Probabilistic Safety Assessment for LNG Tank Farm with seismic Events

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Natural disasters are able to trigger technological disasters and these associated events known as NaTechs may bring tremendous risks to communities and countries when they are unprepared for such risks. In South Korea there are many industrial sites having too many hazards in one place and located near residential areas. Some of them are vulnerable to earthquakes driven incidents or subject to other kinds of natural hazards with increased risks for their impacts due to small land and high population density. Especially nuclear plants and LNG storage farm can be candidates for NaTech disasters. The main intention of this paper is to quantify the risk specifically when a seismic event initially triggers a failure of one tank and the failure subsequently cause domino effects to nearby tanks due to proximity between tanks. Since that massive Natech disasters can generate domino effects as shown in Fukushima accident, the methodology used in the case study using Probabilistic Safety Assessment (PSA) has focused on the risk aggregation due to multiple failures escalated. In addition to traditional risk analysis, the main intention of this paper is to quantify the risk specifically when a seismic event initially triggers a failure of one tank and the failure subsequently cause domino effects to nearby tanks due to proximity between tanks.

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I. Introduction

Recently, large disaster cases that occur simultaneously throughout the world to cause huge damage have been occurring frequently. In particular, the nuclear power plant accidents occurred in 2011 due to the great east Japan earthquake clearly showed the seriousness of complex disasters that can occur when natural disasters and technical disasters are combined and aroused attention to disaster management of various countries in the world including South Korea. In such changes in disaster environments, studies of measures to manage complex disasters and searching for policy alternatives can be said to be a very important task.

The Seveso directive established in Europe that has the highest level of standards for safety in the world to ensure high levels of protection of citizens, communities, and environments has large implications on site risks. European Union's Seveso directive Seveso directive III and risk management system show advanced risk management systems by requiring plans to prevent major accidents to be prepared and implemented, ensuring that the standards are designed to ensure high levels of protection of humans' health and environments, and emphasizing that for risk management and ensuring safety, disclosure of information to citizens and public participation are essential. In particular, the directive requires member countries to impose the obligation to prepare plans to prevent serious accidents (article 8 of the directive) in writing and appropriately perform the plans on facility enterprises. In addition, the directive regulates Domino-effects (article 9), safety reporting on high grade facilities (article 10), changes in facilities (article 11), internal emergency plans of high grade facilities (article 12), supervision of the installation of or changes in facilities (article 13), and information provision when an accident has occurred (article 16). The revised Seveso directive III is characterized by the fact that it has become stricter such as stipulating that enterprises that input chemicals should be more frequently controlled and should provide better information on industrial facilities and emergency plans. The Seveso directive requires individual European countries to establish their own criteria for risks and requires to examine Domino-effects that make an accident occurred in a part of a facility propagate to other facilities without fail. Although no method to be used for risk assessment considering Domino-effects, it is obvious that as the number of facilities increases, risks due to Domino-effects will increase. Since increases in risks lead to increasing in the risk of individuals in facilities and the risk may eventually exceed the criteria by country, the number of facilities may be limited. Table 1 shows accident cases in overseas LNG complexes and accident cases in LNG complexes due to earthquakes.

Table I. Accident cases of LNG Facility (Ref. 1)

Year	Location	Accident Description
1944	Cleveland, Ohio, USA	At the peak-shaving plant a tank failed and spilled its contents into the street and storm sewer system. The resulting explosion and fire killed 128 people. The tank was built with a steel alloy that had low-nickel content, which made the alloy brittle when exposed to the extreme cold of LNG.
1964	Arzew, Algeria	During loading operations, lightning struck the forward vent riser of the Methane Progress and ignited vapor which was being routinely vented through the ship venting system. A similar event happened early in 1965 while the vessel was at sea shortly after leaving Arzew. In both cases, the flame was quickly extinguished by purging with nitrogen through a connection to the riser.
1965	Jules Verne Spill, Arzew, Algeria	LNG liquid spill caused by overflowing of a cargo tank that resulted in the fracture of the cover plating of the tank and adjacent deck plating.
1965	Methane Princess Spill	LNG discharging arms were disconnected prematurely before the lines had been completely drained, causing LNG liquid to pass through a partially opened valve and onto a stainless steel drip pan placed underneath the arms. This caused a star-shaped fracture to appear in the deck plating in spite of the application of seawater.
1969	Portland, Oregon, USA	An explosion occurred in an LNG tank under construction. No LNG had ever been introduced into the tank. The cause of the accident was attributed to the accidental removal of blinds from natural gas pipelines which were connected to the tank. This led to the flow of natural gas into the tank while it was being constructed.
1971	La Spezia, Italy	This accident was caused by "rollover" where two layers of LNG with different densities and heat content form. The sudden mixing of these two layers results in the release of large volumes of vapor. In this case, about 2,000 tons of LNG vapor discharged from the tank safety valves and vents over a period of a few hours, damaging the roof of the tank.
1972	Montreal, Quebec, Canada	A back flow of natural gas from the compressor to the nitrogen line occurred during defrosting operations at an LNG liquefaction and peak shaving plant in Montreal East. The valves on the nitrogen were not closed after completing the operation. This caused over-pressurization of the compressor and the natural gas entered the control room (where operators were allowed to smoke) through the nitrogen header. An explosion occurred when an operator tried to light a cigarette.

