UNIVERSITÀ DEGLI STUDI DI PADOVA
DIPARTIMENTO DI INGEGNERIA INDUSTRIALE
CORSO DI LAUREA MAGISTRALE IN INGEGNERIA CHIMICA E DEI PROCESSI INDUSTRIALI

Tesi di Laurea Magistrale in
Ingegneria Chimica e dei Processi Industriali

Risk analysis in atmospheric and pressurized tank subjected to seismic effects

Relatore: Prof. Giuseppe Maschio
Correlatore: Ing. Chiara Vianello

Laureando: ANTONIO GNESOTTO

ANNO ACCADEMICO 2015-2016

Riassunto

Lo scopo di questo elaborato è di proporre un metodo che permetta il calcolo del rischio di incidenti rilevanti in serbatori costruiti su di una zona sismica. Partendo dall'analisi dell'albero dei guasti, unitamente alla conoscenza delle distribuzioni probabilistiche è possibile ottenere le distribuzioni di probabilità di guasto per l'apparato meccanico coinvolto, grazie all'uso di un programma di calcolo. Questi dati sono, dunque, compatibili con quelli che è possibile ottenere dall'analisi sismica: attraverso la matrice di distribuzione dei terremoti, al vettore frequenza e alle curve di fragilità dei materiali si ottiene la probabilità di guasto legata all'evento sismico. La somma dei due contributi permette di ottenere un dato generale, che tenga conto di tutte le possibili origini del rischio (meccaniche e naturali) in ottemperanza alla "Direttiva Seveso III". A seconda della zona sismica prescelta è possibile notare come questi due contributi siano comparabili in zone mediamente sismiche, quello meccanico sovrasti il naturale in aree asismiche e viceversa in zone ad alto rischio sismico. Da notare come i dati utilizzati provengano da due forme di analisi diverse: quelli relativi al rischio meccanico sono derivati dall'analisi strutturale, frutto di anni di studi e di tecnologie sempre migliori; i dati relativi agli eventi sismici sono raccolti nelle serie storiche. Queste ultime riguardano gli ultimi cento anni di storia, da quando la sismologia ha cominciato a studiare i terremoti, e sono limitati e di carattere generale. Prendendo le mosse da questa precisazione il presente lavoro raggiunge risultati che, nonostante le semplificazioni adottate, sono promettenti e consigliano la prosecuzione dello studio. Le semplificazioni utilizzate riguardano il design delle apparecchiature (sprovviste della maggior parte dei sistemi di sicurezza solitamente utilizzati) e non considerano il fenomeno dello scuotimento cui vanno incontro i liquidi che subiscono un fenomeno sismico.

Abstract

The aim of this study is to develop a methodology that allows the risk assessment for storage vessels located in a seismic zone. Starting from the analysis of the fault tree and from the knowledge of probability distributions and using a calculation program specially developed, is possible to obtain the failure probability distributions concerning the equipment from a mechanical point of view. In this way, these data are compatible with the ones that is possible to obtain performing a seismic analysis: through the matrix of distribution of earthquakes, the frequency vector and the fragility curves of the equipment it is possible to obtain the probability of failure due to earthquakes. The sum of the two contributions allows to reach a global result, which takes into account all possible sources of risk (due to mechanical failure and natural events) in compliance with the "Seveso III Directive". Depending on the selected seismic zone it can be seen how these two contributions are comparable in medium seismic zones, the mechanical risk overhangs the natural in non-seismic areas and vice versa in high seismic zones. It is worth noticing that the data used are given by two different forms of analysis: those related to mechanical risks are derived from the structural analysis, results of years of study and technology improvement; The data for the seismic events are collected in historical series. These series give quantitative parameters only for the last one hundred years of history, since the seismology began to study earthquakes with proper instruments, and are limited and general. Starting on this specification, this work achieves promising results that have to be improved with further studies. In order to reach these results, some specifications were adopted: tank design didn’t take into account all safety measures that are used in a plant nowadays, also the shaking of the liquid wasn’t considered.

Index

Introduction

Nowadays, the risk assessment of chemical plants is considered a key parameter in terms of investment opportunity. In particular, safety perception in public opinion is an important factor that can determine the acceptance of a plant by surrounding inhabitants.

The regulatory framework is discussed in Chapter 1 (concerning safety in chemical plants), in particular Seveso Directive and its modification are described. In 2012 the “Seveso III Directive” was promulgated and it considers, for the first time, domino effect due to natural events such as flooding and earthquakes. Seismic events are a characteristic of Italy: in fact, there are several seismic areas and almost all the peninsula is subject to this risk.

This work tries to evaluate the risk that affects simple equipment located in seismic areas. An atmospheric and a pressurized tank are studied. These vessels were designed without all safety measures, so results obtained are simple to analyse.

In order to evaluate the risk, it is important to choice the right method: it is important that the result of the analysis is a numerical value. There are a lot of possibilities, as in Chapter 2, some qualitative methods and some quantitative ones. In the first case, the result of the risk assessment will be a word or a risk level described with a phrase; in the second one, the method will give a number that can be used in calculation. Fault tree analysis results to be the best method for this study: the presence of frequency parameter, derived by structural analysis, give well established results. Also the high and low limit of frequency will permit an analysis in terms of maximum and minimum calculation.

In Chapter 2, the seismic aspect will be discussed: how seismic waves develop, which scale are adopted and how it is possible to evaluate the seismic risk for a chemical equipment. It is worth to be noticed that seismic parameters are obtained with an historical analysis. This is the critical point of the work: it is possible to obtain the historical series of several centuries but only for the last century, when the seismology became well established, there are also quantitative instrumental data. Their value is more general.

Last in Chapter 2, design features of tanks will be discussed. With this analysis it is possible to comprehend which part of the equipment is subject to mechanical and seismic risk.

Chapter 3 focuses on the combination between structural and historical data, trying to combine them. First of all, it is important to decide to use a deterministic or a probabilistic approach. In deterministic analysis results are expressed in pure numbers, giving directly the value of the risk; on the other hand, probabilistic analysis originates a distribution of probability in which it is possible to see most probable values and calculate a mean. This choice influences results.

In Chapter 4, the case studies will be discussed. First of all, specific of the two vessel are presented, with maximum storage and measures. Then, the fault tree analysis is performed for mechanical risk.

Starting from mechanical fault tree, the possibility of a seismic event is added and some modification to the previous fault tree will be done.

In Chapter 4, the locations of case studies are described. In fact, location can determine the final value of the risk analysis.

Chapter 5 shows the results of risk analysis for seismic event associated to equipment.

The methodology used in this work allows to give a first try in risk analysis as the "Seveso III Directive" asks. Results are obtained using techniques well established in their field of application, so it is possible to assess that these results will give a good approximation to the real behaviour of the risk.

Chapter 1
Regulatory Framework

After II World War, global economy had a huge development. At the same time, also chemical industry knew this fast improvement without taking into account possible critical points: safety of workers and of the environment. Some laws were promulgated by the UE, in order to reduce the chances of a relevant accident. First one was “Seveso directive” (in 1982), improved by “Seveso II directive” (in 1996) and “Seveso III directive” (in 2012). The most important change was to not consider the industrial process itself but the substances involved in it and the possible compresence of natural hazards for chemical plant.

1.1 Chemical industry evolution

Chemical industry had known a huge and fast development in terms of type of productions and quantity of products in last 150 years. The growth of market of chemicals has brought out many safety problems: initially, when chemical industries were small, a relevant accident did not cause problems to the area surrounding the plant, but only within the plant. So, safety was considered a “private” question and every company would control it with its own regulation. But this system couldn’t stand long: big industries were affected by big accidents and the Countries began to approve laws in order to avoid them.

In Italy, the first law that defends workers’ safety was promulgated in 1942 in the “*Codice Civile*”. It states that physical and moral safety in the work spaces has to be guaranteed by the employer. Unfortunately, this law began to work in a moment in which historical events didn’t allow to applicate it completely. Six years later, the 1st January of 1948, what was stated before became a constitutional law. Afterwards, a lot of improvements were applied to it.

The Flixborough and Seveso accidents did emerge the following problems: one is the lack of knowledge and underestimation of risks arising from the presence of manufacturing plants and across the next growing attention to the protection and preservation of the environment and quality of life of individuals. Then, these incidents put the issue of industrial risk at the centre of the Italian and European public opinion debate.

In the following paragraphed, the incidents of Flixborough and Seveso are briefly described.

1.1.1 Flixborough

A Sunday in June 1974, in the Flixborough Works of Nypro Limited took place an accident, the first with a huge resonance in the chemical industry. The plant was designed to produce 70000 tons per year of caprolactam, a raw material for nylon production. The main chemical used in the reaction was cyclohexane, a dangerous flammable substance. The process took place at 155°C and 7.9 atm, conditions that immediately volatize the cyclohexane when depressurized to atmospheric conditions. For the production chain, six reactors in series were designed; each one, in normal operating conditions, contained 20 tons of reactant.

Several months before the accident occurred, reactor 5 was found to be leaking: there was a crack in the structure. The decision was to remove and repair the reactor, while the plant continued the production with a direct connection between reactor 4 and 6. The connection was made using a 20” pipe instead of the 28”, used for connecting other reactors, because there was the only pipe diameter available in the plant. This choice caused the accident. The most accepted hypothesis was that the bypass pipe section broke down because of inadequate support and overflexing of the pipe section as a result of internal reactor pressure.

As a consequence of the rupture of the bypass, a release estimate in 30 tons of cyclohexanone volatilized and form a large vapour cloud. Then there was an ignition and an UVCE (unconfined vapour cloud explosion) with 28 fatalities.

Figure 1.1 shows the area involved in the accident after the intervention of the fire brigade. It all could be avoided if a serious risk analysis was carried out during plant modification.

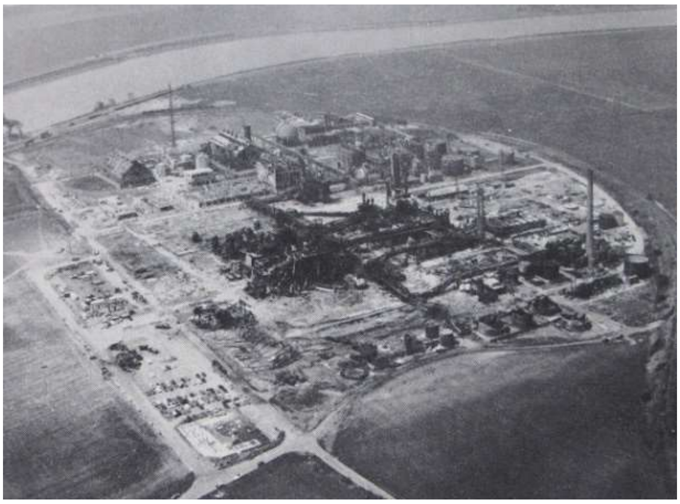


Figure 1.1*: Flixborough area after UVCE. The accident caused the complete destruction of the plant.*

1.1.2 Seveso

The plant involved in this accident was owned by Icmesa Chemical Company. The product was hexachlorophene, a bactericide, with the production of trichlorophenol as intermediate. Under normal operation, a small amount of a dioxin (2,3,7,8-tetrachlorodibenzoparadioxin also named TCDD) was produced as side-product. This dioxin is one of the most toxic agent produced in chemical processes. This substance is insoluble in water, so the decontamination can be very difficult.

On 10th July 1976, the trichlorophenol reactor went out of control, with a higher temperature than the normal one. This caused an increasing production of TCDD and their release in the atmosphere as a cloud: to avoid the explosion of the reactor, safety valves opened. The area, where some little towns are located, was surrounded by this toxic product that settled to the ground with heavy rain; so it had to be evacuated and isolated, as shown in ***Figure 1.2***. This intoxication caused a lot of damage for an area that was mainly agricultural: a layer of soil was removed where the contamination was higher. Also today, forty years after that accident, the effects on the health of people are not clear.

Figure 1.2: *a policeman in the anti-contamination suit puts the seals in the area.*

1.2 Seveso Directive

These events induced the European Community to adopt a legislation directed to prevent industrial accidents. So, in 1982 was promulgated the so called “Seveso Directive” (82/501/ECC). In this first attempt of legislation there are some key points:

- Obligation to inform inhabitants about risks linked to the industrial production;
- Importance of the prevention of relevant accidents;
- Need to teach and inform workers how to react in some situation and how to avoid them;
- Direct link with institution that will control the industry in terms of safety.

In Italy, “Seveso Directive” became effective only in 1988 with the D.P.R. 175/88. Some significant passages are reported below:

- The employer has to draw up a safety report in terms of dangerous substances, plants and other relevant accidents with all measures adopted in order to avoid risk and minimize damages. This report has to be sent to the ministry of health and of environment. (Art.4)
- The employer has to declare to the region and to the prefect that all risks were analysed and all corrective measures were taken. (Art.6)

- The population of the area have to be informed about production, process, substances and risks by the mayor. (Art.11)
- The prefect has to draw up an external emergency plan and to secure that population knows it. (Art17)

After Seveso directive, legislation seems to be quite prepared to all accidental events.

If the European Community claimed to have a good legislation in terms of risk analysis, the rest of the world was still backward in this field: in fact, two huge accidents take places in 1984. Two cities were involved: Bhopal (India) and Mexico City (Mexico).

In the following paragraphed, these incidents are briefly described.

1.2.1 Bhopal Incident

The first incident took place in the Union Carbide plant near Bhopal (in Madhya Pradesh state, central India). The plant produced pesticides for local farmers. The price of this product is prohibitive for Indian people and there were labour disputes so the production was interrupted.
An intermediate for the reaction was methyl isocyanate (MIC), an extremely dangerous compound: it is reactive, volatile, toxic, flammable and it create respiratory disease in people exposed to it. The boiling point of MIC is 39°C and when it vaporizes, it settles to the ground. The main problem, in this case, is the exothermic reaction with water, that can generate vapours if doesn't cooled.
Somehow, the MIC tank become contaminated maybe with water, and the substance temperature rose over the boiling one. Vapours released travelled within the scrubber and the flare system that were unfortunately not operating, for reasons stated before. An estimation of 25 tons of toxic vapours were released. The cloud travelled to the near the city of Bhopal and killed 3000 people. Other deaths took places in the following days and months. In the end, at least 15000 people died and more and more were affected by serious diseases. In Figure 1.3 there is a picture of the plant after the accident in 1984.

Figure 1.3: *Union Carbide plant after Bhopal disaster in 1984.*

The exact cause of contamination of MIC in not known, but the real cause of the accident was the abandon state of the plant, stopped without an operating schedule. If there had been a precise plan, all safety measures would not have been turned off while a reactant was in the tank.

1.2.3 Mexico City Incident

The Mexico City accident took place in San Juanico, near the capital. During some transfer operation in a LPG storage site, a pipe leaked and a cloud of gas settled to the ground. After 10 minutes, there was the first ignition near the tanks that generated the first BLEVE (boiling liquid expanding vapour explosion). Other 11 explosions were registered that day and 11000 m^3 of LPG were burned. There were 550 fatalities and the plant area was wasted. Figure 1.4 represents the accident area after explosions.

Figure 1.4: *San Juanico site after tanks explosion. A part of the LPG still burns.*

This event is useful for this work: an LPG tank will be one of the case studies.

1.3 Seveso II Directive

Due to these accidents, a revision of the first law take place and in 1996 was promulgated "Seveso II Directive" (96/82/CE). The most important change affects consideration of areas surrounding the plant: in the last two fatal accidents, plants were situated in a high density populate area. This arises a lot of problems in the definition of an emergency plan that were not taken in account in the first directive.

The most important differences between the first directive and the second one are summarized below:

- Whereas Seveso I takes in account risks linked to the industrial activity in the site, the second one considers dangerous substances and risk of relevant accidents related to them;
- In the second directive is introduced the obligation for the employer to draw up a document where is reported his own policy about safety and prevention of accidents;
- Domino effect become a key element in the evaluation of the risk associated to a plant;

- Policies about urbanization have to be discussed in terms of safety of population living nearby chemical plants;
- Population has the right to read all documents about safety report;
- All authorities have to be informed by the employer about relevant accidents occurred in the plant.

This new directive introduces an important concept that will reach an important position in this work: domino effect. It is worth to define these terms now. Domino effect is "the situation in which something, usually something bad, happens, causing other similar events to happen" (Cambridge dictionary). In chemical terms, an accident, however a small one, can generate a lot of consequences until a relevant event occurs.

"Seveso II Directive" was adopted in Italy with the D.Leg. 334/99, tracing the changes to the first directive. The key issue became communication between the industry, competent authorities and population.

As in previous cases, another relevant accident, that occurred in Fukushima Daiichi, has highlighted of the issues not included in the earlier directives. In the following paragraphed, this incident is briefly described.

1.3.1 Fukushima incident

This disaster is not related with chemical industry but with a nuclear plant. The 11th March 2011 an earthquake with a magnitude of 9.0 in the Richter scale took place 70 kilometers away from Japan coast. The seismic movement also caused a tsunami with a 40m tall wave. There were a lot of consequences for industrial activities such as refinery set on fire, interruption of the electricity in a wide area and problem for transports. The main event, unfortunately, was the melt down of the third reactor of the Fukushima nuclear plant with a release of radioactive material. The tsunami enabled the cooling system for this core and the temperature arose significantly. The concrete melted and the radioactive material was free to spread out. The effects on health an environmental required a lot of countermeasures by authorities and continue until today. In Figure 1.5 an overview of the nuclear plant after the tsunami is represented.

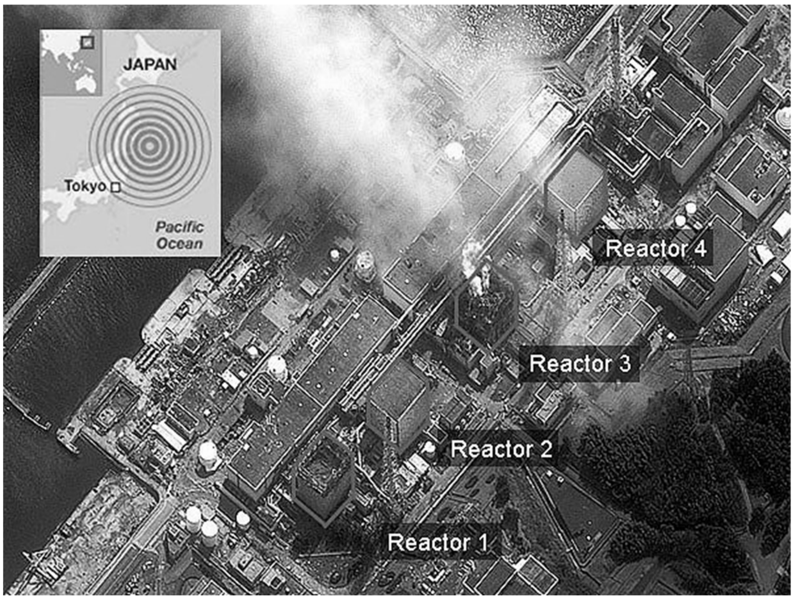


Figure 1.5:*Fukushima Daiichi nuclear power plant after the earthquake and the tsunami. It is possible to see the third reactor burning because of the core meltdown.*

The causes of this disaster can be found in the safety procedure of the plant: all possible mechanical risks were taken into account, otherwise, the seismic component was unexpected. There were studies that considered the possibility of a tsunami in the area but they were ignored. With an accurate study of all risk component, this disaster could have been avoided.

1.4 Seveso III Directive

In following years, lot of improvements were applied to the second directive and a new one was redacted, taking into account that also natural events could lead relevant accidents. In 2012, the "Seveso III Directive" (2012/18/EU) was promulgated. June 2015 was the deadline for the transposition of this law in Italy. There are three important news in this new directive:

- All substances have to be classified with the European regulation 1272/2008, in terms of packaging and labelling;
- Population has the right to see all documents about safety and risks linked to a chemical plant and these documents have to be written in non-technical terms, understandable and clear;
- The accidental scenarios have to take in account all natural events, such as earthquakes or flood.

The last point is the most important one: until now all studies about safety in plants take in account either chemical risks, either natural risks but not together.

The aim of this study is to try to combine what we know about damages carried out from earthquakes with our knowledge about chemical risk. All this information will be applied in a simple situation: a standard cylindrical tank at atmospheric pressure with floating roof and a pressurized tank. In both there is a simple fluid such as water. Then, a statistical analysis will be carried out in order to analyse probability of earthquakes and frequency of chemical accidents.

Anyhow, first of all an analysis of what is the so-called "State of art" has to be done.

Chapter 2

State of Art

Risk analysis reaches a good degree of reliability either in the chemical field, either in the seismic one. There are some techniques that allow to calculate the global value of the risk in chemical plant such as the fault tree and the event tree. For seismic aspects, the analysis is based on the possibilities of an earthquake and the fragility of materials. These two branches have to be applied in a simple system, such as tanks. In this case is worth to know how floating roof tanks and pressurized one are build.

2.1 Analysis of chemical risk

In order to analyse chemical risks in a plant, some useful techniques are used. All them have to recall the key points of all directive described above.

There are two groups of methods that could be used to assess the risk in a chemical plant: qualitative and quantitative. The first kind of methods include all procedure that to the question "What is the risk in this plant?" answer with a phrase or a word. Examples of these methods are the Dow-chemical exposure index or the What-if analysis. Quantitative methods are objective: they answer with a probability of fault or event, considering the plant equipment. It is unnecessary to say that these quantitative methods are both more accurate and more expensive than the first one.

For a good understanding of risk analysis, it is worth to start with simplest ones that are presented as "indexes methods" in which the operative procedure is quick and simple:

1. Plant is divided in section characterized by a key process;
2. Main substance is identified;
3. To each section is assigned a negative factor that rises risk value;
4. Non compensated risk is calculated;
5. Compensation factor analysis;
6. Calculation of compensated risk indexes.

To give an objective analysis, if it's possible for a qualitative method, a checklist is used: all aspects of the plant are written in them, which are materials, which are procedures and which are equipment. The employer has to verify if safety parameters are satisfied in each phase of the plant life: project, construction, start, running and stop.

