2) Center for Chemical Process Safety (April 2008). Guidelines for Hazard Evaluation Procedures (3rd ed.). Wiley. ISBN 978-0-471-97815-2.
3) Personal Communication (19March, 2014) Ana Maria Cruz, JX Refinery, Sendai
4) Evacuation and fire-fighting activities, Field visit to Sendai Industrial complex, March 2014
5) Methods for accident investigation, The Norwegian University of science and technology.
6) Overview of the Fire and explosion at Chiba Refinery, the cause of the accident and the action plan to prevent recurrence, August 2,2011, Press Release, Cosmo Oil Marketing Co. Ltd.
7) Field visits to industrial areas affected by the Great East Japan Earthquake and Tsunami, Japan, 28/11-02/12 2011: A summary report by Krausmann (2012)
8) Report on the effect of Tohoku Earthquake on Cosmo Oil Refinery (Natech ID 14): European Commission, Joint Research Centre, eNatech