1973	Staten Island, NY, USA	In February 1973, a fire started while repairing the interior of an empty storage tank at Staten Island. The resulting increase in pressure inside the tank was so fast that the concrete dome on the tank lifted and then collapsed down inside the tank killing the 37 construction workers inside.
1974	Massachusetts Barge Spill, USA	After a power failure and the automatic closure of the main liquid line valves, 40 gallons of LNG leaked as it was being loaded on a barge. The LNG leaked from a one-inch nitrogen-purge globe valve on the vessel's liquid header, causing several fractures to the deck plates.
1977	Aquarius Spill, Bontang, Indonesia	During the filling of a cargo tank, LNG overflowed through the vent mast serving that tank. The incident may have been caused by difficulties in the liquid level gauge system. The high-level alarm had been placed in the override mode to eliminate nuisance alarms.
1978	Das Island, U.A.E.	An accident occurred due to the failure of a bottom pipe connection of an LNG tank. The tank had a double wall (a 9% nickel steel inner wall and a carbon steel outer wall). Vapor from the outer shell of the tank formed a large heavier-than-air cloud which did not ignite.
1979	Mostafa Ben Bouliad Spill, USA	While discharging cargo at Cove Point, Maryland, a check valve in the piping system of the vessel failed releasing a small quantity of LNG. This resulted in minor fractures of the deck plating.
1979	Cove Point, Maryland, USA	In October 1979, a natural gas leak at Cove Point caused an explosion killing one plant employee and seriously injuring another and causing about $3 million in damages.
1983	Bontang, Indonesia	A rupture in an LNG plant occurred as a result of over-pressurization of the heat exchanger caused by a closed valve on a blow-down line. The exchanger was designed to operate at 25.5 psig. When the gas pressure reached 500 psig, the exchanger failed and the explosion occurred.
1987	Mercury, Nevada, USA	In August 1987 an accidental ignition of an LNG vapor cloud occurred at the U.S. Department of Energy Nevada Test Site during large-scale tests involving spills of LNG. The cloud was accidentally ignited and damaged and propelled polyurethane pipe insulation outside the fence.
2003	Bintulu, Malaysia	A major fire occurred in the exhaust system of the propane gas turbine in the first train (Train Number 7) of the MLNG Tiga project at the Petronas' LNG Complex.

2004	Skikda, Algeria	A steam boiler that was part of an LNG production plant exploded, triggering a second, more massive vapor-cloud explosion and fire. The explosions and fire destroyed a portion of the LNG plant and caused 27 deaths, 74 injuries, and material damage outside the plant's boundaries.
2004	Ghislenghien, Belgium	A pipeline carrying natural gas from the Belgian port of Zeebrugge to northern France exploded, resulting in 23 known fatalities. The cause of the incident is still under investigation but it appears that a contractor accidentally damaged the pipe.
2004	Trinidad & Tobago	In June 2004, workers were evacuated after a gas turbine at Atlantic LNG's Train 3 (Trinidad & Tobago) facility exploded.
2005	District Heights, Maryland, USA	A Washington Gas Company-sponsored study released in July 2005 pointed to subtle molecular differences in the imported liquefied natural gas the utility began using in August 2003 as the cause of a house explosion in March 2003.
2005	Nigeria	A 28-inch LNG underground pipeline exploded in Nigeria and the resulting fire engulfed an estimated 27 square kilometers.

In the case of South Korea, due to the continuous oil price increases and the two oil crises in the 1970s, efforts to reduce dependence on oil following the experience of have been continuously made as part of government policies. In this situation, demand for natural gas is expected to gradually increase as a major energy source equipped with all of cleanness, stability, and convenience. Unlike the USA and Europe that are directly supplied with natural gas through pipelines, South Korea imports LNG (Liquefied Natural Gas) that is natural gas liquefied with ultra-low temperatures and supplies it to consumers. Therefore, along with increases in demand for natural gas, demand for LNG storage tanks for storage of LNG has been also increasing. The government has established a long-term natural gas supply plan in 2003 and has been implementing projects with a view to securing a total of 56 LNG storage tanks by 2010. In addition, the government has been continuously establishing and expanding LNG export bases in major natural gas producing countries such as Malaysia, Australia, and Indonesia and the construction and expansion of LNG import bases are planned in energy import countries such as Japan, Spain, and China.

Therefore, in the present study, quantitative risk assessment considering the external factor-earthquakes that can simultaneously affect large LNG storage facilities and resultant Domino-effects is conducted to present a case for development of quantitative risk assessment methodologies applied with Natech and Domino-effects.