For a more accurate study, the Dow-chemical exposure index is used. With a table, this method assigns a coefficient to all hazards of the plant. With some relation, sum and multiplication of factors, a qualitative result is obtained. It is worth to be noticed that results are expressed in a qualitative way: every risk class has a range in numerical results linked to the nominal value of the risk (from light to heavy).

These indexes methods are an excellent preliminary analysis because they are very quick and they have the support of a software: it is enough to know substances and equipment to assign coefficients and to calculate the risk. But this analysis is not complete: there are a lot of possibility for a failure and a lot of consequences that these methods don't take into account. It is a better idea to choose another analysis strategy that will suggests also what to do to avoid accidents.

2.1.1 "What if?"

The "What if?" method is more similar to a guide to the correct use of the plant than a risk analysis. The core feature of this procedure is to verify what happens if somewhere in the plant there is a deviation from standard condition.

It is worth to be noticed that this method is less accurate than the previous one and, for this reason, it is often coupled with other analysis in order to give also a numerical result.

The common procedure for the "What if?" method is:

1. Definition of boundaries of the study in terms of physical system (which part of the plant or of the surrounding area) and of consequences target (population, workers or production).
2. Collection of information linked to the categories chosen above.
3. Definition of the working team (size of this group depends on problem complexity, sometimes is sufficient only one person).
4. Perform the analysis.
5. Results communication.

To find out how accurate this method is, just check the definition of boundaries in point 1. More complex is the plant and more are the interaction with the surrounding areas, bigger the team has to be. To coordinate the work of each component a leader is required. In Table 2.1 is reported the duration of each phases of the "What if?" method for a simple system and for a complex one.

Table 2.1: *duration of phases in "What if?" analysis*

Scope	Preparation	Performing analysis	Information collection
Simple/ Small System	4/8 hours	4/8 hours	1/2 days
Complex/Large System	1/3 days	3/5 days	1/3 weeks

When all the information are collected (plant scheme, mechanical scheme of equipment, check-list for operating procedures and for emergencies).

With all these information and with the knowledge of chemical mechanism in the plant, is possible to write down a relation. An example is reported in Figure 2.1.

What If	Causes	Consequences	Risk Matrix			Safeguards	Recommendations	Responsibilitie s
			S	L	RR			
1. Overfilling?	1.1. LV-201 or controller LC-201 malfunctioning	1.1. Reverse flow backs up into condenser and reduces performance	1	3	3	1.1. Level Gauge (LG-101)	1. Establish operational procedures for inventory control of ammonia	Anna D
	1.2. Overfilling on initial fill of ammonia					1.2. Level Alarm High (LAH-201)	2. Design to ensure that inventories of ammonia in receiver and accumulator plus piping are compatible and do not result in flooding.	Nigel W

Figure 2.1: *example of a what if analysis concerning overfilling problems of a tank.*

2.1.2 Hazop

When a further analysis in needed, the technique that should be used is the HAZOP. The name means "Hazard and operability study" and it is similar to the "What if?" with a methodical scheme as represented in Figure 2.2.

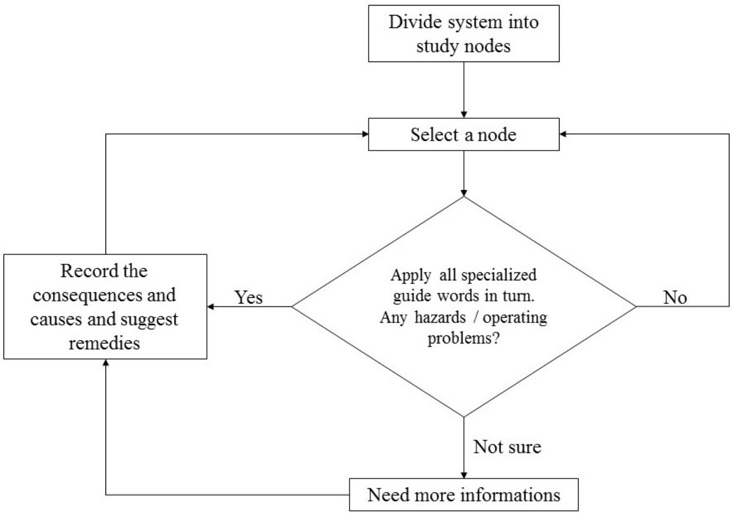


Figure 2.2: *Hazop operative scheme.*

The first step in the analysis is to divide the plant in nodes. A node is a unit where there are few processes and that is independent from other nodes.

Second step concerns the study of a single node with its processes and flows. When all the mechanisms are well studied, it is possible to go further.

For each parameter involved in the node (such as temperature, flowrate, pressure and composition), some guide words have to be used:

- No: when there is a negation of the design intent (e.g. a liquid doesn't flow in a pipe).
- Less: when the amount of a specific parameter is lower form the design value (e.g. a lower temperature in a boiler).
- More: when the amount of a specific parameter is higher form the design value (e.g. a higher pressure in a reactor).
- Part of: when the quality of a flow is decreasing (e.g. the composition of a product is less than the design value).
- As well as: when the quality of a flow is increasing (e.g. a reactor is producing more than the design value).
- Revers: when the logical scheme is reverted from the designed one (e.g. pressure in two tanks is inverted).
- Other: when other operations are going on in the plant (e.g. during plant start).

To go further, it is necessary to evaluate all possible consequences for each guide word in each node. Then, a possible solution to the problem arisen have to be formulated and to be written down in a safety report.

It is worth to be noticed that this method requires a good organization of the working team, that is usually very large: there is a chairman, a safety engineer, who has to coordinate other people; a scribe, who takes note and will write the safety report; one representative of each discipline involved in design (process, mechanical, control and instrumentation, …), who will answer the issues raised in his field; eventually other specialist, for every particular issues.

Moreover, an accurate documentation is needed: all papers about the plant (PFD, P&I and layout) and about substances have to be read and analysed.

The result is a document where all possible deviations are taken into account. An example can be seen in Figure 2.3.

HAZOP Review of Barge Filling Operations at a Typical Small Fueling Terminal					
2.0 Barge Transfer System Piping					
Item	**Deviation**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**
2.1	High flow rate	Tankerman sets the flow rate into a barge tank too high. May be because tankerman was in a hurry, not paying attention, not knowledgeable, fatigued during a long transfer operation, misled by faulty instrumentation such as a pressure gauge, failing to gauge tanks to verify filling rates, misinformed about desired flow rate, distracted by other duties (especially while filling multiple tanks), etc.	Potential to overpressurize the barge tank during filling if the relief valve is not sized to pass sufficient vapor (see deviation 3.7) Potential to create a static charge as liquid enters an empty tank (e.g., during the "cushioning" phase of transfer), possibly resulting in an internal fire or explosion within a barge tank (see deviation 3.7) Potential to fill tanks faster than the tankerman can control or to create a situation in which the valve cannot be closed, possibly resulting in a high level in a barge tank (see deviation 3.1)	Tankerman and dockman monitoring to detect problem Regulations require slow fill during cushioning and during topping off Fatigue standards apply to tankerman, but a loophole exists for "shore tankermen" who are not standing watches Modern barge tanks do not have the liquid free fall problems that older barges had	**Rec. 1** - Verify that the relief valves on the barges are sized to vent the maximum vapor flow during (1) the highest reasonable fill rate and (2) a fire on the barge that heats a cargo tank. **Rec. 2** - Explore the possibility of applying personnel fatigue standards and enforcement to marine terminal personnel. **Rec. 3** - Consider installing flow rate indicators in the filling lines **Rec. 10** - Consider having terminal operators provide emergency transfer shutdown capability on board the barge instead of relying solely on communication with the dockman. **Rec. 11** - Consider emphasizing to terminal operators the Coast Guard's concern about extended work hours for "shore tankermen."
2.2	Low flow rate	Pump operator, dockman, or tankerman closes a valve at the wrong time Valve fails closed	Potential to cause high pressure in the line if the discharge of the pump is blocked while operating (see deviation 2.8)	Tankerman and dockman monitoring to detect problem	**Rec. 3** - Consider installing flow rate indicators in the filling lines. **Rec. 4** - Consider formalizing the use of visual cues to help tankermen easily identify valve positions (e.g., opened/closed) as they move around the deck.

Figure 2.3: *example of an Hazop analysis, with reference to the plant scheme.*

2.1.3 FMECA

One last qualitative method is FMECA that stands for: "Failure Mode, Effects and Criticality Analysis". This technique is very similar to the "What if?" for the approach: is brainstorming-based and wants to evaluate all possible failures and effects of them to the plant.

The key points of this method are:

- Simple and systematic analysis, also with some support software.
- Useful also in project phase because it can highlight the weak points of the plant.
- Used as a support for fault tree and for reliability studies.
- Influenced by the degree of experience of the safety engineer.
- Takes in account only a single failure.

This technique is mostly used in mechanical industry for this last point: chemical industry involves a lot of substances and processes that influence each other. A little failure in a little section of the plant can lead to a catastrophic accident due to the domino effect.

An example of FMECA is represented in Figure 2.4.

Item	Potential Failure Mode	Potential Cause of Failure	Current Prevention Controls	Current Detection Controls	Recommended Action
Disk Brake System	Vehicle does not stop	Mechanical linkage break due to corrosion	Designed per material standard MS-845	Environmental stress test 03-9963	Change material to stainless steel
		Master cylinder vacuum lock	Carry-over design with same duty cycle requirements	Pressure variability testing on system level	None
		Loss of hydraulic fluid due to back off of connector	Designed per torque requirements - 3993	Vibration step-stress test 18-1950	Modify connector from crimp style to quick connect.
		Loss of hydraulic fluid due to hydraulic lines crimped or compressed	Designed per material standard MS-1178	DOE tube resiliency test	Modify design from MS-1178 to MS-2025 to increase strength.

Figure 2.4: *example of a FMECA analysis. With causes of the failure and possible solutions.*

The FMECA also introduces the concept of frequency, a key parameter for the quantitative analysis.

2.1.4 Fault Tree

The qualitative analysis can not reach objective results. In order to obtain better results that can be compared each other, quantitative methods were created. The aim of these techniques is to quantify the value of the risk through a number: higher the number, higher the risk. A safety engineer has to know how to reduce this number under a parameter that is the acceptable value for the risk.

It is time to introduce a new topic: failure frequencies. A frequency is a number between 0 and 1. It represents how many cases will occur in one year. For example, a failure frequency of $2.8 \cdot 10^{-7}$ means that there will occur 2.8 failure in 10000000 years, a very low value. It is worth to be noticed that the value used for this analysis is a mean: the number representing the frequency is obtained by a graphic of the failure distribution, represented by a normal distribution curve (Figure 2.5), and so it is impossible to determine a unique value without making some approximations. This procedure simplifies the analysis of the risk and allows to reach a result quickly.

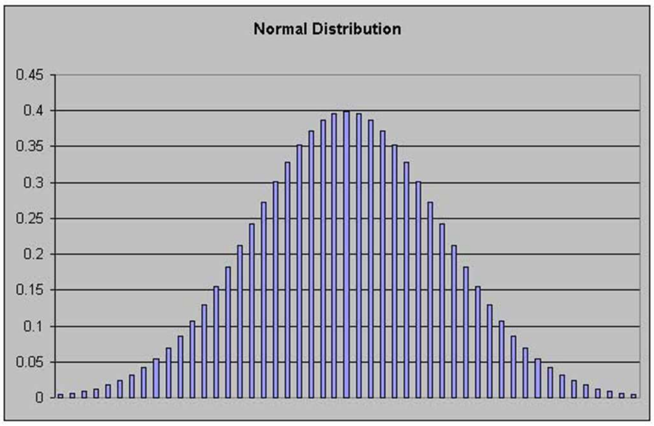


Figure 2. 5: *normal distribution curve. The shape is influenced by the mean value and the standard deviation.*

Every equipment has frequencies for the rupture of each mechanical part, so it is possible to take in account all possibilities for a failure. But there is another problem: there are a lot of data for frequencies of single section, such the one reported in Table 2.2, but none for the entire equipment. How is it possible to calculate it? A probability study will answer the question. As stated before, the mean value of the frequency is used (written in the central column). Other value will be discussed further below.

Table 2.2: *example of failure frequencies for a floating roof tank. As can be seen, there are three possible values for this parameter.*

Type of release	**Event per 33,909 tank years**	**Frequency and 99% reliability intervals (10^{-3}/tank year)**		
		Minimum	Mean	Maximum
Tank structure leaks (corrosion)	19	0.3	0.56	1.0
Tank structure leaks, including drainage	33	0.6	1.0	1.5
Tank structure leaks and leaks due to operational overfilling	47	0.94	1.4	2.0
Tank structure leaks. leaks due to operational overfilling and steam coil breakage	50	1.0	1.5	2.1
Release outside tank shell – all causes	96	2.1	2.8	3.7

The probability analysis is called “Fault tree”. It is a very useful technique for risk analysis because it links all possible failures to a top event that is the scenario in which the equipment is broken, a release is occurred with a lot of consequences for the entire plant and the surrounding area. To reach this event, various little failures have to be linked with a hierarchical approach: there are many roots in this “Fault tree”, each one will divide its path up to an elementary failure with a specific frequency. Only considering all contributions, it is possible to reach a result for the probability of the event.

Some operators are very useful to comprehend how to reach a unique result from these little accidents. Two of them are mostly used in risk assessment: “and” and “or”. To best explain their meaning, an example is used. It is based to Figure 2.6.

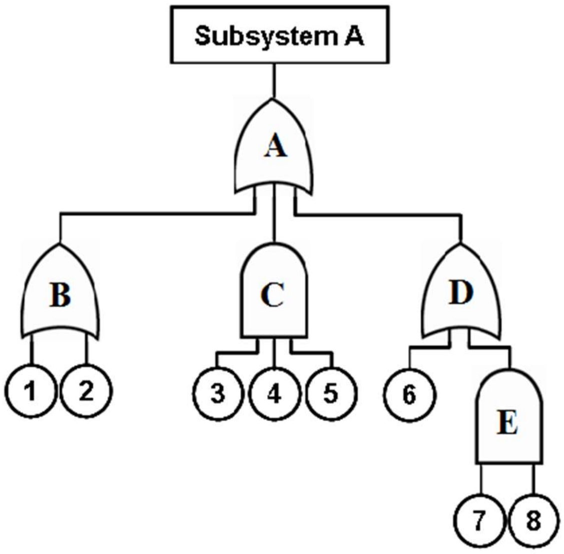


Figure 2.6: *example of a Fault tree. All possible failures are linked together using "and" and "or" operators.*

Operator in A, B and D are "or", so the logical path is true if one of the event below is true. In practise, node B will be true if 1 or 2 will verify, one of them is sufficient. Therefore, in terms of frequencies, values of 1 and 2 have to be summed.

Instead, in C and E there is an "and" operator. Logically, it means that the event will verify only if both event will occur. The node E will be true only if 7 and 8 will verify. Frequency in E is the product of frequencies of 7 and 8.

To resume and be clear, it is possible to write the Equation 2.1 below in order to determinate the probability for the event "subsystem A" to occur. The operator "or" in A leads to a simple sum of all contribution of B, C and D; another sum in presented in B; in C there is a product due to the "and" operator; in D there are a sum for the contribution of 6 and E, and a product of the frequencies in E.

$$Event\ probability = [1 + 2] + [3 * 4 * 5] + [6 + (7 * 8)] \tag{2.1}$$

The "Fault tree" technique in well established in risk analysis because it is simple and it leads to reliable results, at the same time.

2.1.5 Event Tree

If "Fault tree" can be compared to a tree and its roots, the "Event tree" will be the upper half: it begins with the top event and then divides in branches.

The mechanism is different from the previous one: starting from a unique event, safety engineer has to think what are the possible scenarios. In a chemical plant, there are 3 different possibilities when a substance enters the atmosphere:

1. Dispersion: the substance is dispersed in the air, moved by wind. If it is a toxic compound, there will be problems for people living in the surrounding area and it is necessary to evacuate the inhabitants. If the substance is not toxic, there are no problems. A good knowledge of atmospheric condition will be determinant to avoid serious consequences.
2. Fire: if the substance is flammable, it is possible that it will burn. This can occur only with a trigger in the area. The fire can be a pool fire, for a liquid substance that quits the tank before to burn; a tank fire, when the compound burns in the tank; a jet fire, when the tank is pressurized; a flash fire, a fire that burns all the substance in a short fraction of time; a fireball, a ball of flammable vapours burn until all the substance is consumed. Which fire type will occur is determined by timing of the trigger and substance proprieties. Also in this case, a knowledge of atmospheric condition and of the flammability limits of the substance will help to avoid catastrophes.
3. Explosion: this is the worst case for an accident. A vapour cloud is released in the atmosphere due to the top event. The vapour mixes with air and then the cloud is triggered. If the burning reaction creates an overpressure, this event will be called explosion. It is called deflagration an explosion where pressure wave and combustion wave are distinct and the overpressure amount is low (few bars); it is called detonation an explosion where the combustion and the pressure wave are coupled and they have a supersonic speed, also the overpressure is high and it can reach dozens of bars.

As stated before, only the knowledge of the atmospheric condition, of the surrounding areas and of the substances allows the engineer to anticipate consequences and to take countermeasures.

An example of event tree is reported in Figure 2.7.

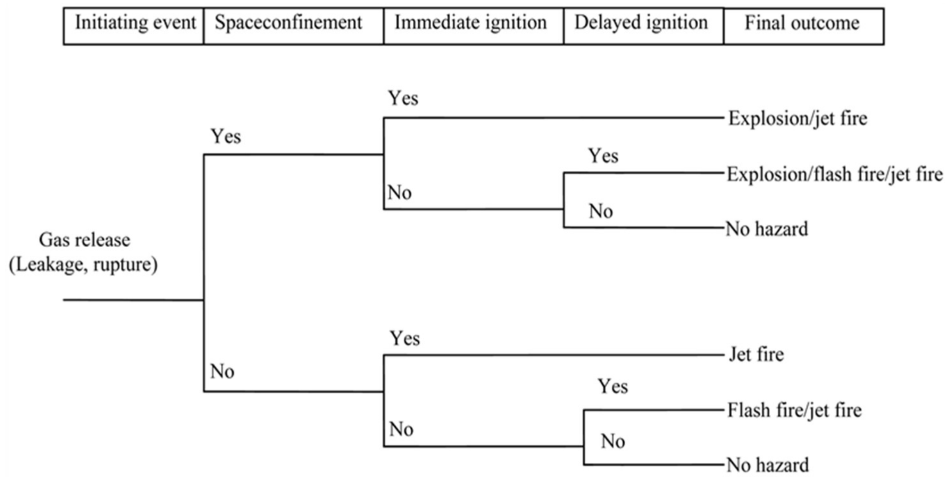


Figure 2.7: *example of an Event tree. In each node it is important to identify the trigger that differentiates two branches.*

These two techniques, "Fault tree" and "Event tree", are used together to examine how an accident could occur, from a little fault to the top event and to the accidental scenario. An example of this coupling is represented in Figure 2.8, where there is a unique tree diagram with both fault and event part.

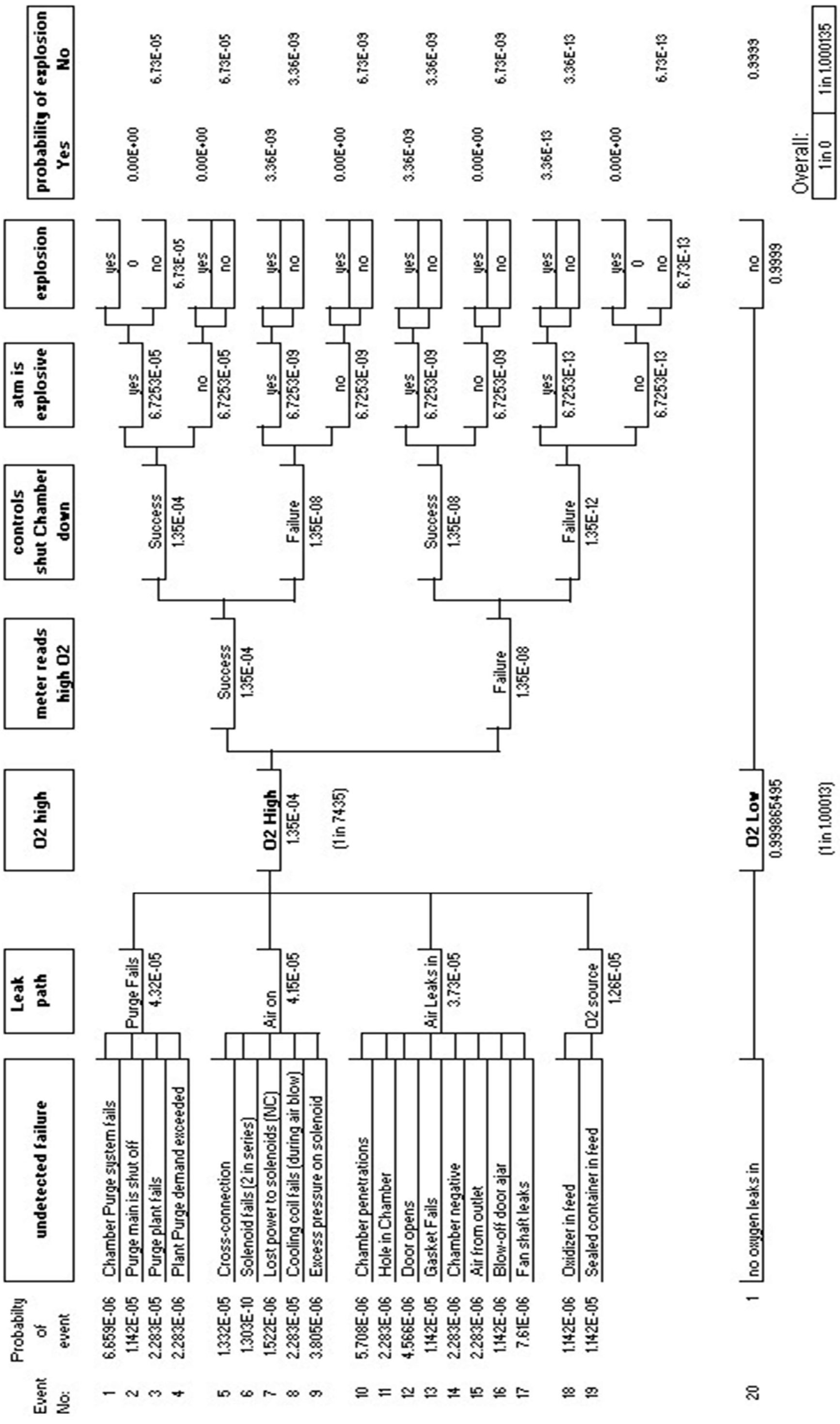


Figure 2.8: *fault tree and Event tree linked together.*

2.2 Analysis of risk relate to earthquakes

The next step in the risk analysis concerns about earthquakes: the chemical risk satisfied the first and the second "Seveso directive", but it is not enough for the third one. In order to consider all aspects about the risk the natural component is not negligible anymore. The greatest risk factor in terms of natural event is earthquake, for this reason, seismic movements are studied in the work.