II. Methodology

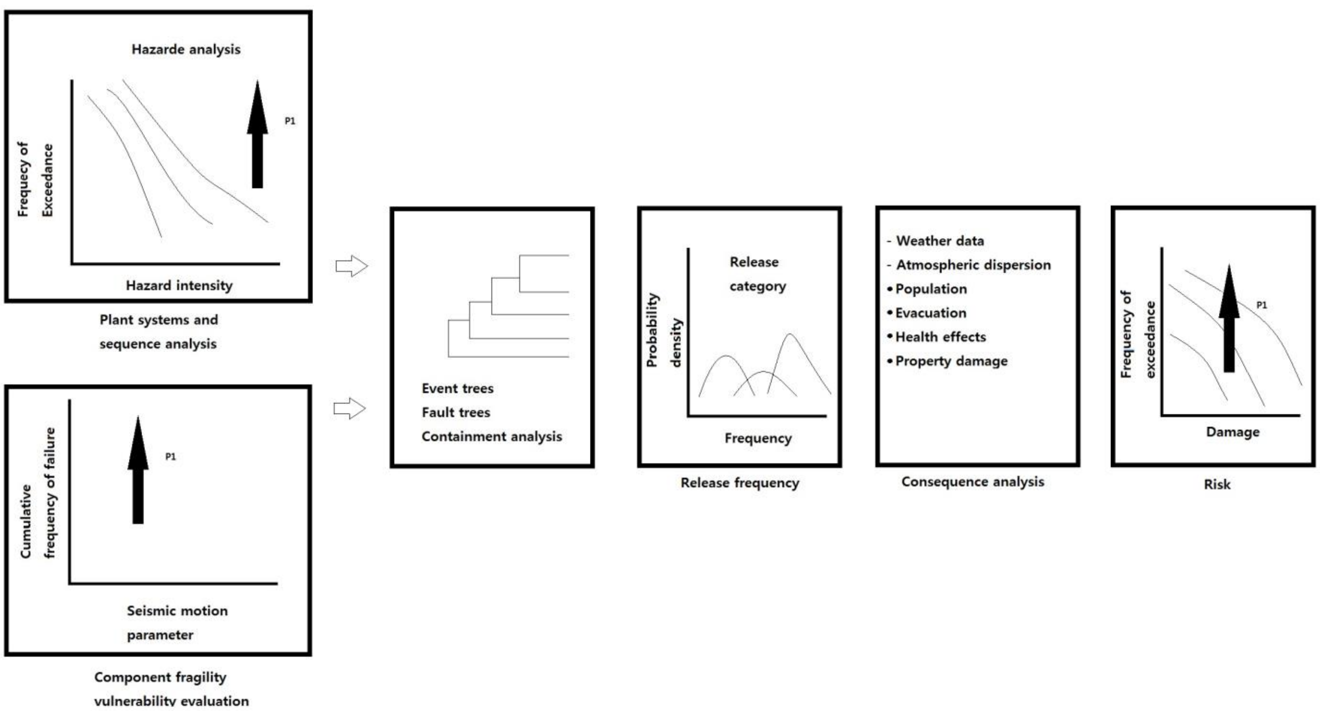
An LNG tank which stores cryogenically inflammable LNG with a temperature below -160C and the tank farm in the case study has 20 tanks located in a place far from residential area. The existing farm locates on an uninhabited island 3 km away from the residential area and some tanks stores up to 200,000 kilo liters. South Korea efforts to implement a risk-based approach for LNG facility siting and site analysis for adoption in the regulations for approval of new plants. In general risk analysis of LNG release hazards include LNG pool fire thermal radiation at the site and flammable vapor travel off site in the situation of LNG releases. First the traditional risk analysis is done for default and then the new methodology with seismic frequency and domino effects is used for comparison.

Table II. Flow of Risk Assessment for considering seismic event & domino effect

1	Traditional way to QRA(Quantitative Risk Analysis) without considering the seismic event & domino effect
2	Identification of reference scenarios for a Peak Ground Acceleration(PGA)
3	Identification of reference Fragility curve of LNG Tank for seismic event
4	Estimation of accident frequency with given PGA and Fragility curve
5	FN curve compared with the calculated consequences for each combination

This methodology is similar with what has been what NRC(Nuclear Regulatory Commission U.S.) had investigated incidents due to seismic events in the past. NRC method is briefly described in the schematic diagram as shown in Figure which is designated as PRA, Procedures Guide.

Figure I. Procedures for Analyzing External Events (courtesy reproduced form Ref. 2)



For incident scenario in the process of hazard identification, more realistic scenarios have been selected to make pool fires. Considerations for the risk assessment are as followings;

II.A. LNG tank farm

Figure II. Layout of 20 Tanks

Table III. Description of Tanks

Tank Number	Type of Tank	Quantity (㎘)
1~8	Membrane Tank	20,000
9~10	Membrane Tank	14,000
11~20	9% Ni	10,000

II.B. Weather information

Table IV. Weather information of Target Area

Date	Average Temperatures(℃)	Wind Speed(m/s)	Most Wind Direction(deg)	Average Humidity(%)	Atmospheric Stability
2015.1	-0.8	3.5	340	72	D or F (Pasquill-Gifford)
2015.2	1.2	3.5	340	75	
2015.3	5.4	3.4	340	69	
2015.4	12.5	3.5	230	72	
2015.5	17	2.9	250	78	
2015.6	21.8	2.6	250	84	
2015.7	24.5	3	250	91	
2015.8	25.8	2.8	340	93	
2015.9	22.5	2.7	20	75	
2015.10	16	3.1	340	76	
2015.11	9.4	3.3	20	86	
2015.12	2.4	3.3	20	72	
Average	13.14	3.313	228.33	78.58	

Table IV shows the weather information of the target location for the year of 2015. Averaged temperature, wind speed, prevailing wind direction and humidity are input for each month respectively. Air stability class of D or F are chosen to represent Day and Night of each day.

II.C Frequency

There are two kinds of tank design, such as membrane type and full containment type shown in Figure III and IV. Incident frequency for LNG tank is taken from the result of previous research performed using fault tree analysis (FTA). (Ref. 3)

Figure III. Full-containment LNG storage tank design

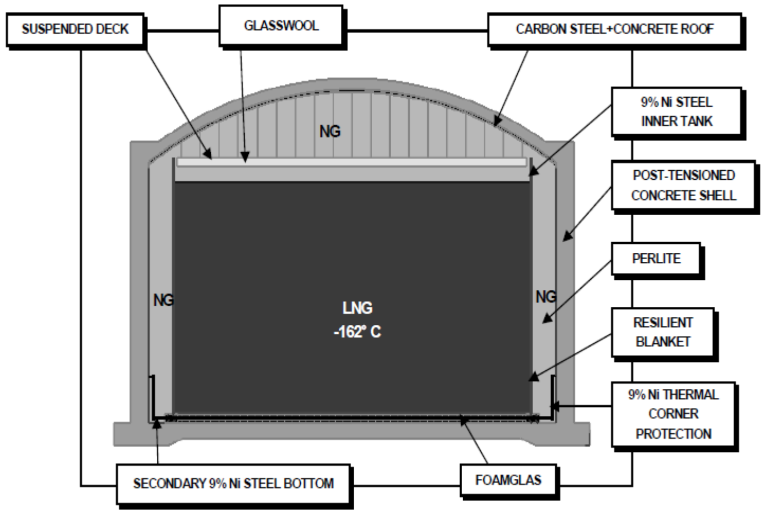
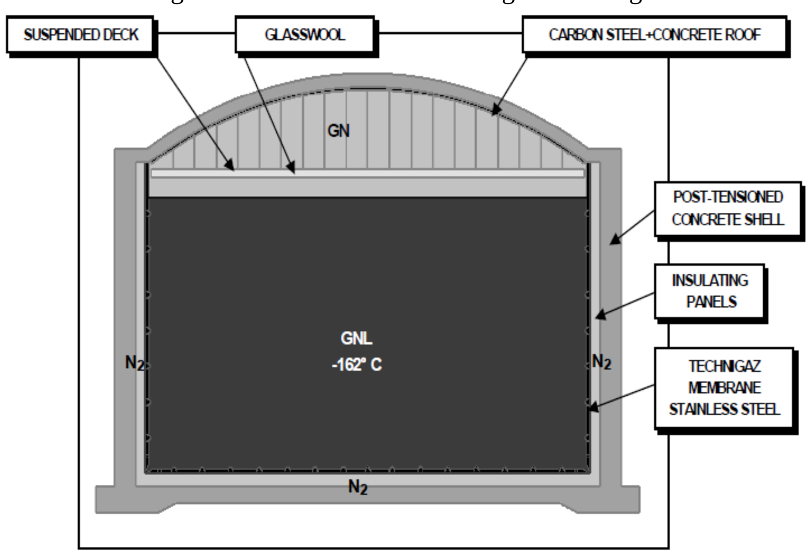


Figure IV. Membrane LNG storage tank design



Frequencies used for this study are in Table V.