2.2.1 Earthquakes

An earthquake is "a sudden violent shaking of the ground, typically causing great destruction, as a result of movements within the earth's crust or volcanic action."[1] The earth's crust is not a single block but is formed by many plaques, floating on the asthenosphere, the external part of the mantle. Convective movements in the asthenosphere causes movements on the plaques. These movements are completely chaotic and there is not a dominant direction in them. Some of the plaques are free to move and permit these displacements, otherwise some problems could arise. In fact, when two plaques are in contact, every move of the mantle create an accumulation of potential energy that can last for years. This energy reaches a peak and then is released in an earthquake.

When an earthquake occurs there are four types of seismic waves, two of them are defined as body waves because they develop themselves in the deep part of the crust, the other two are called superficial for the movement above the crust:

- Primary waves (P-type) are compressive waves with a longitudinal that origins in the mantle and reach the surface. They are pressure waves and their name is due to the speed that characterize them, in fact they are the firs waves that reach seismographs. They propagate through every material.
- Secondary waves (S-wave) are shear waves that are transverse in nature. They displace the ground perpendicular to the direction of propagation. They can only travel through solids because fluids don't support shear stress.
- Rayleigh waves (ground roll) travel on the surface with a movement similar to water waves.
- Love waves (SH waves) are horizontally polarized shear waves.

The graphic representation of this four types of waves is reported in Figure 2.9.

[1] Definition from the Oxford Dictionary, https://en.oxforddictionaries.com/definition/earthquake

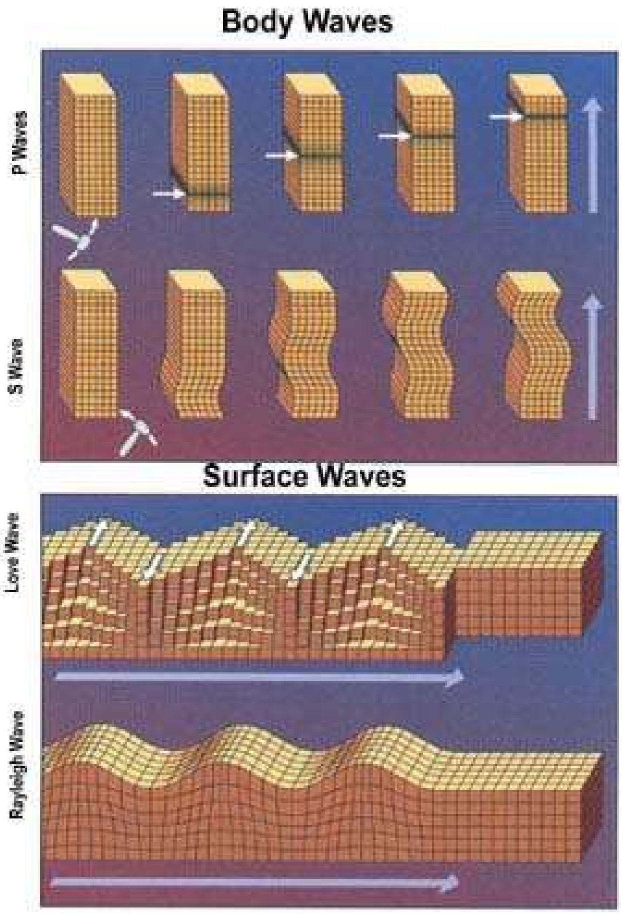


Figure 2.9*: types of seismic waves and their mechanism of propagation. P and S waves are body waves and move from the origin of the earthquake to the surface. Rayleigh and Love waves propagate in the surface in a circle area from the origin of the earthquake.*

In order to measure the power of an earthquake, some scale have been created. Three of them are well established today:

- Mercalli scale: it measures damages suffered by structures, mainly civil building, affected by an earthquake. This scale heavily depends from constructive criteria of an area, so the same earthquake can create huge damages in an ancient house and none in a modern skyscraper.
- Richter scale: was developed to avoid all possible dependence in the calculation of the power of an earthquake. It represents simply the logarithm of the amplitude of waves registered by seismographs with some adjustments to compensate the variation of distance between the center of the earthquake and every single seismograph.
- PGA: is the index of the maximum ground acceleration that occurred in a location during the earthquake. It measures not the power of the earthquake but the ground shaking. This parameter is very useful for risk analysis because every material has a maximum solicitation that it can adsorb. When this level is passed, the fracture is possible. The PGA is measured in g (gravity acceleration) fraction or, rarely, in m/s^2.

The PGA scale is very important for further analysis; it is necessary to explain how a change in PGA affects the power of the earthquake perceived. In Table 2.3, PGA scale is reported.

Table 2.3: *PGA scale for earthquakes.*

Instrumental Intensity	Acceleration (g)	Velocity (cm/s)	Perceived Shaking
I	< 0.0017	< 0.1	Not felt
II-III	0.0017 - 0.014	0.1 - 1.1	Weak
IV	0.014 - 0.039	1.1 - 3.4	Light
V	0.039 - 0.092	3.4 - 8.1	Moderate
VI	0.092 - 0.18	8.1 - 16	Strong
VII	0.18 - 0.34	16 - 31	Very strong
VIII	0.34 - 0.65	31 - 60	Severe
IX	0.65 - 1.24	60 - 116	Violent
X+	> 1.24	> 116	Extreme

2.2.2 Seismic areas in Italy

In seismic terms, Italy has two great areas. It is visible in Figure 2.10 that the high risk areas are Apennines, Sicily and Friuli.

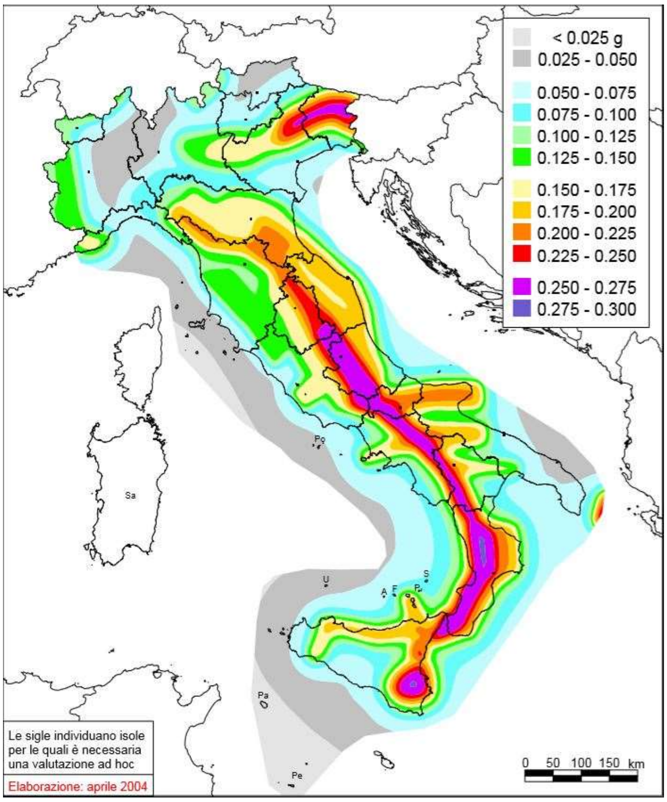


Figure 2.10: *seismic map of Italy. The legend expresses all the PGAs in terms of g. Two great seismic areas are along Apennines and in Friuli, due to orogeny.*

This danger is due to the orogeny mechanism: in these two area there are relatively young mountains, created by the clash between the Eurosiatic plate and the African one. For this reason, in order to study effects of an earthquake on an industrial production, is important to choose wisely the location. In this work, the two examples are located in Osoppo (UD) in the middle of the highest seismic zone in Friuli, in Falconara Marittima (AN) where the recent earthquakes caused the shaking of some columns, in Priolo Gargallo (SR) near Mount Etna. These choices have a precise aim: the seismic aspect is even more important if the risk of a relevant earthquake is high; so a study of the risk with these extreme conditions will represent a very good approximation and a precise test for the methodology. With these three locations, all possible ranges of seismic risk are analysed and so the results will lead to a complete representation of the seismic phenomena. If results are good, the method used in this case will fit also in other possible location, ensuring that results are reliable.

2.2.3 Seismic risk for chemical plants

Seismic risk analysis in chemical and industrial plants is based on a probabilistic approach. There are two main phases that are useful to comprehend the mechanism of this analysis:

1. In the first phase, the seismic hazard analysis is carried out: it is important to know how many earthquakes are expected in an area and how much is the power released by them. On this base, using databanks it is possible to create a graphic that represents how the seismic risk will change in terms of PGA and probability of occurrence. For example, Figure 2.11 represents the seismic hazard curve for three places located in Campania region, southern Italy. Is worth to be noticed that there are high probability of low power earthquakes and vice versa, as can be expected. Another important parameter in order to design properly these curves is the time interval. It is an important discriminant for the analysis: probability is a cumulative concept, so create a proper time interval helps to obtain results that are reliable for a further analysis of data. In order to realize these curves, it is necessary to take in account the history of earthquakes in a region.

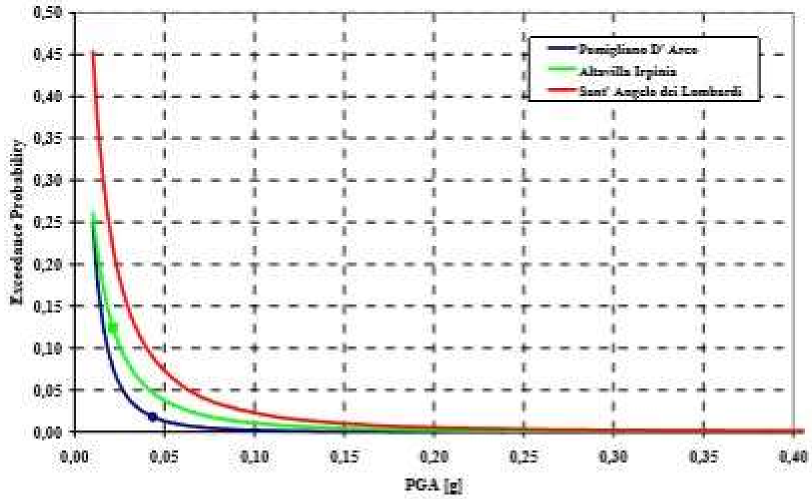


Figure 2.11: *seismic curves for three locations in southern Italy with a time interval of 1 year. As expected, the probability of an earthquake with low power is very high. Otherwise, a destructive event will have almost no probability to occur in the time interval considered.*

2. In the second phase, a failure model for all equipment is carried out: on the base of the previous analysis is possible to study how materials will react when there are earthquakes of different intensities. This phase is based on the fragility curves of materials used in the plant. To determine the curve is used the Equation (2.2). In it the probability of a failure (P_f) is the integral of the probability of the seismic demand D to exceed the seismic capacity C for all PGA possible values. The seismic demand is what is required by the earthquake in terms of shakes absorption; the seismic capacity what the equipment can absorb. From this formula is possible to draw the fragility curve of a material. An example of these curves is reported in Figure 2.12.

$$P_f = \int_0^{\infty} d(\Pr[D > C]) \tag{2.2}$$

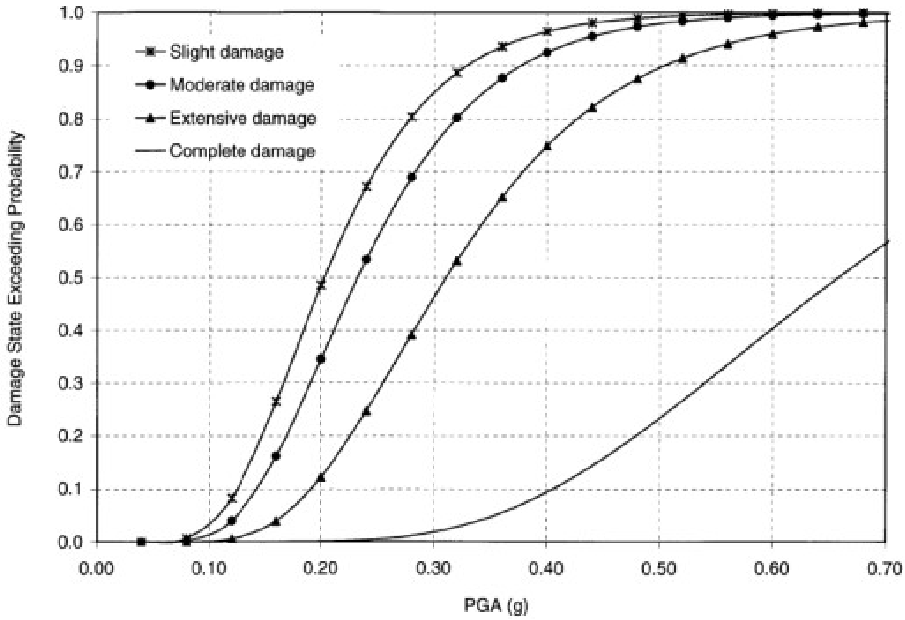


Figure 2.12: *example of fragility curves. The amount of damage to the equipment depends on the PGA. At medium PGA value, probability of an extensive damage is lower than that for a slight damage, as can be expected.*

Another important aspect is the progression of damage: the same earthquake, with the same PGA in a site, can create different damages. The probability of a little damage is higher than the probability of a heavy one because when the seismic demand exceeds the seismic capacity, the probability of a little excess is higher than the one of a huge excess.

2.3 Tank design features

Substance stocking is an important stage of all industrial operation: decide how to storage compounds used or produced by the plant can change the approach to the entire production.

There are many types of tanks, schematized in Figure 2.13 below.

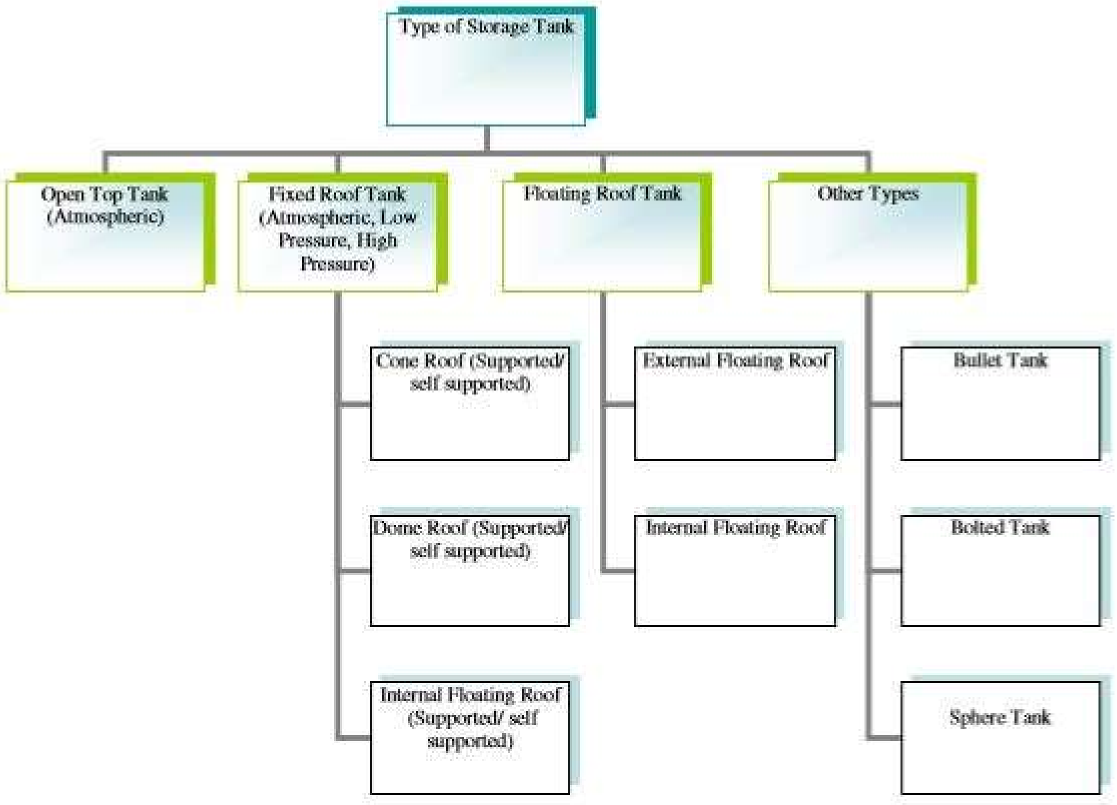


Figure 2.13: *types of tanks sorted by main characteristics and uses.*

Some of them are very simple to understand:

- Open top tanks: they have no roof. It is important to remember that only non-dangerous substances are allowed to be stored in them, such as cooling water.
- Fixed roof tanks: the roof can not move so they are susceptible to any pressure change in them. Also normal operation as loading and discharging can create a huge pressure drop with possible damages to the shell or the roof. It is worth to be noticed that there are many systems to avoid damages: a simple pipe that links the content of the tank to the external pressure could be a good solution, for atmospheric storage, or a valve calibrated with the right pressure, for high and low pressure storage. If the substance is dangerous, an appropriate purification process is needed before gas releasing.

For the analysis, two types of tanks have to be analysed properly: floating roof tanks and spherical pressurized tanks.

2.3.1 Atmospheric pressure tank with floating roof

One of the commonly used techniques for industrial storage of liquids is the floating roof thank. The scheme of this equipment is reported in Figure 2.14.

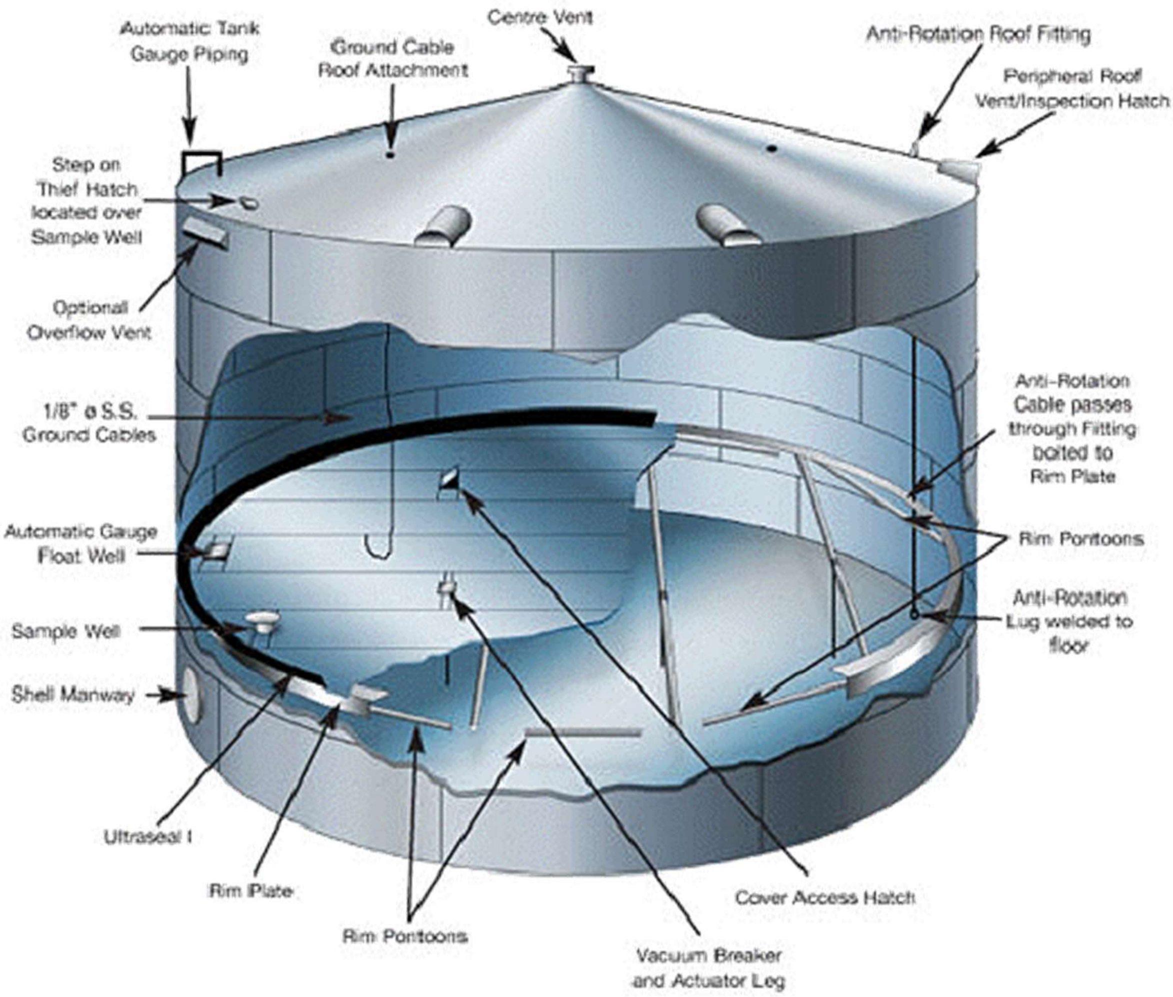


Figure 2.14: *example of floating roof tank with main equipment.*

This tank has two roofs and it is called internal floating roof: the second roof, placed on the top of the shell has the function to prevent atmospheric events to reach the floating roof. In fact, when an external floating roof tank is used, it is possible that the rain accumulates over the roof. This could lead to an imbalance of the structure and to the loss of roof sealing with substance spill. Also the snow could be a problem: the weight of a layer of snow could affect the pressure in the tank and all process in the plant with that. There are two solutions for this problem, the first one is to build an internal floating rood tank, the second involves the construction of a drainage system for rain water.