Table V. Top Event Frequencies (Ref. 3)

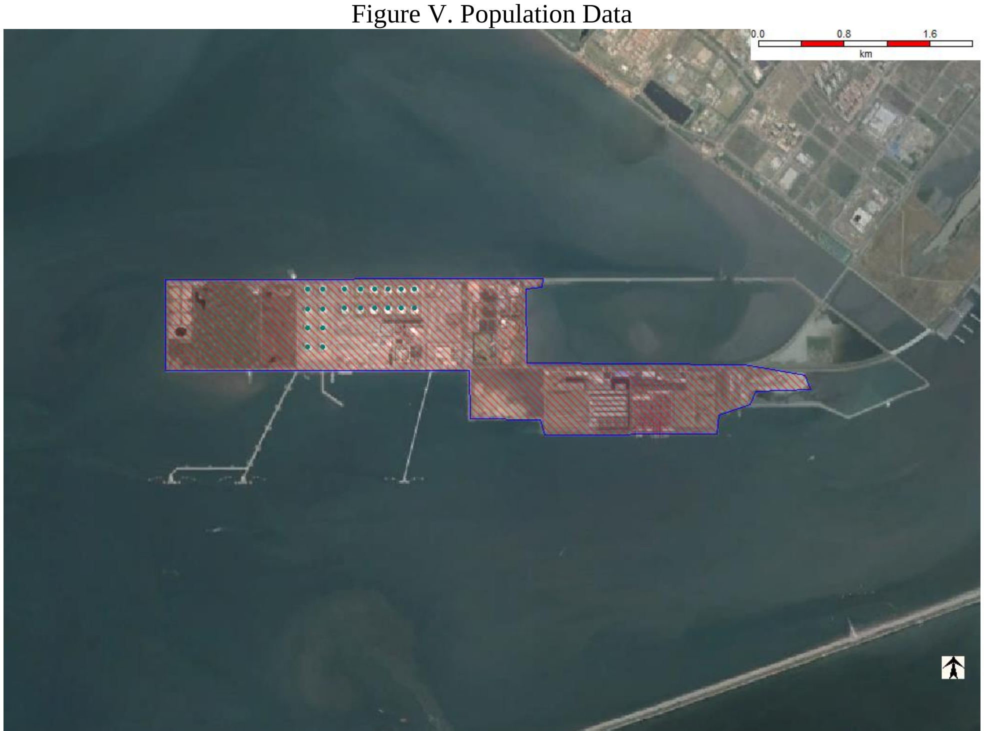
Category	Full-containment Tank (/yr)	Membrane-containment Tank (/yr)
LNG Leak (20 mm)	6.32×10^{-10}	3.47×10^{-6}

Table V, Top Event Frequencies are calculated by FTA analysis. It considered external leakage of fluid from the surrounding LNG tanks(External LNG leak), internal leakage(internal liquid leak), steam leakage to the atmosphere(vapor leak).
Tree of external LNG leak is as follows fault that starts with the failure of the wall or floor of the outer concrete tank, breakdown beginning with concrete roof, fault starting with the failure of the tank body. Therefore, the frequency of LNG leak scenario that cited in this paper is alternative scenario.

II.D Population

The population of the target location is highlighted in red in Figure V. It was obtained from government source and shown in the table below with the area. In Figure V, the colored in red

Figure V. Population Data

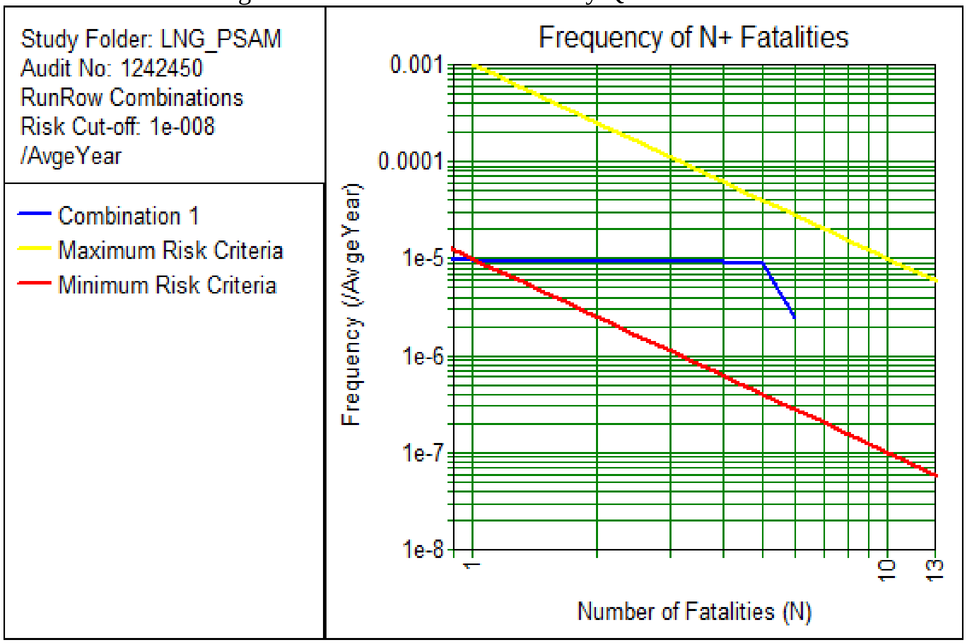


Population Polygon	Population (persons)	Density (/km^2)
	4547	2842

III. Result 1

FN curve is made using QRA software, Phast-risk v.6.54 and shown blue in Figure VI. The yellow line is upper-dutch limit which is generally used for risk criteria not to exceed. If FN curve produced between maximum and minimum risk criteria, it is "tolerable risk". (Ref. 8)