In this case study, an internal floating roof tank for benzene is considered. There are some particular features necessary to build this kind of storage utility:

- There are some vacuum breakers in order to allow the first filling of the tank and the air outlet. They are also useful in the emptying phase.
- For normal operation there are valves to keep constant the pressure in the tank.
- The seal is the most important part of the roof; it has to avoid any substance losses.
- The roof could rotate during operations, so it is important to use methods to avoid this movement. In Figure 2.14 there are some cables fixed to the external roof.

Other features are less important, such as manhole for inspections or wells for sampling the substance in the tank.

In order to improve the safety, a secondary containment should be provided.

For some precise construction specification, the appendix H of the "API 650" standard could be used.

2.3.2 Pressurized tank

Pressurized tanks have many uses. A small vessel could be used as gas bottle in houses and a big one as storage for an industrial production. There are a many possible shapes for a pressurized tank, in dependence from pressure of storage and substance to store. For large amount of compounds to store there are in particular two types of tanks:

- Bullet, a cylinder with a horizontal axis and two hemispherical ends in order to reach higher pressure. It is mostly used in private facilities as houses and gas stations because doesn't have many safety problems. Otherwise, sometimes also large storage plants are composed of this tanks.
- Spherical, the shape of the sphere allows the tank to reach the highest pressure possible in dependence to the shell material. They are the most used in the world in terms of storage of pressurized gases.

In Figure 2.15 below, an example of these types of tanks is reported.

(a) (b)

Figure 2.15: *examples of commonly used pressurized tanks. In (a) it is possible to see the bullet shape, used in medium pressure storage of LPG (in this case). In (b), a spherical tank in reported, placed in the center of an industrial plant. This type of tanks are used fot high pressure installations and large storage capacities.*

The study will last longer on the second one: is the facility used in large storage areas, as was the Juanico before the disaster. As stated before, the spherical shape allows to reach very high pressure. There is a correlation to determine how much of a substance a spherical tank can contain, known its material, its pressure and its volume. The Equation (2.3) is reported below.

$$M = \frac{3}{2} PV \frac{\rho}{\sigma} \tag{2.3}$$

In terms of design, the spherical tank is very simple: it is composed by a shell with two outgoing pipes, linked to two valves. These valves are used for incoming and outcoming fluxes of the substance. For a simple storage one valve will last, but often this tanks are used in continuum in a plant, so an entrance and an exit are required.

The next step in the analysis is to evaluate how to express the risk in term of probability.

Chapter 3
Statistic Approach

The next step in risk calculation concerns on identification of the proper approach to use. There are generally two possibilities: deterministic approach, usually used in mechanical risk calculation, and probabilistic approach, used in seismic risk assessments. The second one is more suitable for this analysis. Another problem is the conversion of mechanical data to probabilistic ones, so it is possible to write a code to resume both risk analysis in a unique one.

3.1 Deterministic or probabilistic approach?

In order to determine the chemical risk in an industrial plant located in a seismic area it is important to choose wisely the method to adopt: this method have to take into account all possible failure due either to breakage due to wear either to seismic shear rupture. There are two possibilities: the first one concerns a deterministic point of view, the second one a probabilistic analysis. Each one of these methods has its peculiar characteristics and for this reason they are used for different applications: in general, the deterministic approach is used in risk analysis for chemical plant, otherwise the probabilistic one is more suitable for seismic analysis. A risk assessment for a plant liable for both these types of accidents have to consider these two aspects at the same time. Which of them have the characteristics more suitable for this case study?

Before a decision on the path to choose, it is worth knowing main characteristics of both of them.

3.1.1 Deterministic approach

A deterministic mathematical model is meant to yield a single solution describing the outcome of some "experiment" with given inputs appropriate for the simulation. In this case all events are determined by a simple cause-effect chain; so if something happens, a consequence will occur with certainty. Starting from this assumption, it is possible to build a chain with scheduled responses to scheduled inputs, knowing in advance all possible events in a plant. Furthermore, it is possible to assume the causes once an effect is analysed, in order to going back gradually to the first event of the chain. Identified this event, that could also be only a small crack in a pipe, it is possible to project a plant where this could not happen. Done this, it is possible to state that the main event will not occur.

Now, it is possible to describe a methodology within chemical risk analysis, based on a deterministic approach. The main feature of this methodology is to analyse the cascade of events. An example of methods in this context is the fault tree.

As stated in section 2.1.4, the fault tree analysis is based on the concept of frequencies. Frequencies are an example of deterministic assumption: they express a number with certainty. For that sureness, engineers will know that if the frequency indicated is $4 \cdot 10^{-2}$ that equipment will suffer of four fault in one hundred years. Despite this evaluation seems good, that number of faults in little time interval will lead to accidents.

In order to use a deterministic approach in the analysis of an equipment's safety, it is worth noticing that rupture frequencies are obtained with the mean of all failure registered for that piece. Therefore, as stated before the frequencies have a distribution and the only value used is the mean.

In Table 3.1, it is possible to see how frequency used in chemical risk analysis can be expressed by a single value. Every event concerning the examined vessel will occur at least 3 times in 10000 years. No additional information are written in that table. In this case there aren't clues of the distribution shape of failure.

Table 3.1: *example of failure frequencies for a tank, sorted by possible scenarios and vessel size.*

Scenario	Vessel Size (dwt)	Frequency per year
Striking	30000	5.60E-04
Striking	30000	5.60E-04
Striking	30000	5.60E-04
Striking	45000	6.40E-04
Striking	45000	6.40E-04
Striking	45000	6.40E-04
Striking	80000	3.04E-04
Striking	80000	3.04E-04
Striking	80000	3.04E-04

Risk engineers use these data because with them it is possible to resume all risks in a unique number and so evaluate all possible improvements in order to reduce it.

Table 3.2 shows the collection data of failure frequency that it is useful to further analysis such as the possibility to convert them in a probabilistic behaviour.

Table 3.2: *example of failure frequency for a tank. It is worth noticing that the average value is used in fault tree analysis. The other two data concern the probabilistic distribution: 99% of failures happen between these values.*

Cause	**Leakage (L) or explosion (E)**	**Probability of occurrence (1/year)**		
		Minimum	Average	Maximum
Manufacturing error	L, E	$4.8\ 10^{-9}$	$4.3\ 10^{-8}$	$1.6\ 10^{-7}$
Material error	L, E	$5.3\ 10^{-8}$	$1.4\ 10^{-7}$	$3.1\ 10^{-7}$
Mechanical stress	L, E	$2.2\ 10^{-8}$	$8.6\ 10^{-8}$	$2.2\ 10^{-7}$
Corrosion	L, E	$2.2\ 10^{-8}$	$8.6\ 10^{-8}$	$2.2\ 10^{-7}$
Overfilling	L, E	$1.5\ 10^{-9}$	$2.9\ 10^{-8}$	$1.6\ 10^{-7}$
Wrong installation	L, E	$7.1\ 10^{-11}$	$1.4\ 10^{-8}$	$1.1\ 10^{-7}$
Disconnection of a non-empty cylinder	L	$9.6\ 10^{-9}$	$5.7\ 10^{-8}$	$1.8\ 10^{-7}$
Connection with incompatible material	L	$2.2\ 10^{-8}$	$8.6\ 10^{-8}$	$2.2\ 10^{-7}$
Fall	L	$2.2\ 10^{-8}$	$8.6\ 10^{-8}$	$2.2\ 10^{-7}$
Other	L, E	$2.5\ 10^{-7}$	$4.3\ 10^{-7}$	$6.7\ 10^{-7}$
Total	L, E	$7.4\ 10^{-7}$	$1.1\ 10^{-6}$	$1.4\ 10^{-7}$

Tanks to this table it is possible to analyse the main problem of the deterministic approach: whereas the mean states that there is only one manufacturing error every 25.255 million years, the third value states that that there is a possibility that an error occurs in 6.250 million years, an order of magnitude differences. In this case frequencies are really little and the difference is high but negligible. What will happen if frequencies are higher and this difference between the mean value and the last one is still one order magnitude? A 100 years' recurrence could become a 10 years one in one of the boundary. This situation is not sustainable in chemical and safety engineering.

For this reason, the probabilistic approach is used.

3.1.2 Probabilistic approach

The other possibility in risk assessment is the probabilistic approach. Unlike the previous one, the outcome of the analysis in not a number in this case, but only probability that the event will occur. The probabilistic approach simulates those future top events which, based on scientific evidence, are likely to occur.

In the context of chemical risk, probability refers to the frequency of occurrence or the return period of losses associated with hazardous events. The return period is a key concept in order to comprehend how probability is calculated. An example of return period calculation is reported below.

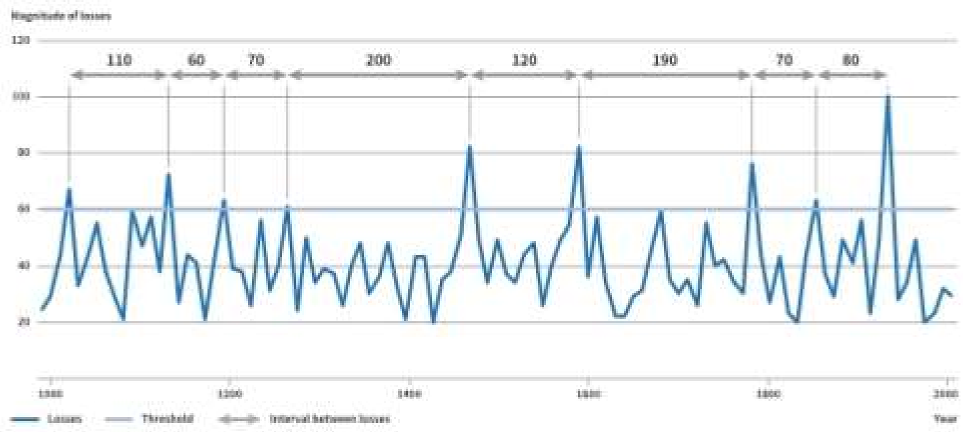


Figure 3.1: *possible losses in a plant in 1000 years. The relevant accident limit is placed where there is a loss of 60 in the order of magnitude. Over the graph are reported time-intervals between an accident and the subsequent. With these value, it is possible to evaluate the probability of a failure. The graph is only an example of possible scenarios in a plant.*

The Figure 3.1**Errore. L'origine riferimento non è stata trovata.** shows a record of top events: an atmospheric release. In one thousand years it is possible to select all these events with a magnitude higher than 60, that is assumed as the limits for relevant accidents. Measuring time period between an event and the subsequent one it is possible to have an idea of the trend of the system: time period ranges from sixty to two hundred years. The average of the period between losses is 100 years, so this time interval is called return period. In simple terms, one loss will occur almost every one hundred years. The annual probability of exceeding a loss characterized by a 100-years return period is 0.01 or 1%.

The probabilistic approach is based on the distribution of all possibilities for an event to happen. Also in the example, it is possible to see how time-intervals are widely different from each other. If there were an infinite number of trials, the result would be similar to a normal distribution.

It is possible to assess that a probabilistic approach can reach a better representation of the problem considered because of its capability of comprehend all possible solution and not only the central one, as the deterministic approach do.

To resume, a probabilistic approach is used to determine the likelihood of a number of different events. Otherwise, a deterministic approach fits perfectly to test an evacuation plan or mitigation strategy against a selected event. However, even if the interest is knowing a specific risk scenario for a specific event, it is possible to obtain it from a probabilistic assessment. In fact, probabilistic approaches allow to identify and model scenarios whilst also accounting for their return period. Measuring the likelihood of events means that decision-makers are more informed and better able to select appropriate strategies for different scenarios, as risk reduction in the case of relevant risks and risk transfer in the case of more high-impact, but less likely, events.

Assessing risk probabilistically is a challenge, particularly because of the number of factors to account for and because risk is not static and is influenced by a number of other drivers. But probabilistic risk assessments are becoming the standard for risk assessment because they are a comprehensive approach, taking into account all possible variations. These assessments provide with a means of quantifying the impact and likelihood of events, while also accounting for the associated uncertainty.

For these reasons, a risk assessment that comprehend both mechanical and seismic risk has to be written using the probabilistic approach. Whereas for a simple chemical risk assessment based only on mechanical failure the deterministic model fits well; in a seismic analysis, that is based on the probability of the PGA to exceed the seismic capacity of a tank, only a probabilistic model can generate a good report.

It is worth to be noticed that final results of a probabilistic analysis are resumed in distribution graphs. It is important to know how to read these graphics in order to understand them in the right way. A resuming table that reports the mean values for all risks will be very useful for a quick idea of results.

3.2 Data conversion

The chosen method is the probabilistic one but, as stated in the previous paragraph, failure frequencies are presented as numbers and not with their probabilistic distribution.

In order to use failure frequencies in the system, it is important to convert these value properly. In statistical terms the failure rate of mechanical components is described with a lognormal distribution. The formula of this distribution is reported in Equation 3.1.

$$x = e^{\mu+\sigma Z} \tag{3.1}$$

"Random variable X has the lognormal distribution with parameters $\mu \in R$ and $\sigma \in (0,\infty)$ if $ln(X)$ has the normal distribution with mean μ and standard deviation σ. The parameter σ is the shape parameter of X while e^{μ} is the scale parameter of X."[2] Z represents a constant.

In Figure 3.2 is reported an example of lognormal distribution.

It is worth to be noticed that determining the shape of the distribution is a key parameter in the data conversion. To do that, some equations are needed:

1. The first thing to do is to choose data from a databank. Data has to have the form of Table 3.2***Table 3.***, so it is possible to evaluate all parameters. The upper boundary (UB) and the lower one (LB), expressed in event over year, are fundamental to calculate the error e_f with the (3.2).

[2] Definition of "Lognormal distribution" by math department of the University of Alabama, http://www.math.uah.edu/stat/special/LogNormal.html, visited on 20.9.2016.

$$e_f = \sqrt{\frac{UB}{LB}} \tag{3.2}$$

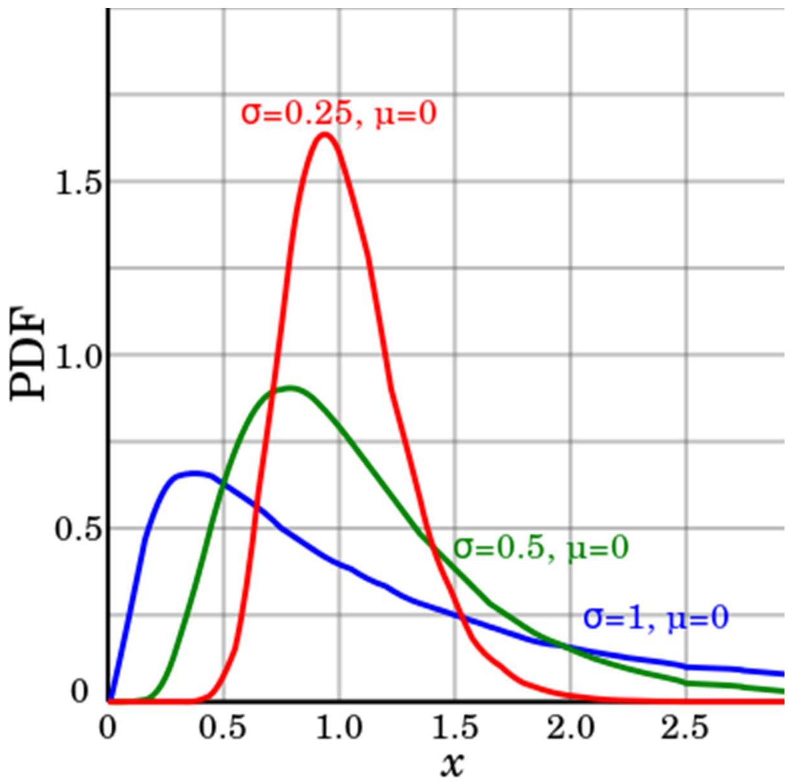


Figure 3.2: *example of lognormal distribution. As can be seen in the image, the standard deviation (σ) affects the shape of the distribution: lower the σ, higher the symmetry. The mean (μ) affects the position.*

Now, the calculation of the standard deviation is simple, using the (3.3).

$$\sigma = \frac{\ln e_f}{1.645} \tag{3.3}$$

2. For the calculation of μ, the mean, it is necessary to introduce another parameter, *v*, as in the (3.4). In order to do that, the medium value for the frequency (m) is needed. This value is reported on the central column in Table 3..

$$v = m^2 * (e^{\sigma^2} - 1) \tag{3.4}$$

3. Last passage concerns on μ calculation. Tanks to the definition of *v*, it is a simple operation that can be seen in (3.5).

$$\mu = \frac{\ln m^2}{\sqrt{v + m^2}} \tag{3.5}$$

With this procedure, used for the vector of all frequencies, it is possible to generate the lognormal distribution for mechanical faults. These probabilities need now to be combined with the seismic ones in order to calculate the total value of the risk.

3.3 Numerics

To simulate all possible PGAs in a seismic zone and to calculate as precisely as possible the value of the risk, a Matlab code was written.

This program is formed by three parts. The first and second require the calculation of a different aspect of the risk, the third one resume all risks using the fault tree analysis.

3.3.1 Seismic failure

The first part of the code concerns about the calculation of seismic risk. In order to resume how the calculation is performed, a part of the program is reported below.

```
R=xlsread('DistribuzioniOsoppo.xlsx', 'distanza', 'A1:A20');
M=xlsread('DistribuzioniOsoppo.xlsx', 'Magnitudo', 'A1:G1');
MP=xlsread('DistribuzioniOsoppo.xlsx', 'matrice', 'A1:G20');
F=xlsread('DistribuzioniOsoppo.xlsx', 'Frequenza', 'A1:G1');

r=length(R);
m=length(M);
logPGA=[];
for i=1:r
    for j=1:m
        logPGA(i,j)=-3.37+(1.93-0.203*M(j)).*M(j)+(-
3.02+0.00744*M(j)^3)*log10(sqrt(R(i)^2+7.3^2));
    end
end

sigma=0.358;
mu2=0.38;
sigma2=0.8;
mu3=1.18;
sigma3=0.61;
PeqRS1=[];
PeqRS2=[];
PeqRS3=[];
PeqRS1=zeros(rand,1);
PeqRS2=zeros(rand,1);
PeqRS3=zeros(rand,1);

for i=1:rand
%     PGA1=10.^(logPGA+sigma);
    PGA1=random ('norm',logPGA,sigma);
    PGA=(10.^PGA1).*9.81;
    RS3eq= cdf('logn',PGA,mu3,sigma3);
    RS2eq=cdf('logn',PGA,mu2,sigma2);
    Prs1=(1-RS2eq).*(MP./100);
    Prs2=(RS2eq-RS3eq).*(MP./100);
    Prs3=RS3eq.*(MP./100);
```

```
        PfRS11=sum(Prs1).*F;
        PfRS1=sum(PfRS11(:));
        PfRS22=sum(Prs2).*F;
        PfRS2=sum(PfRS22(:));
        PfRS33=sum(Prs3).*F;
        PfRS3=sum(PfRS33(:));
        PeqRS1(i)=[PfRS1 ];
        PeqRS2(i)=[PfRS2 ];
        PeqRS3(i)=[PfRS3 ];
        i=i+1;
end

PeqRS =[PeqRS1 PeqRS2 PeqRS3].
```

The first part uses data by the national institute of geology and volcanology (INGV), were it is possible to find the databank concerning the seismic risk of every area of Italy. These value were reported in an excel document divided in distances, magnitudes (both of them using the mean value of the interval considerate), frequencies and the matrix of possible probabilities.

Using a random value of distance and magnitude, it is possible to simulate an earthquake with a defined PGA, calculated and expressed in this case in logarithmic scale. The next step concerns the calculation of the lognormal distribution of PGAs, before risk calculation.

It is important to know that there are three possibilities for a seismic impact in a plant, divided by the dimension of the leakage. To obtain a precise representation, all possibilities have to be examined. Next step defines three vectors, one for each failure severity. Then, calculating the cumulative distribution function using lognormal and parameters, it is possible to achieve a result expressed by a matrix of seismic risk.

3.3.2 Mechanical failure

In the mechanical part, the procedure replicates the procedure of section 3.2. As stated before, some data about failure frequencies are needed: the medium value, upper and lower limits. After the calculation of the error and other variables as described before, the two cycles "for" allows to calculate the distribution of fault probabilities with the lognormal trend.

```
m= [0.0016 0.0011 0.0028];
LB=[0.0011 0.0007 0.0021];
UB=[0.0023 0.0016 0.0037];

ef=sqrt(UB./LB);

sig=log(ef)/1.645;
v=(m.^2).*(exp(sig.^2)-1);
sigma=sig;
mu = log((m.^2)./sqrt(v+m.^2));

T=50;
X=[];
for i=1:rand
    for j=1:length(m)
        X(i,j)=random ('logn',mu(j),sigma(j));
          if (X(j)<=UB(j) && X(j)>=LB(j))
```

```
            X(i,j)=X(i,j);
          else
              if (X(j)<UB(j))
                  X(i,j)=UB(j);
              end
              if (X(j)>LB(j))
                  X(i,j)=LB(j);
              end
          end
%           DF(i,j) = pdf('logn',X(i),mu(j),sigma(j));
          P1(i,j) = X(i,j);
          RS1(i,j) = P1(i,j).*0.84;
          RS2(i,j) = P1(i,j).*0.08;
          RS3(i,j) = P1(i,j).*0.08;
    end
end
PmRS1=sum(RS1,2)-(RS1(:,1).*RS1(:,2))-(RS1(:,2).*RS1(:,3))-
(RS1(:,3).*RS1(:,1));
PmRS2=sum(RS2,2)-(RS2(:,1).*RS2(:,2))-(RS2(:,2).*RS2(:,3))-
(RS2(:,3).*RS2(:,1));
PmRS3=sum(RS3,2)-(RS3(:,1).*RS3(:,2))-(RS3(:,2).*RS3(:,3))-
(RS3(:,3).*RS3(:,1));

PmRS =[PmRS1 PmRS2 PmRS3].
```

The last passages highlight how the risk for the three pieces of equipment is calculated and summed in a unique vector.

The calculation of single contribution for mechanical and seismic risk is done.

3.3.3 Combination of risks

To sum up the two contribution a modification of the fault tree technique is used: the two branches represent the calculation of mechanical and seismic risk that will be summed in an unique distribution as below.

```
PRS1=PeqRS1+PmRS1-(PeqRS1.*PmRS1);
PRS2=PeqRS2+PmRS2-(PeqRS2.*PmRS2);
PRS3=PeqRS3+PmRS3-(PeqRS3.*PmRS3);
P=[PRS1 PRS2 PRS3].
```

The three contribution are computed in separate equations and then resumed in a vector. During the summation of probabilities due to the operator "or" of the fault tree, a correction factor is used: in order to avoid possible double counting of probabilities, to the sum is subtracted the product of the two frequencies.

It is wort to be noticed that some the one presented in this chapter is a simplified version of the total code: the complete one is attached in the Appendix. Furthermore, all quantities present in this code are used as an example of calculation: in case studies of the chapter 4, the seismic location parameters and the mechanical failure frequencies will change. Also, the conformation of the fault tree will change due to the influence of seismic value also in the mechanical part.

Figures presenting results are also described in the complete code at the end of this discussion.

Chapter 4

Case Studies

In order to perform a good simulation, it is important to define proper case studies: all data required by the program had to be chosen wisely considering all possible condition for failure. The two fault trees can be build. As case studies, an atmospheric tank is located in Osoppo (UD) and a pressure vessel in Priolo (SR), two areas with high seismic risk with different characteristics in our country. As comparison terms, also the risk in Falconara Marittima (AN) will be calculated for both tanks. The presence of seismic risk influences the two fault trees, so they need some correction due to earthquake fragility.

4.1 Atmospheric floating roof tank

The first case study concerns a floating roof tank containing benzene at atmospheric pressure. As in 2.3.1, technical knowledge in tank design is well established, with global standard. In this contest, it is simple to design a storage vessel based on specification in the Table 4.1.

Table 4.1: *technical specification for the atmospheric tank of the case study.*

Height	11.5 m
Diameter	7.6 m
Maximum storage	500 m^3

These data have a relevant importance for the study of possible consequences of a relevant accident as an atmospheric release: knowing the amount of stored substance allows to simulate possible accidental scenarios; knowing the form factors involved, instead, the spill velocity of the liquid.

In order to analyse all possible fault of the floating roof tank, Figure 4.1 represents a scheme of this equipment.

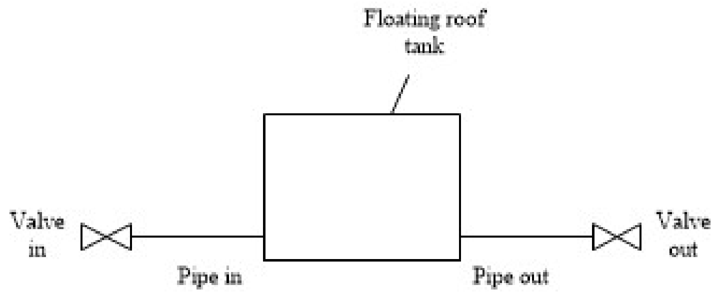


Figure 4.1: *simplified scheme of the vessel. With the floating roof tank, there are also the two pipes and valves for liquid income and outcome.*

Starting from this scheme, it is possible to define all the risk associated with the equipment. The first part of the risk analysis will concern those risks that are linked with mechanical components.

4.1.1 Stored substance and chemical risk

In this case study, the substance stored in the floating roof tank is benzene. There are a large number of industrial plant producing this chemical, one of the most used in the word.

In safety terms, benzene is a dangerous substance. It is associated with seven hazard sentences by the GHS (the international system for chemical classification ad labelling):

- H225, highly inflammable liquid and vapour.
- H304, may be fatal if swallowed and enters airways.
- H315, causes skin irritation.
- H319, causes serious eye irritation.
- H340, may cause genetic defects.
- H350, may cause cancer.
- H372, causes damage to organ (blood) through prolonged or repeated exposure.

Furthermore, benzene is a volatile substance so, in case of vessel rupture, there are three possibilities for an accidental scenario: if the benzene doesn't ignite, a toxic dispersion will surround the incidental area; if it ignites immediately or from the pool formed on the ground, pool fire or jet fire will develop near the vessel; if vapour doesn't ignite and the benzene vaporizes forming a cloud, a trigger will cause a flash fire or an explosion (UVCE).

In the tank considered in this simulation, some possible faults are identified. Each one of these faults can cause the top event (a release). For a general view, in the Table 4.2 are reported every single fault and its frequency.

Table 4.2*: failure frequencies of components involved in the study. Reported values are three in order to calculate the probabilistic distribution in a lognormal form.*

Fault Type	Frequencies		
	Lower Bound	**Median Value**	**Upper Bound**
Spill on roof	$1.1\ 10^{-3}$	$1.6\ 10^{-3}$	$2.3\ 10^{-3}$
Sunken roof	$5\ 10^{-4}$	$9\ 10^{-4}$	$1.4\ 10^{-3}$
Vessel leakage	$9\ 10^{-4}$	$1.4\ 10^{-3}$	$2\ 10^{-3}$
Pipe release (all causes) *	$2\cdot10^{-8}$	$4.8\cdot10^{-8}$	$1.12\cdot10^{-7}$
Valve release **	$2.4\cdot10^{-8}$	$1.0\cdot10^{-7}$	$4.1\cdot10^{-7}$
Acoustic alarm failure	$3.8\cdot10^{-6}$	$2.1\cdot10^{-5}$	$5.3\cdot10^{-5}$
Operator error ***	0.001		

(*) pipes' frequencies are calculated considering a length of 1m and a 0.4m diameter.
(**) the valves used to regulate the income and the outcome from the tank are defined as a fail-to-close check valves.
(***) the human error is defined as a probability.

Possible problems arise when the roof leaks, in terms of rupture of seals or roof sinking, or when the vessel itself develop a leakage. Other possibilities concern the fault in an external part of the vessel such as the pipe for the income and outcome or valves regulating these flows. Last but not least, the human error is a concrete factor: it is computed an accidental error of the operator and not a deliberate sabotage.

In Figure 4.2, the fault tree for mechanical risk is reported.

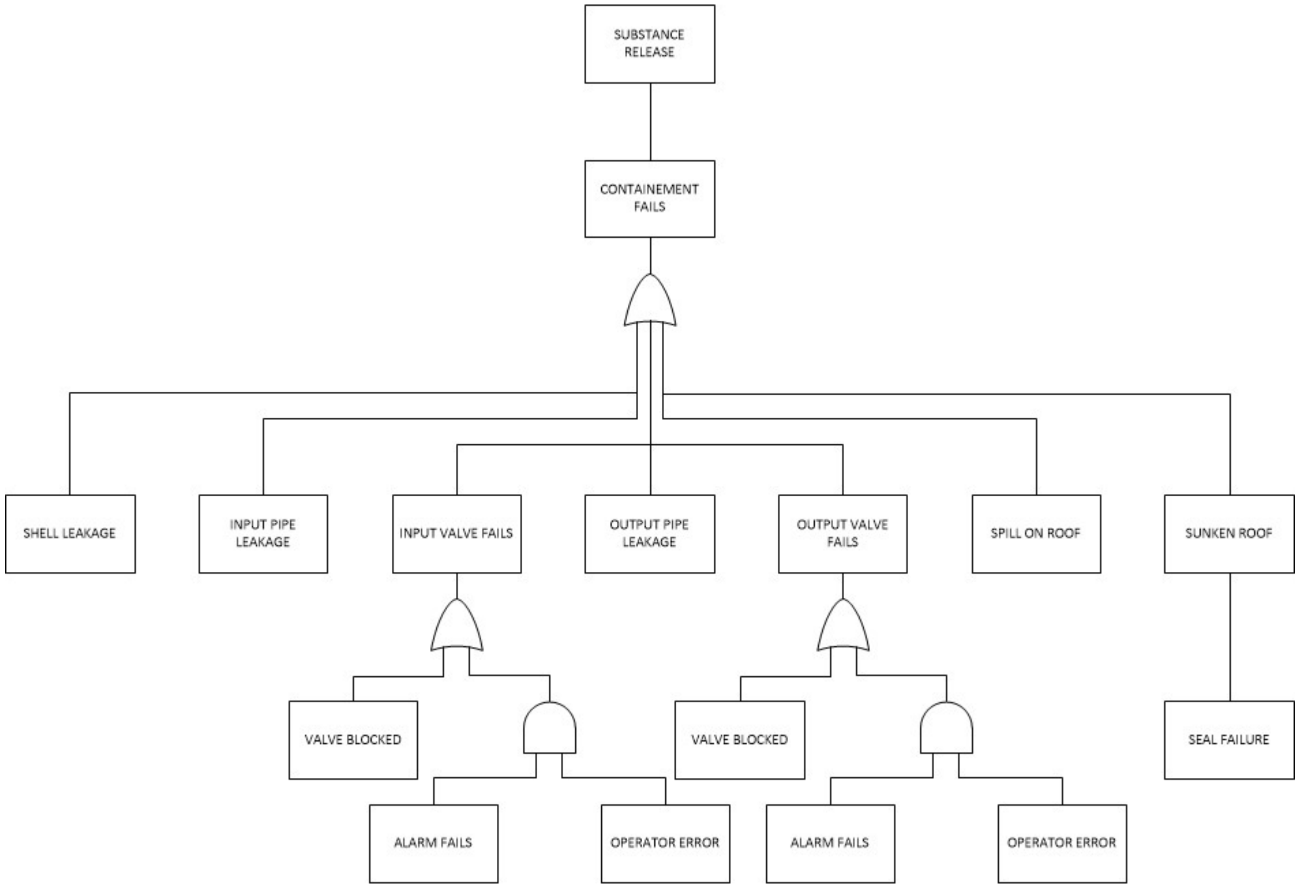


Figure 4.2: *fault tree for a floating roof tank concerning only mechanical accidents.*

4.1.2 Seismic risk

Applying the seismic risk to the mechanical fault tree allows some modification: in Figure 4.3 the complete fault tree with seismic effect is reported. This tree guarantees a god estimation of all possible damages due to earthquakes, wherever the plant is located.

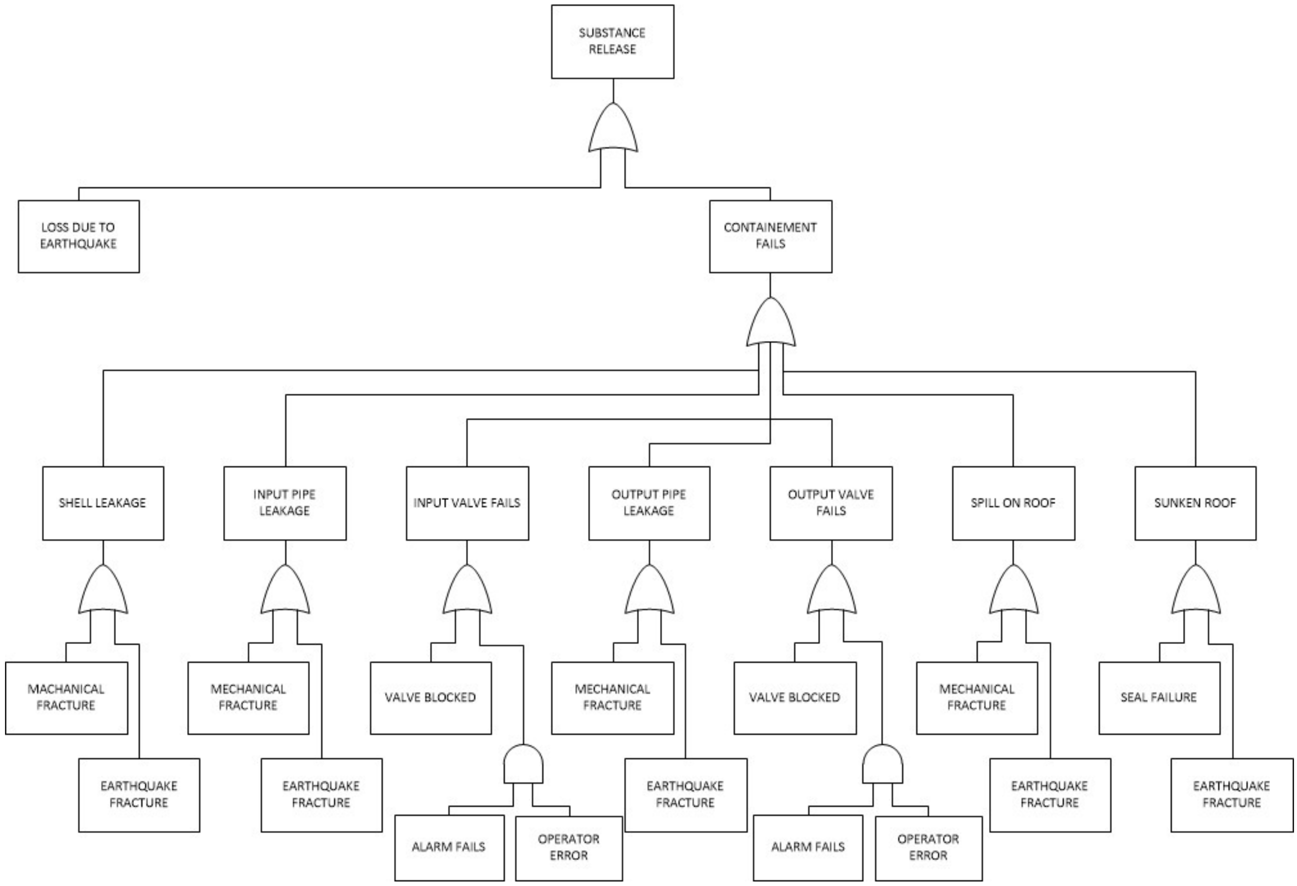


Figure 4.3: *fault tree for a floating roof tank located in a seismic area.*

In Figure 4.3 it is possible to notice that each branch of the fault tree is influenced by a new contribution due to seismic risk. Valves don't present this risk because their seismic capacity is high and the effect of an earthquake on them is negligible compared with other equipment.

Data used in calculation of components depending on the tank are:

- $\sigma_1 = 0.358$; this value represents the form factor in order to create the lognormal distribution.
- $\mu_2 = 0.38$; mean value of fragility distribution for medium holes.
- $\sigma_2 = 0.8$; shape factor of fragility distribution for medium holes.
- $\mu_3 = 1.18$; mean value of fragility distribution for large holes.
- $\sigma_3 = 0.61$; shape factor of fragility distribution for large holes.

For pipes, the situation is similar in terms of data requirements, but values are different:

- $\mu_2 = 0.4522$; mean value of fragility distribution for medium holes.
- $\sigma_2 = 0.39$; shape factor of fragility distribution for medium holes.
- $\mu_3 = 0.7116$; mean value of fragility distribution for large holes.
- $\sigma_3 = 0.20$; shape factor of fragility distribution for large holes.

These specific are referred to a pipe with an undefined diameter. Although there are specific curves for the diameter considered in this study (0.4 m), their contribution in the calculation of the risk will cause an inversion between the light risk and the medium one: this last will have a higher probability, an illogical conclusion. To have a more precise idea of the condition that will cause a pipe leakage, in Figure 4.4 the fragility curves for these equipment are reported.

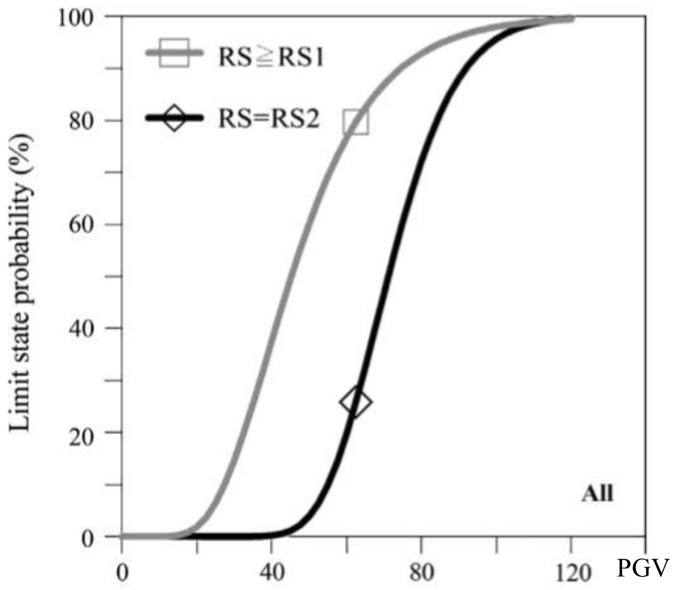


Figure 4.4: *fragility curves for pipes. It fits well with all possible diameters. The black curve represents the possibility of a large damage, the grey one the probability of a medium one. In abscissa the peak ground velocity (PGV) is reported.*

4.2 Pressurized tank

The second case study concerns a pressurized spherical vessel for LPG storage. Some technical specifications are needed also in this case study to design a proper scenario. Tank data are reported in Table 4.3, with reference to the paragraph 2.3.2.

Table 4.3: *technical specification for the pressurized spherical tank of the case study.*

Radius	6.2 m
Maximum storage	1000 m^3

With these data it is possible to assess an event tree concerning how the substance will interact with the surrounding area. Knowing the amount of stored compound is a key parameter in order to evaluate possible consequences and also the tank size in useful for pressure calculation.

A simplified scheme of the equipment is reported in Figure 4.5. This image allows consideration on possible fault.

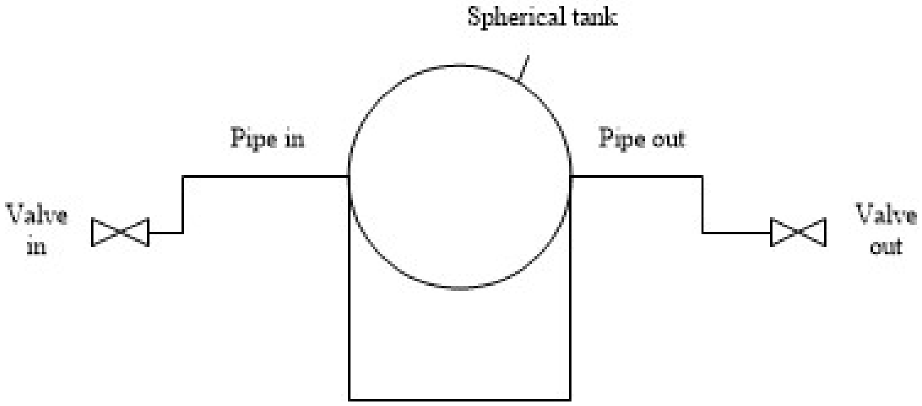


Figure 4.5: *simplified scheme of the pressurized vessel. In addition, also valves for the income and outcome of the substance, with relatives pipes, are reported, in order to represent the most likely scenario for the equipment construction.*

This figure allows a preliminary analysis that can be developed in a proper mechanical risk assessment.

4.2.1 Stored substance and chemical risk

The stored substance in this case study is LPG (liquefied petroleum gas). This substance is a mix of propane and butane with other component in negligible quantities. At atmospheric pressure and temperature, each of components is a gas phase. For transport and storage necessities, it is compressed and liquefied.

LPG is a clean combustible with no environmental dangers and few residues. Its dangerous potential is due to the high pressure storage and to the high flammability. The GSH associate it with four hazard statement:

- H220, extremely flammable gas.
- H280, contains gas under pressure, may explode if heated.
- H340, may cause cancer.
- H350, may cause genetic defects.

This substance is used in some civil applications in many countries for economic reasons. It is also adopter in rural heating plant: it is simple to provide a house with a little bullet tank for heating and cooking facilities. Another use regards the automotive sector: it is a combustible for internal combustion engines, spread all over the world. One more useful function is the refrigeration one: in industrial productions, exist some refrigerating mixes for off-the-grind processes.

In terms of possible accidental scenarios, a fire or an explosion are the more probable ones: it is very simple for a dispersion of the gas to find a trigger and ignite. If the reaction causes an overpressure, then an UVCE will develop; else, all types of fire are possible.

The next step of the analysis is to identify possible faults that can cause the top event. Some frequencies reported in Table 4.4 are the same of the previous case because the equipment are the same.

Table 4.4: *failure frequencies of components involved in the study. Reported values are three in order to calculate the probabilistic distribution in a lognormal form. The tank presents three values, in order to represent all possible sizes for a leakage in a pressurized spherical vessel.*

Fault Type	**Frequencies**		
	Lower Bound	**Median Value**	**Upper Bound**
Small vessel leakage (< 25mm)	$4.6 \cdot 10^{-5}$	$8.1 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$
Medium vessel leakage (25-50mm)	$2.5 \cdot 10^{-5}$	$5.2 \cdot 10^{-5}$	$9.5 \cdot 10^{-5}$
Big vessel leakage (50-150mm)	$1.4 \cdot 10^{-6}$	$9.7 \cdot 10^{-6}$	$3.6 \cdot 10^{-5}$
Pipe release (all causes) *	$2 \cdot 10^{-8}$	$4.8 \cdot 10^{-8}$	$1.12 \cdot 10^{-7}$
Valve release **	$2.4 \cdot 10^{-8}$	$1.0 \cdot 10^{-7}$	$4.1 \cdot 10^{-7}$
Acoustic alarm failure	$3.8 \cdot 10^{-6}$	$2.1 \cdot 10^{-5}$	$5.3 \cdot 10^{-5}$
Operator error ***	0.001		

(*) pipes' frequencies are calculated considering a length of 1m and a 0.4m diameter.
(**) the valves used to regulate the income and the outcome from the tank are defined as a fail-to-close check valves.
(***) the human error is defined as a probability.