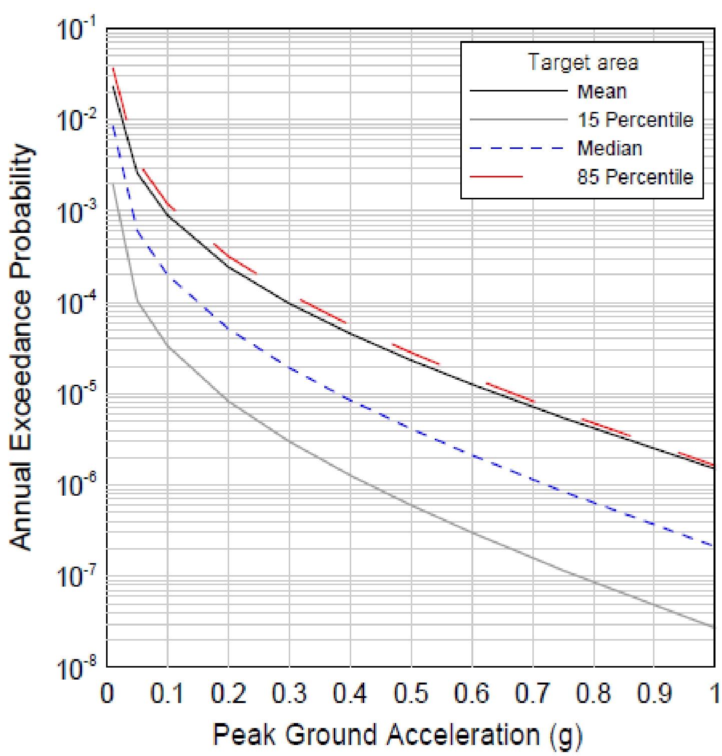
Figure VI. FN-Curve with Ordinary QRA Method



IV. Result 2 (Considering Seismic Event)

To consider seismic event for the frequency, Peak Ground Acceleration (PGA) values in Figure VII were used for the target location.

Figure VII. Annual Exceedance Probability (Ref. 4)



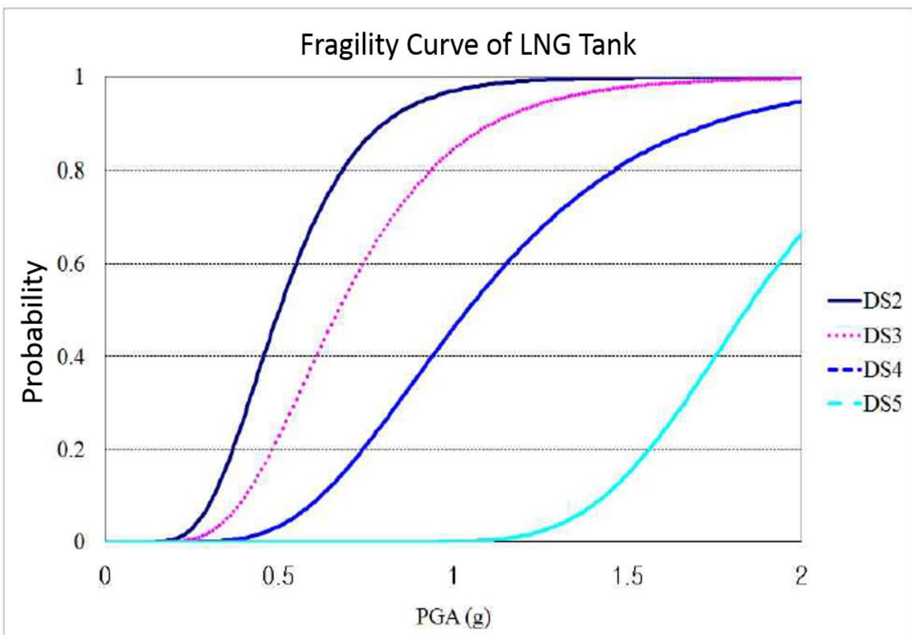
Vulnerabilities of LNG tanks against PGA were analyzed using damage state category in Table VI and fragility curve in

Figure VIII.

Table VI. Damage State of LNG Tank (Ref. 5)

Damage State Category	Damage State
DS1 None	No Damage
DS2 Slight / Minor	Minor damage occurred in the tank, but the contents or functionality normal. Tank roof has minor damage because of liquid sloshing. Minor cracks in concrete tanks.
DS3 Moderate	Slight loss of the contents by damage occurs in the tank. Buckling bottom of steel tank(elephant foot buckling) without loss of contents. A crack with slight loss of contents in concrete tanks.
DS4 Extensive	Occurred serious damage to tank caused operating failure. Buckling bottom of steel tank with loss of contents. shear cracks in the concrete tank walls.
DS5 Complete	Tank collapse and loss of contents.

Figure VIII. Fragility Curve of LNG Tank (Ref. 6)



0.5g of PGA was assumed for this study and the incident frequency was adjusted (increased) by that. Equation (1) shows the increased incident frequency..

$$\mathbf{S = F_{T} + AEP\mathit{l} \times FP_{g}} \qquad \mathbf{(1)}$$

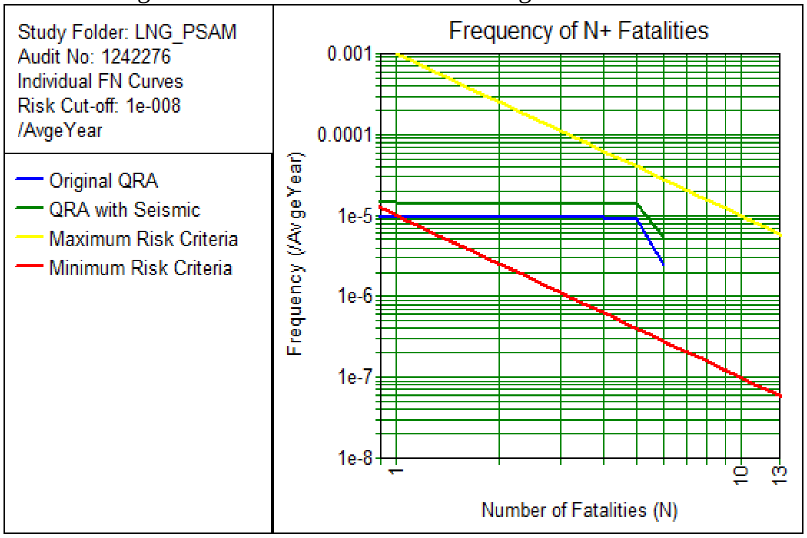
- S : Top Event Frequency with Considering Seismic Event
- F_T : F_m or F_f : The Initial Event Frequency (Table 5; F_m for membrane tank, F_f for Full-containment Tank)
- AEPl : Annual Exceedance Probability (Fig 7) at Location
- FP_g : Fragility Probability at PGA (Fig 8)

Table VII. Top Event Frequencies with considering Seismic Event

Category	Full-containment Tank (/yr)	Membrane-containment Tank (/yr)
LNG Leak Frequency	6.32×10^{-10}	3.47×10^{-6}
LNG Leak Frequency with Seismic Event	8.26×10^{-7}	4.30×10^{-6}

Finally FN curve was made considering seismic events of the location and shown in green in Figure IX.

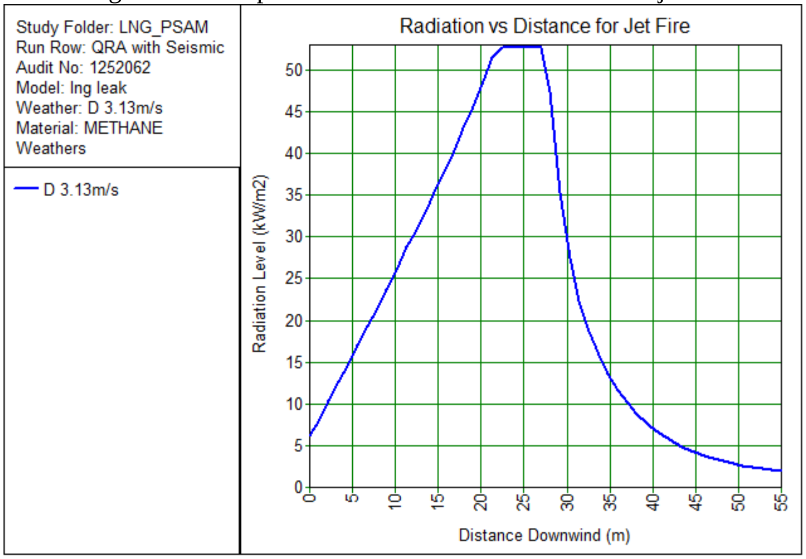
Figure IX. FN-Curve with Considering Seismic Event