Possible problems arise in the income/outcome line as in the previous case study. The situation of the vessel changes a lot in this case: there are three possible size for the leakage with three different probability distributions. It is important to implement well this fact in the code, in order to avoid possible miscalculations.

The last possibility for a fault is the human error. As stated before, the considered error is an accidental one. The sabotage is not computed because it isn't a mechanical or a seismic fault but a deliberate damage to the plant.

In Figure 4.6 is reported the fault tree for only mechanical components.

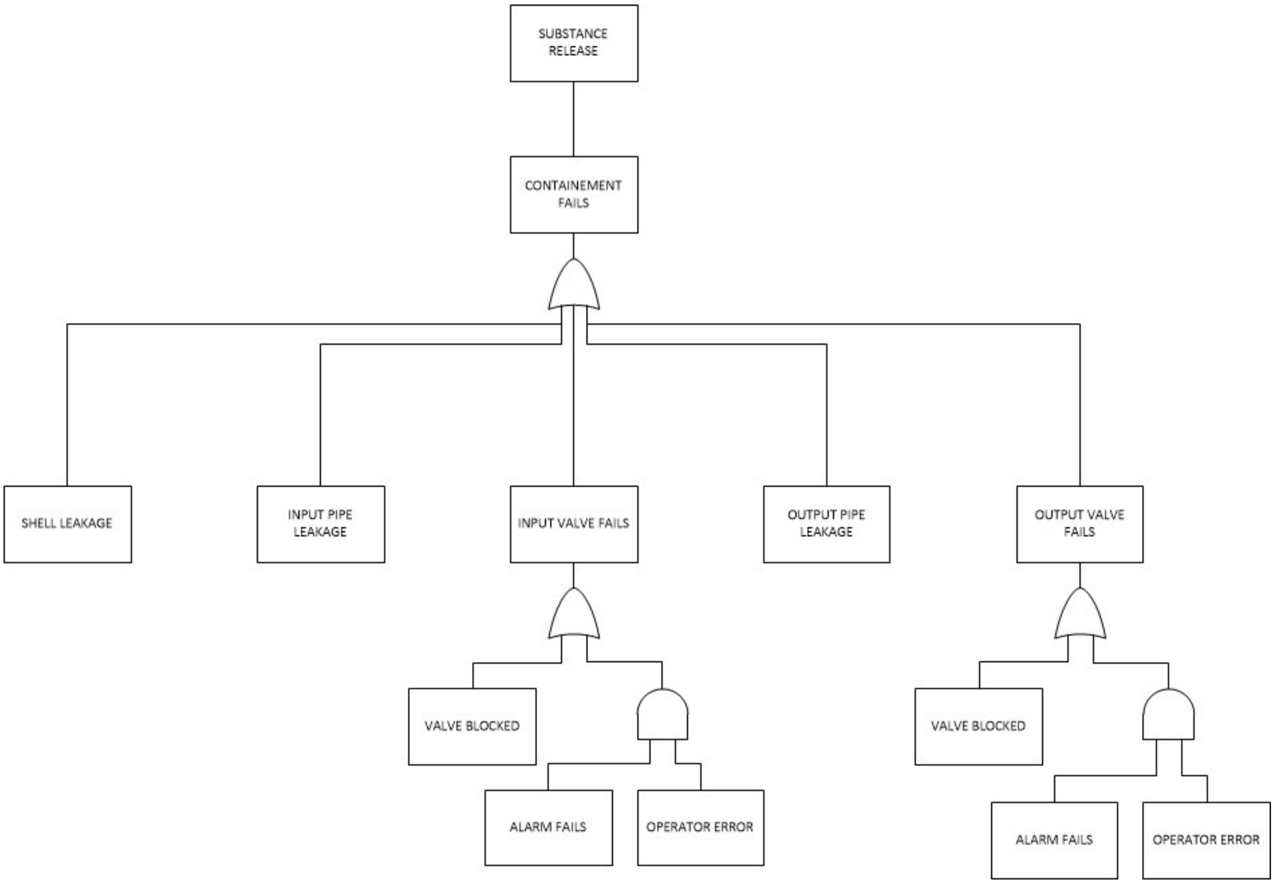


Figure 4.6*: fault tree for a pressurized spherical vessel only concerning mechanical accidents.*

4.2.2 Seismic risk

Next step is the modification of fault tree in Figure 4.6 in order to add also seismic faults. Also in this case, the contribute of the operator error is negligible, as it is the possibility of a valve leakage. The results of this analysis are reported in Figure 4.7.

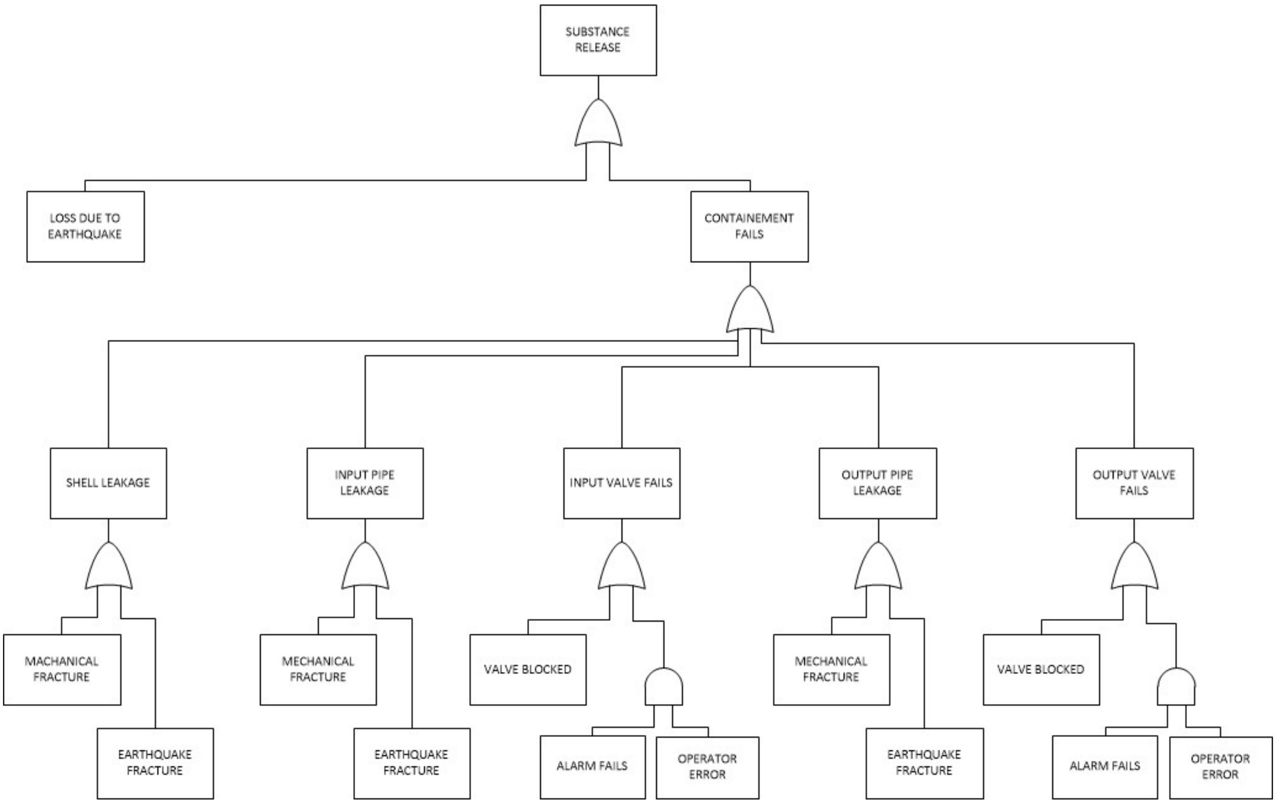


Figure 4.7: *fault tree for a spherical pressurized vessel located in a seismic area.*

Value of fragility for pipes are considered the same of the previous case, with a pipe of 1m length and 0.4 m diameter. Fragility values for pressurized tank are different in respect to the previous one:

- μ_1 = 0.83; mean value of fragility distribution for small holes.
- σ_1 = 0.99; shape factor of fragility distribution for small holes.
- μ_2 = 1.85; mean value of fragility distribution for medium holes.
- σ_2 = 0.85; shape factor of fragility distribution for medium holes.
- μ_3 = 4.91; mean value of fragility distribution for large holes.
- σ_3 = 0.84; shape factor of fragility distribution for large holes.

With these data, risk calculation is possible.

4.3 Plant Location

The choice for a proper location in order to represent in the better way the seismic risk is the key point for this analysis. As stated in 2.2.2, there are two great seismic areas in Italy: the first one is in the north, in Friuli, where Osoppo (UD) is located; the second one comprehend the Apennines and the occidental part of Sicily where are located Priolo Gargallo (SR) and Falconara Marittima (AN). This last place isn't part of the area with the highest seismic risk, but the proximity with the Apennines results in the possibility of huge earthquakes. To go further in the representation, it is important to locate the floating roof tank in an area that already is used with that intent.

4.3.1 Osoppo

Osoppo, in Friuli, has already a storage area for various amount of substances. For this reason, the floating roof tank is placed there. From data of national institute of geology and volcanology (INGV) it is possible to find the map of the area in terms of possible values of PGA. It is possible to see, in Figure 4.8, how the seismic risk is very high and all industrial facility located there have to pay attention on the earthquake probability. Furthermore, all risk analysis has to satisfy the requirements of Seveso III, considering effects of seismic domino effects.

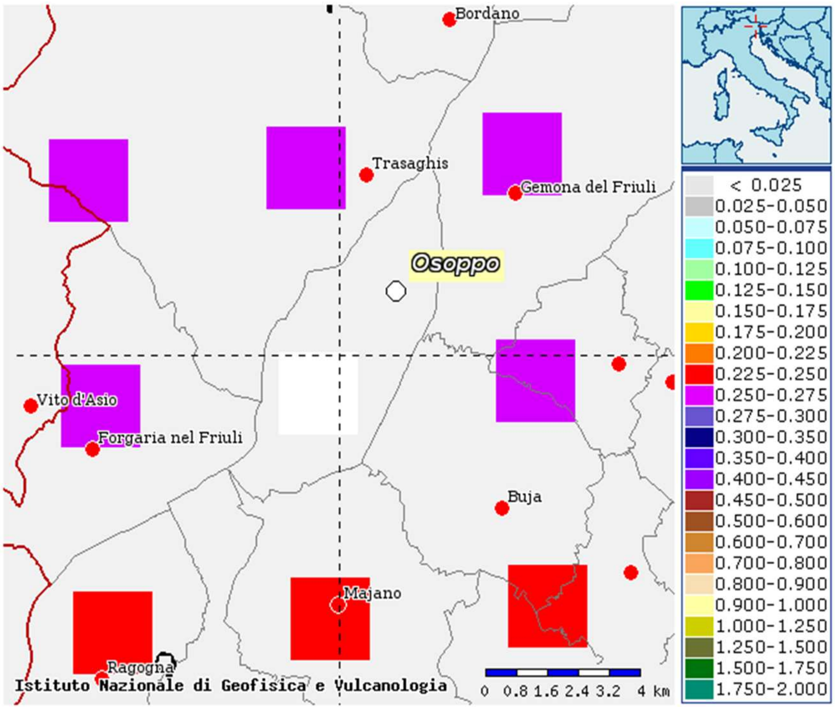


Figure 4.8*: seismic map of Osoppo. Possible PGAs in case of earthquake are represented in coloured squares. On the right, the legend presents the scale: the area is subject to earthquake with PGAs from 0.225g to 0.275g.*

Table 4.5*: probabilities of an earthquake in Osoppo, sorted by magnitude in Richter scale (in the columns) and distance (in the rows) from the epicentre. The value of these quantities are the mean of border values of the interval.*

Distance (km)\Magnitude	4,25	4,75	5,25	5,75	6,25	6,75
5	10,20	24,3	19,67	13,4	7,75	1,03
15	0,45	2,62	4,67	5,63	5,27	0,92
25	0,00	0,01	0,31	1,10	1,67	0,36
35	0,00	0,00	0,00	0,08	0,36	0,09
45	0,00	0,00	0,00	0,00	0,06	0,03
55	0,00	0,00	0,00	0,00	0,01	0,01

With this map, the INGV gives also a table concerning the probability of a seismic event, sorted by the distance and the magnitude. It is possible, so, noticing the influence of all possible seismic events on the system. In this case, the floating roof tank is influenced by earthquakes with epicentre 60 km away from its location. These earthquakes have a magnitude that can vary from the fourth to the seventh degree of Richter's scale. These values are reported in Table 4.5.

A last consideration for seismic risk is the presence of a frequency factor: it represents the frequency of return of an earthquake with a chosen magnitude. The calculation of this vector can be performed using the Equation 4.1:

$$f_m = \frac{10^{(a-bM)}}{50} \tag{4.1}$$

With this equation it is possible to calculate the frequency distribution that is shown in Figure 4.9.

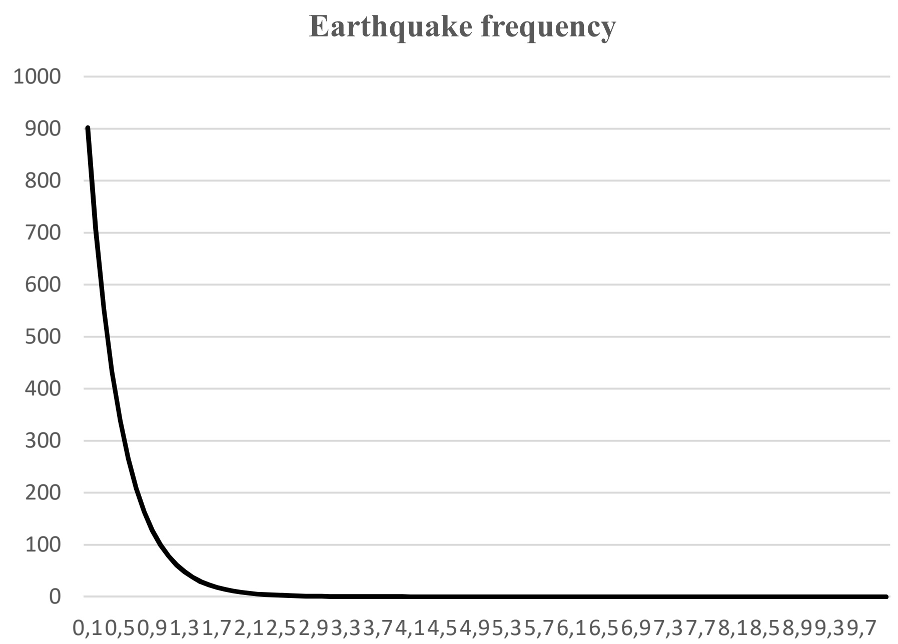


Figure 4.9: *graph of the earthquakes probability in Osoppo (UD).*

This equation highlights the frequency dependence upon three parameters. Terms *a* and *b* are constant derived by seismic analysis of the area. The third term is the simplest: in fact, *M* represents the magnitude of the earthquake as in Table 4.5. It is worth to be noticed the parameter 1/50: it represents the return period considered by INGV in the calculation of the earthquake matrix.

With the map presented in Figure 4.10, below, is possible to identify the seismic area in which the plant is build and, then, choose right parameters.

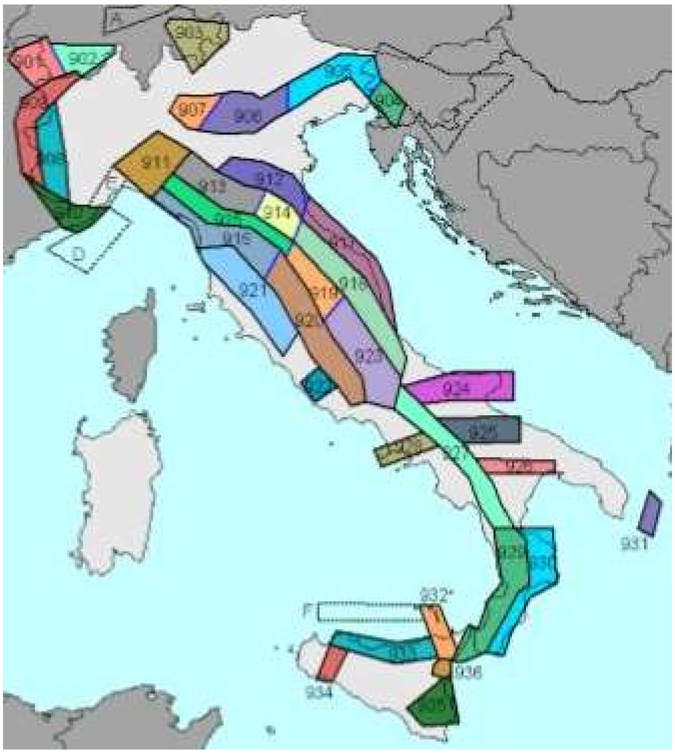


Figure 4.10: *seismic areas in Italy for frequencies calculation. In each area, parameters used for the calculation are different.*

Osoppo is located in the area 905. Required data are:

- *a* = 4,76;
- *b* = 1,06.

The vector used in this case study and derived as described above is reported in Table 4.6.

Table 4.6: *frequency vector of earthquake for Osoppo (UD).*

Magnitude	**4.25**	**4.75**	**5.25**	**5.75**	**6.25**	**6.75**
Frequency	$3.5977\ 10^{-2}$	$1.0618\ 10^{-2}$	$3.134\ 10^{-3}$	$9.25\ 10^{-4}$	$2.73\ 10^{-4}$	$8.05\ 10^{-5}$

4.3.2 Priolo

The location chosen for the pressurized spherical tank is Priolo (SR), a town in Sicily. This choice is not casual: the natural conformation of the place, with a large gulf perfect for a harbour, was chosen in 1949 for one of the biggest industrial district of Italy. What was not taken into account is the seismic danger of the area. This risk has two components: the first one is due to the collision between the Euroasiatic and the African plaques (the so called "faglia dello Stretto" and "Ibleo Maltese"), the second is the presence of Mount Etna, the major active volcano in Italy. This combination of factor originates one of the highest seismic risk area of Italy.

From data of INGV, it is possible to find the seismic map of the area, reported in Figure 4.11.

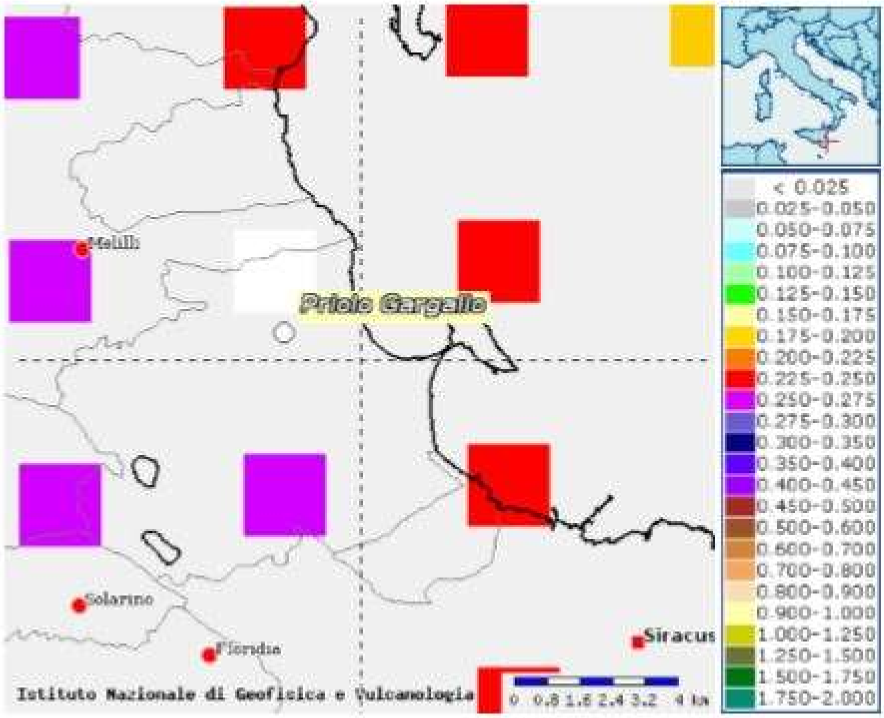


Figure 4.11: *seismic map of Priolo. Possible PGAs in case of earthquake are represented in coloured squares. On the right, the legend presents the scale: the area is subject to earthquake with PGAs from 0.225g to 0.275g.*

The situation of two location seems similar from the comparison of two images. Table 4.7 will chance this impression.

Table 4.7: *probabilities of an earthquake in Priolo, sorted by magnitude in Richter scale (in the columns) and distance (in the rows) from the epicentre. The value of these quantities are the mean of border values of the interval.*

Distance (km)\Magnitude	4,25	4,75	5,25	5,75	6,25	6,75	7,25	7,75
5	3,580	11,400	13,500	13,400	11,200	8,030	5,050	0,726
15	0,037	0,579	1,920	3,670	5,160	5,760	5,250	0,912
25	0,000	0,000	0,036	0,448	1,240	2,120	2,740	0,578
35	0,000	0,000	0,000	0,010	0,210	0,605	1,040	0,253
45	0,000	0,000	0,000	0,000	0,011	0,112	0,266	0,073
55	0,000	0,000	0,000	0,000	0,010	0,014	0,062	0,190
65	0,000	0,000	0,000	0,000	0,000	0,000	0,006	0,002
75	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,002
85	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001

The magnitude interval in this case comprehend also earthquake of the seventh degree of Richter's scale with peak of eighth. These huge earthquakes can be perceived also from 90 km away from the epicentre. Compared from the previous case, the seismic risk associated with Priolo is much higher.

The frequency for this area is influenced by following parameters, used in Equation 4.1:

- a = 4,76;
- b = 0,72.

These values were taken from the area 935 where Priolo is located. The resulting vector is reported in Table 4.8.

Table 4.8: *frequency vector of earthquake for Priolo (SR) sorted by magnitude.*

Magnitude	**4,25**	**4,75**	**5,25**	**5,75**	**6,25**	**6,75**	**7,25**	**7,75**
Frequency	1.002374	0.437552	0.190999	0.083374	0.036394	0.015887	0.006935	0.003027

4.3.3 Falconara Marittima

The third location was chosen to have a different point of view: Falconara Marittima (AN) isn't located in a high seismic area, so it is possible to evaluate how the risk changes. In Figure 4.12 the seismic risk of the area is reported. Falconara is also the seat of an API's refinery. During recent earthquakes of central Italy some of the columns of the plant began to swing. This phenomenon can be explained looking to the Table 4.9: the seismic area of Falconara doesn't expect earthquakes with a magnitude higher than 6,5, but the proximity with the Apennines leads to a low possibility of strong earthquakes (magnitude of 7,5) also from 110 km away.

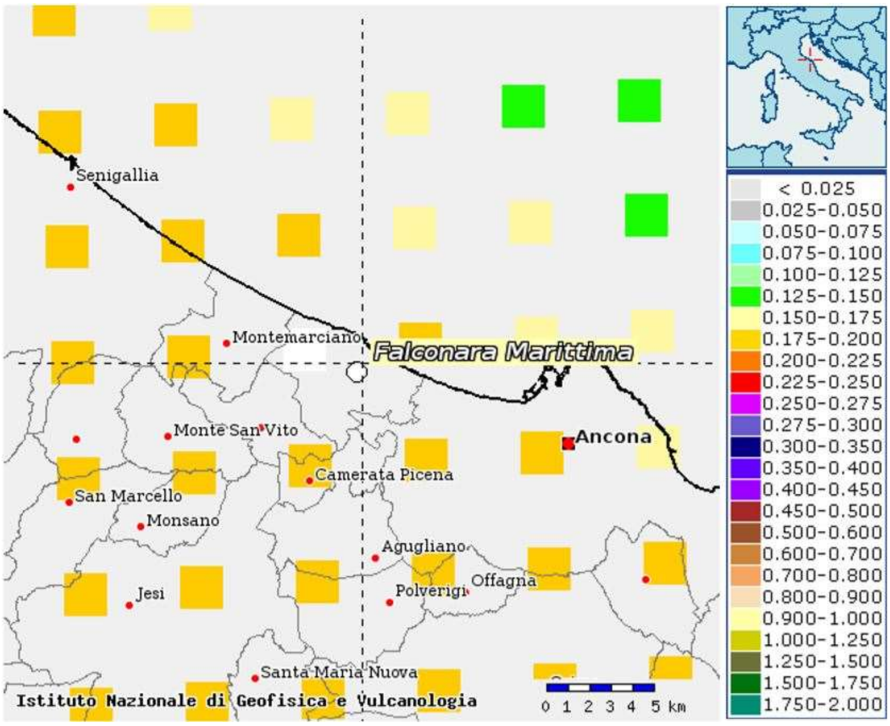


Figure 4.12: *seismic map of Falconara Marittima. Possible PGAs in case of earthquake are represented in coloured squares. On the right, the legend presents the scale: the area is subject to earthquake with PGAs from 0.125g to 0.200g.*

Table 4.9: *probabilities of an earthquake in Falconara Marittima, sorted by magnitude in Richter scale (in the columns) and distance (in the rows) from the epicentre. The value of these quantities are the mean of border values of the interval.*

Distance (km)\Magnitude	4,25	4,75	5,25	5,75	6,25	6,75	7,25
5	11,300	24,600	17,500	10,700	1,470	0,000	0,000
15	1,980	7,030	8,780	8,560	1,570	0,000	0,000
25	0,012	0,427	1,410	2,240	0,873	0,000	0,000
35	0,000	0,001	0,144	0,600	0,401	0,000	0,000
45	0,000	0,000	0,002	0,118	0,161	0,000	0,000
55	0,000	0,000	0,000	0,010	0,050	0,000	0,000
65	0,000	0,000	0,000	0,000	0,005	0,000	0,000
75	0,000	0,000	0,000	0,000	0,000	0,002	0,005
85	0,000	0,000	0,000	0,000	0,000	0,001	0,007
95	0,000	0,000	0,000	0,000	0,000	0,000	0,004
105	0,000	0,000	0,000	0,000	0,000	0,000	0,001

The frequency parameter was calculated using data from area 917 in the Figure 4.9:

- a = 4,76;
- b = 1,04.

The results of the calculation are reported in Table 4.10.

Table 4.10: *frequency vector for Falconara Marittima (AN) sorted by magnitude.*

Magnitude	4,25	4,75	5,25	5,75	6,25	6,75	7,25
Frequency	$4.3755\ 10^{-2}$	$1.3214\ 10^{-2}$	$3.991\ 10^{-3}$	$1.205\ 10^{-3}$	$3.64\ 10^{-4}$	$1.1\ 10^{-4}$	$3.32\ 10^{-5}$

Before to perform the analysis, some approximation in the method had to be done.

4.4 Numerics approximation

Before the result analysis, it is worth to introduce the approximations used for the risk calculation. There main problems to discuss are:

1. The first one concerns how the fault tree is transposed in the code. The presence of only "or" operators allow to calculate the risk as the sum of all single values, without taking into account the order of contributes or any coupling. It is so simple to calculate apart the mechanical and the seismic risk, in order to represent their contribution to the final value.
2. The second approximation is called Minimum cut-set and it is a technique of the Boolean algebra. The Minimum cut-set can be applied if there is a situation like the one in Figure 4.13, with an event linked two times with the same operator "or".

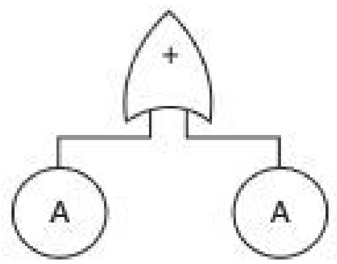


Figure 4.13: *example of situation where the Minimum cut-set can be applied.*

So it is possible to count only one time frequencies for this event. The result can be resumed in the Equation (4.2) below. This approximation is very useful and can simplify the risk analysis reducing the number of factors involved in each fault tree when they are written in the code.

$$A + A = A \tag{4.2}$$

3. Also the introduction of the operator error has to be described. This parameter interacts with the alarm failure through an "and" gate. So the result is a multiplication between a number and a frequency, in which each value of the vector is multiplied by a constant. The result obtained is used in the calculation of the risk under the Minimum cut-set, as other contributions.

On the basis of these approximations, it is possible to analyse the results for the case studies.

Chapter 5
Results Presentation

The results obtained in the case studies show how the location of the industrial storage tanks influences the risk: placing these equipment in a highly seismic area turns the mechanical risk in a negligible variable. Although the method adopted can guarantee a precise analysis of the risks, it is worth noticing that with other choices it is possible to obtain risk values comparable: in this case the sum on seismic and mechanical risk leads to a result in which the two contribution are visible.

5.1 Floating roof tank results

The analysis of seismic and mechanical risk for the floating roof tank is schematized in figures below. Figure 5.1 resume the risk caused by mechanical component, considering the fault tree of Figure 4.2. Due to the methodology adopted in calculation, the medium and high risk have the same value. Their influence is important for further analysis.

In order to reach a complete risk analysis, it is possible to compare the deterministic and the probabilistic result. In Table 5.1 are reported numerical values for the three risk ranges.

In particular, the case of a low release has an order of magnitude equal to 10^{-3} whereas the case of medium and high releases are equal to 10^{-4}. It is a quite high value, but the system described in this analysis is very simple, without all safety equipment used to protect a tank storing Benzene. Also numerical values obtained with probabilistic and deterministic analysis are almost equals.

Table 5.1: *comparison between mechanical risk calculated using a probabilistic approach (mean is reported) or a deterministic one.*

Risk level	Probabilistic value	Deterministic value
Low	$2.9\ 10^{-3}$	$3.3\ 10^{-3}$
Medium	$2.8105\ 10^{-4}$	$3.12\ 10^{-4}$
High	$2.8105\ 10^{-4}$	$3.12\ 10^{-4}$

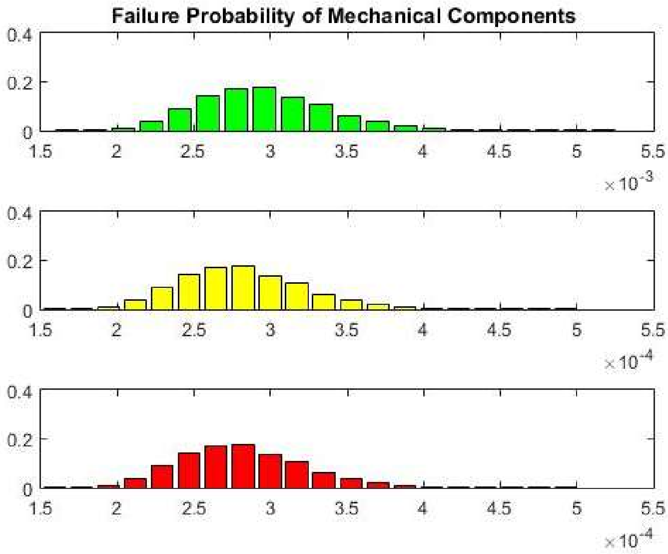
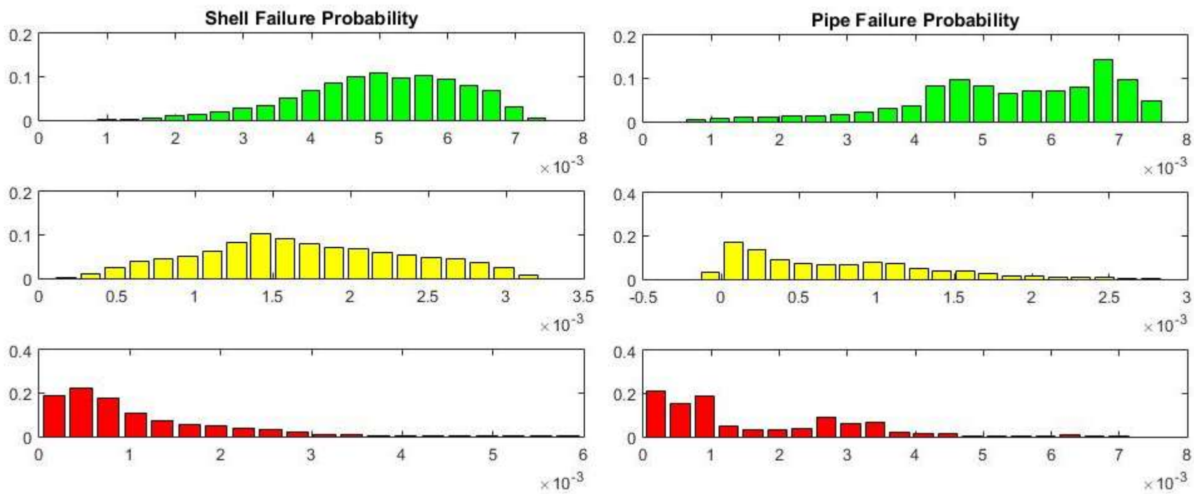


Figure 5.1: *mechanical fault probability in a floating roof tank, for different degree of severity: in green the probability of a small damage, in yellow the one for a medium leakage and in red the distribution for a huge damage. On the x-axis are reported the value of probability distribution, in the y-axis the probability of a result to verify.*

5.1.1 Tank located in Osoppo

In the first case study, the floating roof tank is located in Osoppo.

Figure 5.2 shows the seismic risk of the area for this type of tank. The seismic risk, shown in Figure 5.3 is composed from contribution of probability of shell failure by fractures or holes (in Figure 5.2.a) and contribution of pipes failure probability (Figure 5.2.b).



(a) (b)

Figure 5.2: *seismic failure probability distribution. In (a) it is possible to see the seismic failure probability for tank's shell, with different risk levels. In (b), the probability of a pipe leakage is reported.*

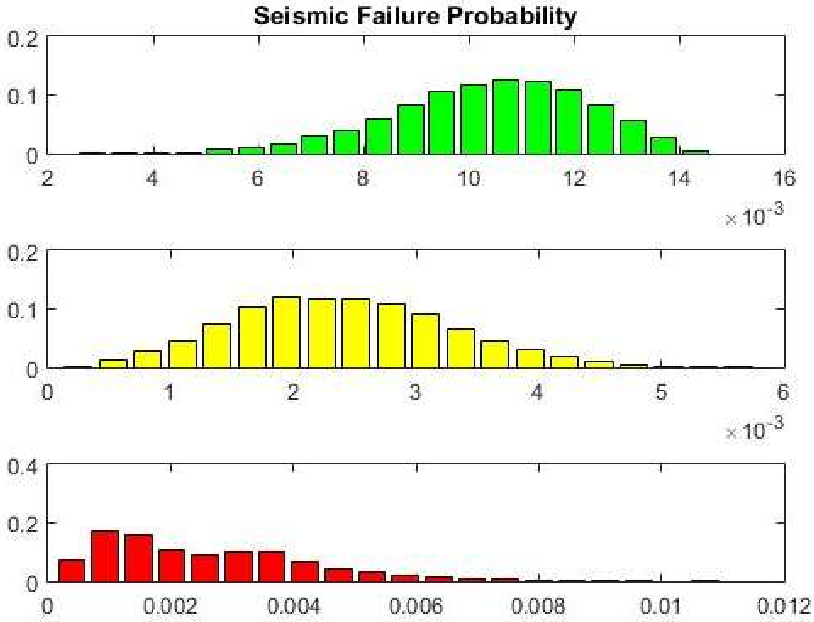


Figure 5.3: *seismic probability distributions. It represents the sum of risks due to earthquakes with the contribution of pipes and shell. On the x-axis are reported the value of probability distribution, in the y-axis the probability of a result to verify.*

From these graphs, it is possible to see that the seismic contribution for pipes have a strange shape: there are two peak, a greater one and a smaller one. This fact is due to the values use to calculate the distribution in the fragility curves. It is also possible to see how if the probability of a light damage of the pipes is higher than the one for a medium or heavy one.

The shape of the shell damage probability (Figure 4.2.b), is more similar to a lognormal one with three different ranges and peaks.

The distribution of the sum of seismic contribution presents a peculiarity only in the heavy damage probability: the pipe damage probability contribution is clearly visible with the presence of the peaks. The distributions are much larger, according with the operation done.

In order to have a numerical representation of the risk, Table 5.2 reports the mean value of the risk (for the probabilistic approach) and the deterministic one. Values obtained are almost equal in the low and medium risk case. For the high risk, it is important to highlight that the peak value in the graph corresponds to the deterministic value, but the shape of the distribution changes the result of the probabilistic analysis.

Table 5.2: *comparison between seismic risk calculated using a probabilistic approach (mean is reported) or a deterministic one.*

Risk level	Probabilistic value	Deterministic value
Low	$1.04\ 10^{-2}$	$1.16\ 10^{-2}$
Medium	$2.4\ 10^{-3}$	$2.9\ 10^{-3}$
High	$2.6\ 10^{-3}$	$0.90992\ 10^{-3}$

The last image, Figure 5.4 represents the global risk of the top event computed with the seismic fault tree for floating roof tank (Figure 4.4).

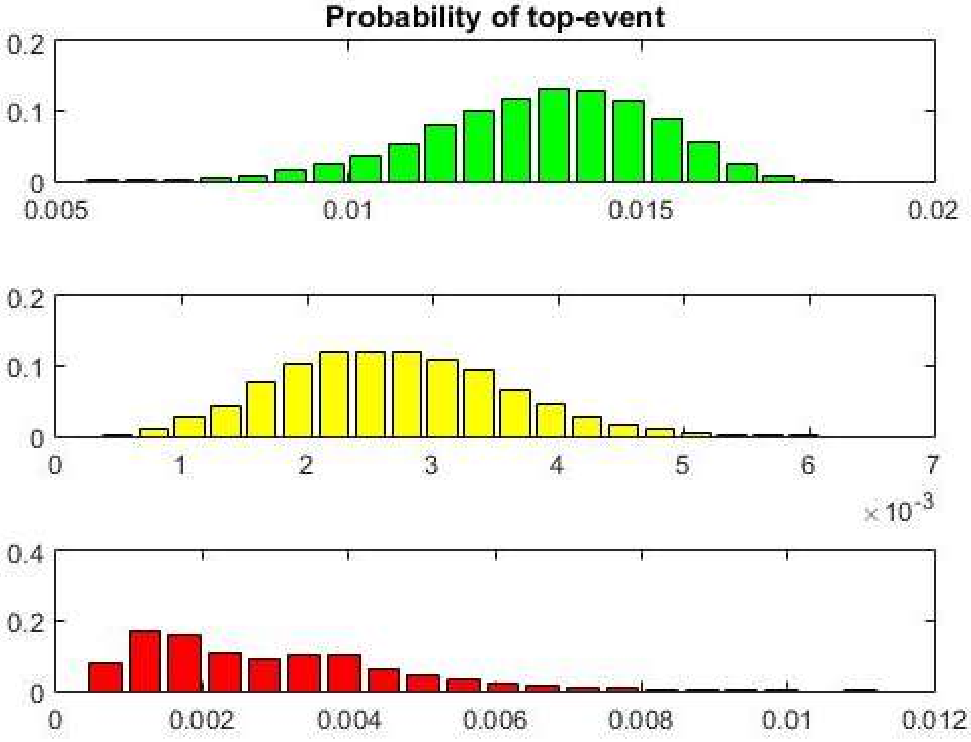


Figure 5.4: *probability of top event in a floating roof tank located in Osoppo (UD). On the x-axis are reported the value of probability distribution, in the y-axis the probability of a result to verify.*

The total value of the risk is almost equal to the seismic contribution, with little modification derived by the mechanical values. This fact will be discussed in the following section. The Table 5.3 resumes the results of the analysis. As stated before, the shape of the distribution chances the probabilistic high risk value. Despite this, values obtained are similar.

Table 5.3: *risk analysis for a floating roof tank in Osoppo (UD) calculated using a probabilistic approach (mean is reported) and a deterministic one.*

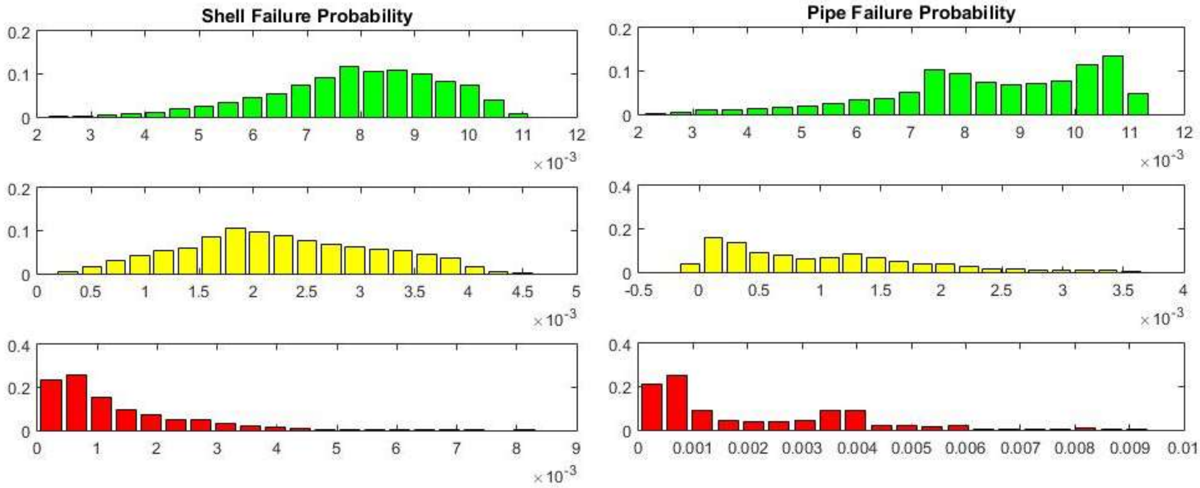
Risk level	Probabilistic value	Deterministic value
Low	$1.33\ 10^{-2}$	$1.48\ 10^{-2}$
Medium	$2.7\ 10^{-3}$	$3.2\ 10^{-3}$
High	$2.9\ 10^{-3}$	$1.2\ 10^{-3}$

5.1.2 Tank located in Falconara

In Falconara Marittima (AN), the situation is a bit different. As can be seen in Figure 5.5, the seismic risk of this area is higher than the previous one. That situation is due to the presence, in the earthquake matrix (Table 4.9), of terms related with heavy seismic phenomena in the surrounding area. In fact, Falconara is located in a place affected by huge earthquakes happening in area 912, 914, 916, 919 and 923 of Figure 4.10.

The shape of the seismic distribution is the same as previously stated: pipes one (Figure 5.4.b) have two peaks due to fragility curves and the shell one is similar to the lognormal distribution (Figure

5.4.a). The sum of these contribution leads to Figure 5.6, where the two peaks are visible only in the high risk diagram.