V. Result 3 (Considering Domino Effect)

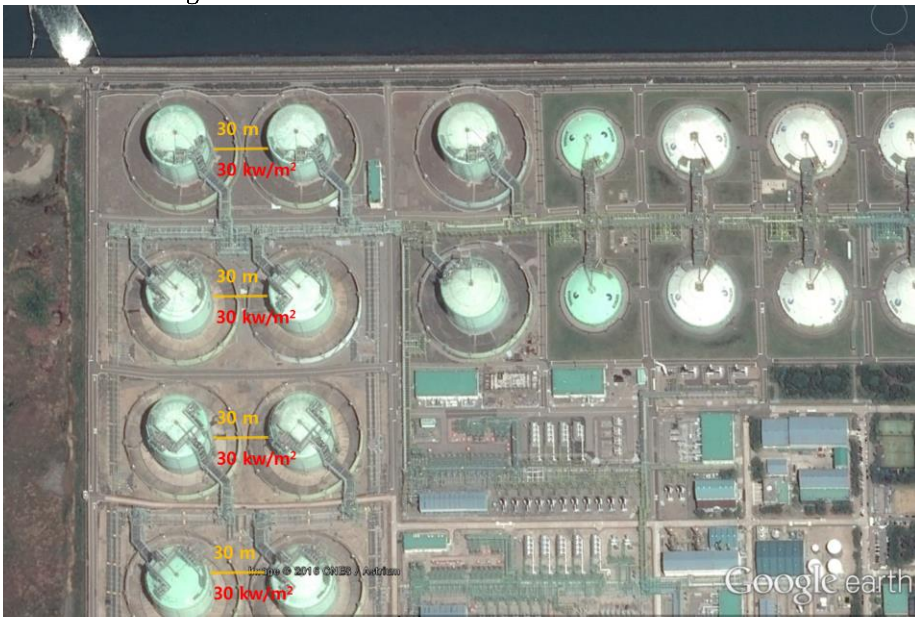
On the other hand, Domino effect can occur when one of LNG tanks gets damaged and makes fire & explosion to affect 2nd accident of other tanks nearby. According to the analysis performed by Phast-Risk, the highest consequences were arisen from tank #1~#8 with jet fires instead of pool fires which had smaller heat radiation impacts due to small pool size made by small leak size of 20 mm. One of heat radiation profile for jet fire is presented in Figure X.

Figure X. Example of Heat radiation vs. Distance for jet fire



The adjacent tank distances of tank #1~8 are all about 30 m as in Figure XII. Therefore heat radiation level is approximately 30 kW/m^2 from Figure X.

Figure XII. Distance of tanks #1~#8 and radiation level



To figure out probability of secondarily effect with previous result, studied as follows.

Table VIII. Models for escalation probability[*Y*: probit value for escalation given the primary scenario; ttf: time to failure (s); *I*: radiation intensity on the target equipment (kW/m^2); *V*: equipment volume (m^3)] (Ref. 9)

Escalation vector and primary scenario	Target equipment	Model for escalation probability
All radiation scenarios	Atmospheric vertical cylindrical vessel	$Y = 12.54 - 1.847 \ln(ttf)$
Probit model based on “time to failure” and simplified models for ttf vs radiation		

To find time to failure (ttf) value, the relationship of heat flux and ttf was used as in Figure XIII.

Figure XIII. Time to failure for vertical cylindrical vessels under distant source radiation (Ref. 7)

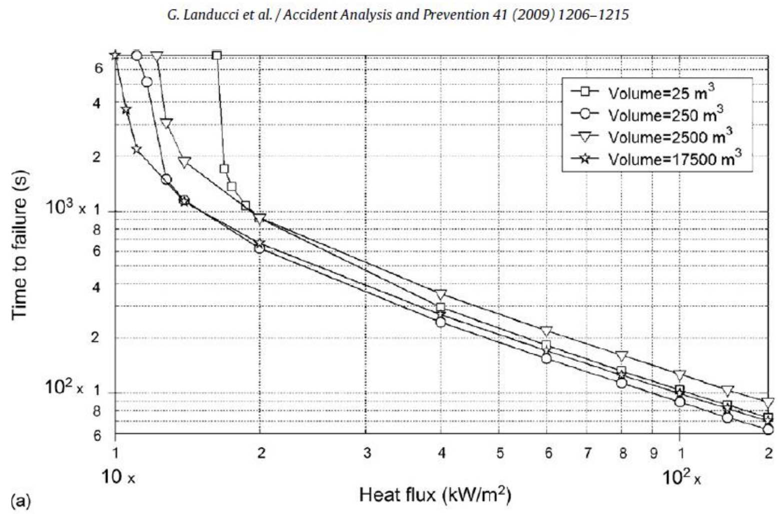


Table IX. Probit Calculation

Time to failure ($V = 17500\ m^3$, Heat flux = $30\ kW/m^2$)	Probit value(Y)	Converted to Percentage
300 s	2.005	~0 %

VI. CONCLUSIONS

This study excluded the worst-case scenario (catastrophic rupture) for more realistic risk assessment, and selected alternative scenarios as 20 mm leaks in tanks. In conclusion, jet fires were identified as the most probable and severe consequence but the domino effect by jet fires has not been predicted to occur since the radiation intensity is not enough to generate secondary damage to the closest tank. Though no domino effect is likely in LNG tank farms, considering seismic events in risk assessment is very important to help in risk assessment for large-scale LNG farm due to the fact that the frequency of large earthquake has been increased and greatly concerned in global. Given risk criteria, this study would help decision-making process on large scale facilities which can have massive impact on risk of the country and how many large tanks carrying hazardous substances are adequate in terms of overall risk.

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