(a) (b)

Figure 5.5: *seismic probability distributions. In (a) it is possible to see the seismic failure probability for pipes, with different levels of risk. In (b), the probability of a leakage of the shell is reported.*

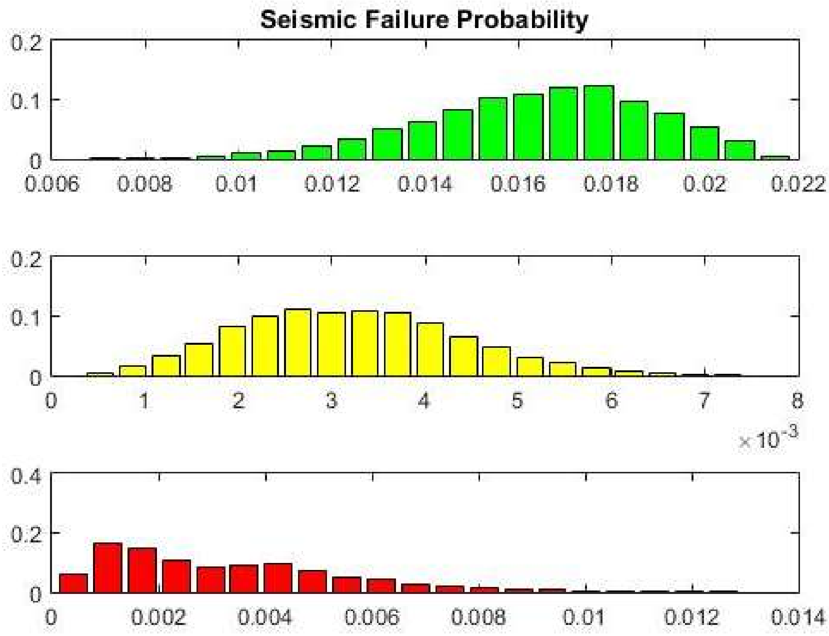


Figure 5.6: *seismic probability distributions. It represents the sum of risks due to earthquakes with the contribution of pipes and shell. On the x-axis are reported the value of probability distribution, in the y-axis the probability of a result to verify.*

In Table 5.4 are reported the numerical values for the seismic failure probability, either calculated with a probabilistic method or with a deterministic one. Values obtained are similar, apart for the high risk that suffers the calculation of the mean.

Table 5.4: *seismic risk analysis for a floating roof tank in Falconara Marittima (AN) calculated using a probabilistic approach (mean is reported) and a deterministic one.*

Risk level	Probabilistic value	Deterministic value
Low	1.64 10^{-2}	1.81 10^{-2}
Medium	3.2 10^{-3}	3.7 10^{-3}
High	3.2 10^{-3}	1.0 10^{-3}

As can be expected also in this case, the probability of the top-event will be the seismic one, without any contribution given by the mechanical risk. This situation is represented in Figure 5.7 below.

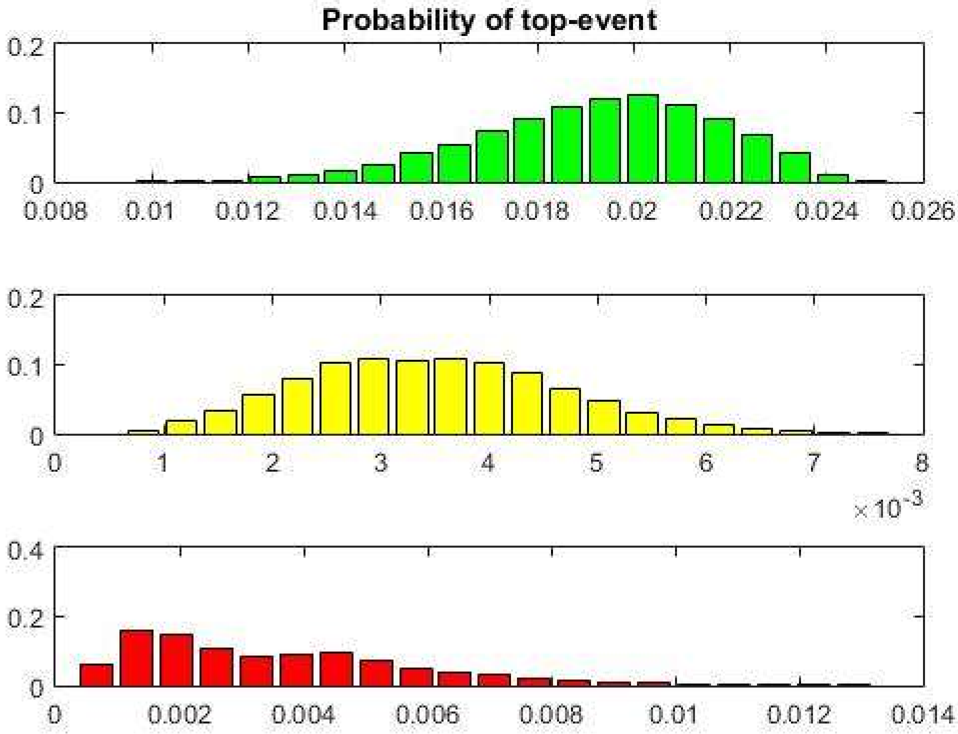


Figure 5.7: *probability of top event in a floating roof tank located in Osoppo (UD). On the x-axis are reported the value of probability distribution, in the y-axis the probability of a result to verify.*

Also data in Table 5.5 are almost equals to the ones in Table 5.4 although they are taken from final result of the analysis or just after the seismic one. The mechanical contribution reflects in a small increase of values.

Table 5.5: *risk analysis for a floating roof tank in Falconara Marittima (AN) calculated using a probabilistic approach (mean is reported) and a deterministic one.*

Risk level	Probabilistic value	Deterministic value
Low	1.93 10^{-2}	2.13 10^{-2}
Medium	3.5 10^{-3}	4.0 10^{-3}
High	3.5 10^{-3}	1.3 10^{-3}

5.1.3 Risk comparison

As can be seen, there is a huge difference between the results in mechanical terms and the seismic contribution. This difference is so high that the mechanical contribution seems to be almost negligible in the final calculations. This consideration will be discussed in section 5.3 because of these results are common with the one of the pressurized tank case study.

Also in the mechanical risk analysis, the values obtained for pipes and valves are overwhelmed by the ones calculated for shell and roof frequencies (as in Table 4.2). This happens because these equipment are well established and their safety is reproved. Also the non-presence of any safety measure for the tank enlarges the risk associated with the vessel.

5.2 Pressurized tank results

The pressurized tank requires more calculation to reach a proper evaluation: in this case, there are two contributions also for mechanical risk. The first one is given by valves and pipes, the second by the shell analysis. That happens because if the risk for external equipment is given with a single frequency (Table 4.4), from which three ranges have to be calculated, the shell presents three values, corresponding to the three levels of risk. In Figure 5.8, the results of the sum are reported.

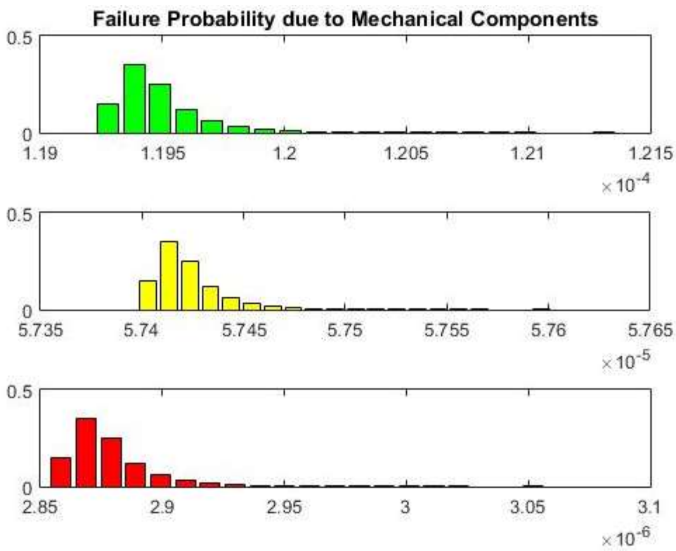


Figure 5.8: *risk related to a pressurized tank due only to mechanical components.*

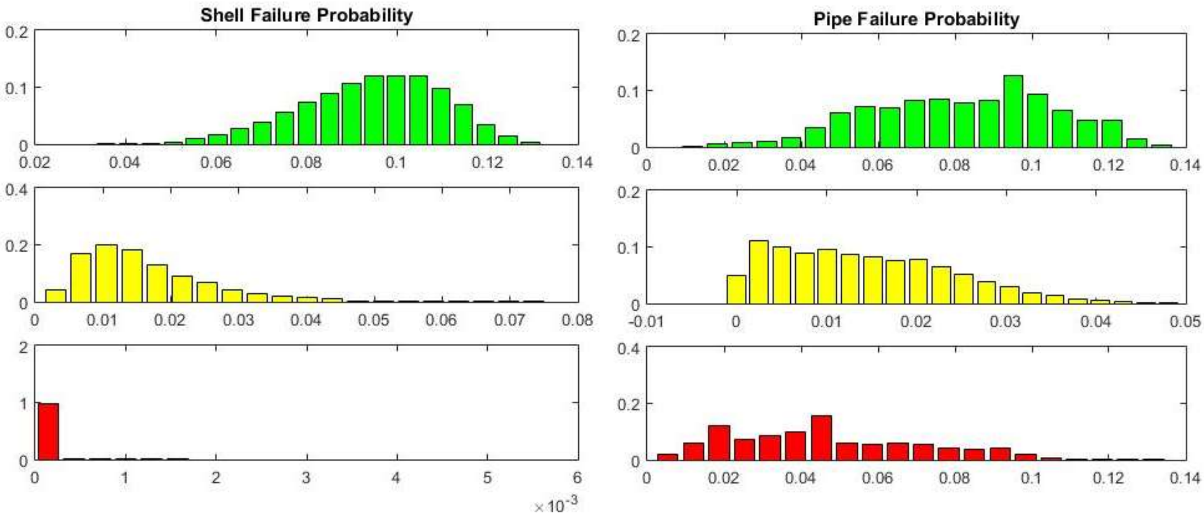
As opposed to the previous mechanical risk analysis, the presence of three risk ranges creates very different results. Each risk, low, medium and high, have a different order of magnitude, respectively 10^{-3}, 10^{-4} and 10^{-5}. To better appreciate these differences, in Table 5.6 each numerical value is reported. The deterministic values are in some case similar to the probabilistic one apart for the high risk: in this case the deterministic result is four times the probabilistic one. This difference is due to the mechanism adopted in the risk summation: as stated in section 3.3.3, a correction factor is used when a sum is performed. This factor changes the final results where the order of magnitude is very low.

Table 5.6: *mechanical risk analysis for a pressurized tank calculated using a probabilistic approach (mean is reported) and a deterministic one.*

Risk level	Probabilistic value	Deterministic value
Low	$1.1948\ 10^{-4}$	$0.81301\ 10^{-4}$
Medium	$5.7423\ 10^{-5}$	$5.2029\ 10^{-5}$
High	$2.8783\ 10^{-6}$	$9.7286\ 10^{-6}$

5.2.1 Tank located in Priolo Gargallo

The seismic contribution is resumed in Figure 5.9: Figure 5.9.a shows the contribution of shell failure probability, Figure 5.9.b shows pipes failure probability. Instead, Figure 5.10 represents the sum of these two contribution.



(a) (b)

Figure 5.9: *seismic risk for Priolo Gargallo (SR) with two different contributions: pipes in (a) and shell in (b).*

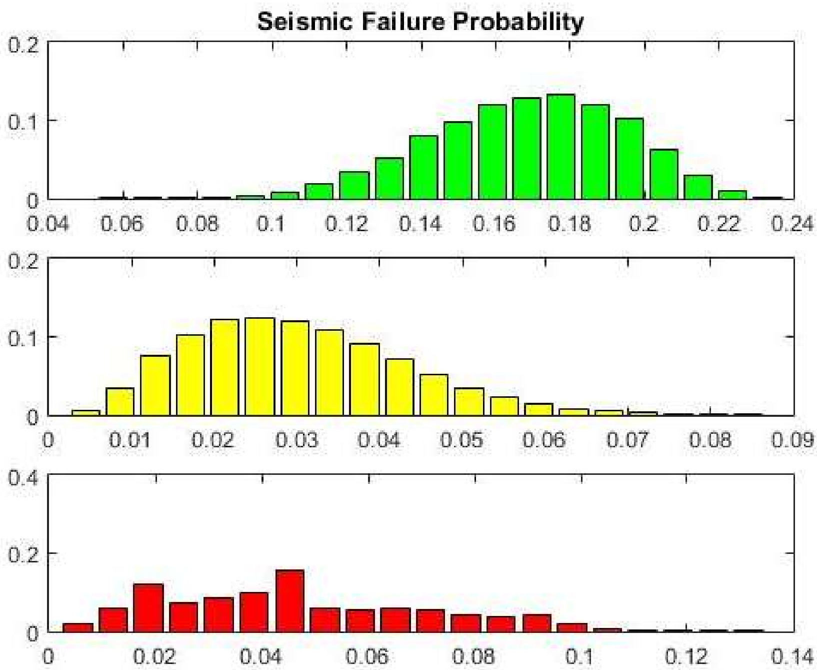


Figure 5.10: *seismic risk for Priolo Gargallo (SR). The graph represents the total seismic risk for a pressure tank.*

For the shell (Figure 5.9.a) it is possible to see how there are three different order of magnitude involved with the risk: the low one have a 10^{-1} value, the medium one 10^{-2} and the high risk 10^{-3}.

Pipes failure probability values (Figure 5.9.b) are due to their diameter and the fragility curves linked to it, so it is possible to see how the shape of the distribution is similar to the one obtained before, with the two peaks. What changes is the range of the seismic risk associated with them. The third risk have values similar to the second one, the order of magnitude in the image may mislead. The results of the sum, Figure 5.10, show a low and medium risk that are comparable, while the high one is the same of pipes. Pipes seismic values overwhelm shell ones.

In Table 5.7 are reported numerical results of the analysis. Values obtained are a consequence of what stated above: the inversion of magnitude of medium and high risk depends on the high results of pipes.

Table 5.7: *seismic risk analysis for a pressurized tank located in Priolo Gargallo (SR), calculated using a probabilistic approach (mean is reported) and a deterministic one.*

Risk level	Probabilistic value	Deterministic value
Low	0.1683	0.2100
Medium	$3.02\ 10^{-2}$	$4.24\ 10^{-2}$
High	$4.70\ 10^{-2}$	$3.38\ 10^{-2}$

The last point of this case study is the global risk, presented in Figure 5.11.

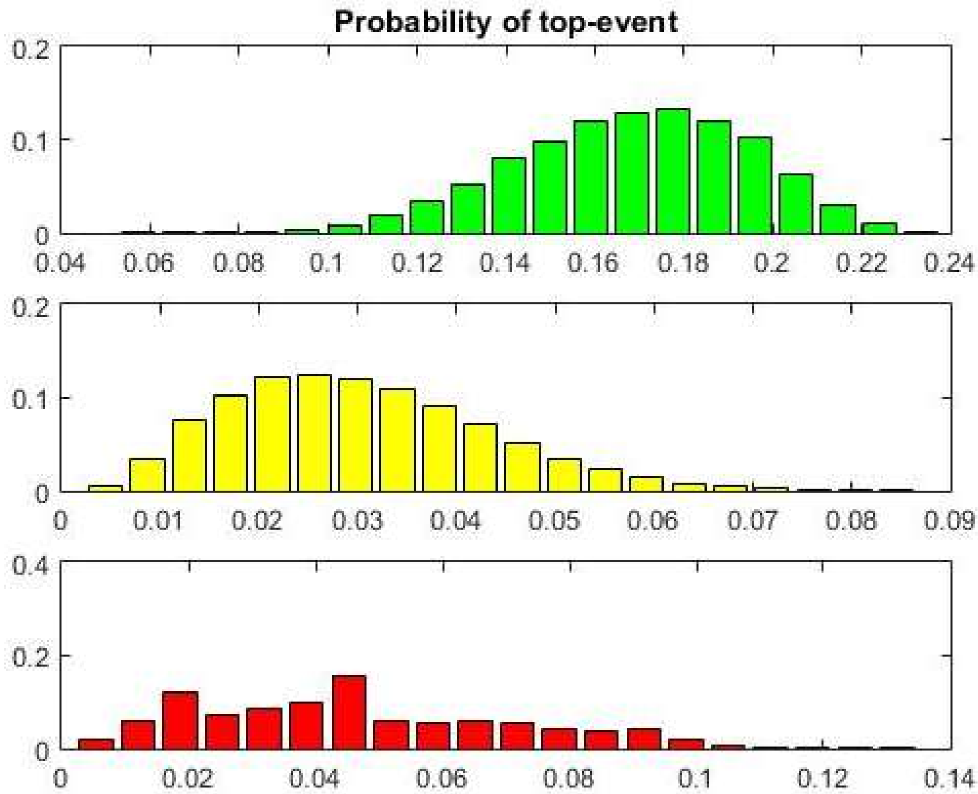


Figure 5.11: *probability of top event for a pressurized tank in Priolo Gargallo (SR). On the x-axis are reported the value of probability distribution, in the y-axis the probability of a result to verify.*

Seismic graph of Figure 5.10 is equal to Figure 5.11 representing the global value of risk.

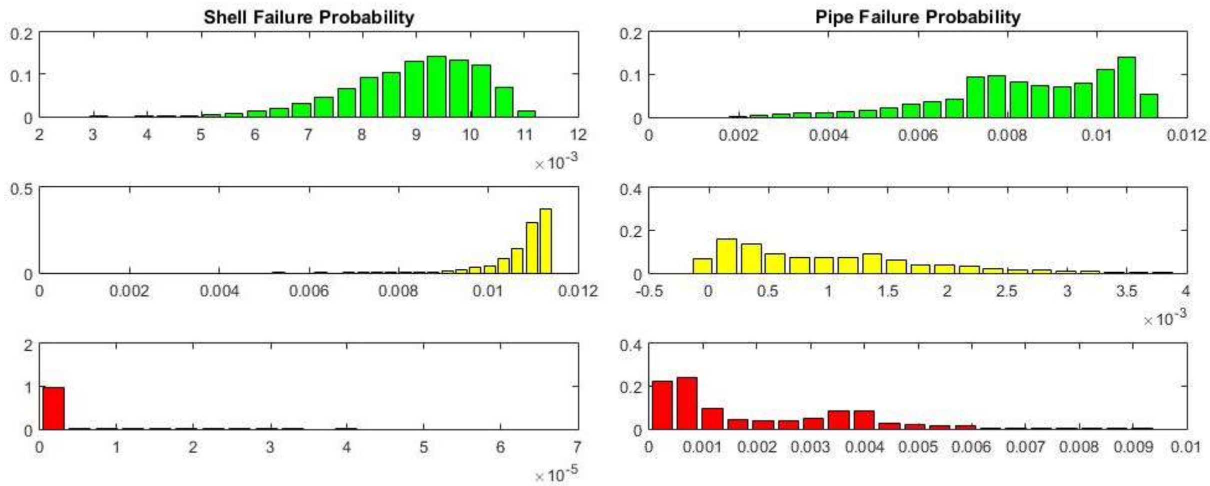
To have a numerical idea of what happen in this case, in Table 5.8 are reported the values obtained with the probabilistic analysis and the one obtained with the deterministic one. It is possible to make the same consideration made above concerning results, with almost no variation from the seismic case.

Table 5.8: *risk analysis for a pressurized tank in Priolo Gargallo (SR) calculated using a probabilistic approach (mean is reported) and a deterministic one.*

Risk level	Probabilistic value	Deterministic value
Low	0.1684	0.2101
Medium	$3.03\ 10^{-2}$	$4.25\ 10^{-2}$
High	$4.70\ 10^{-2}$	$3.38\ 10^{-2}$

5.2.2 Tank located in Falconara Marittima

In Figure 5.12.a the shell reaction to an earthquake is analysed. The medium risk results a little higher to the low one. The pipes (Figure 5.12.b) have the same graph of Figure 5.5.b, because the same pipe diameter and location are considered. The sum of these two contributions is presented in Figure 5.13, where the heavy risk of pipes overwhelms the one of the shell.



(a) (b)

Figure 5.12: *seismic probability distributions. In (a) it is possible to see the seismic failure probability for pipes, with different levels of risk. In (b), the probability of a leakage of the shell is reported.*

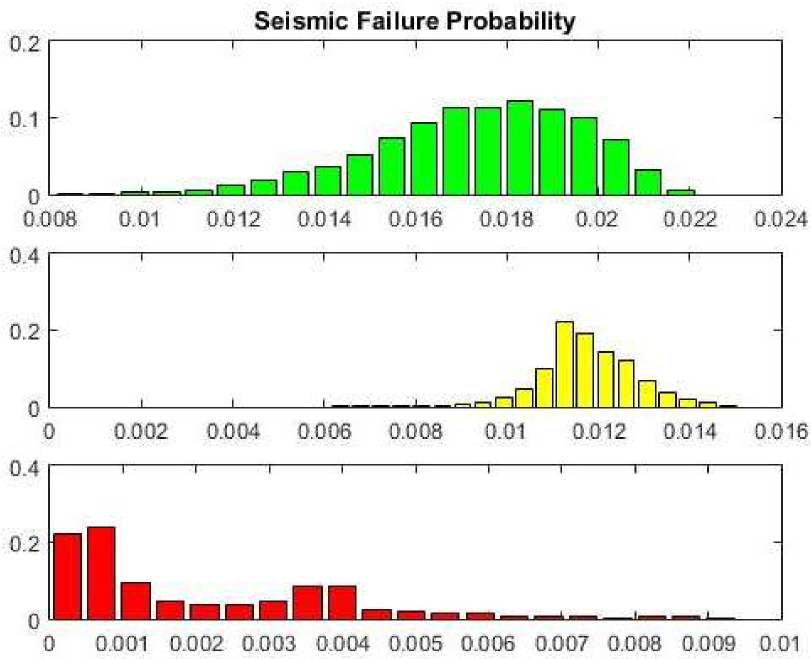


Figure 5.13: *the total seismic risk for a pressure tank located in Falconara Marittima.*

In Table 5.9 numerical results of the analysis are reported.

Table 5.9: *seismic risk analysis for a pressurized tank in Falconara Marittima (AN) calculated using a probabilistic approach (mean is reported) and a deterministic one.*

Risk level	Probabilistic value	Deterministic value
Low	$1.74\ 10^{-2}$	$2.08\ 10^{-2}$
Medium	$1.18\ 10^{-2}$	$7.5831\ 10^{-4}$
High	$2.0\ 10^{-3}$	$5.4470\ 10^{-4}$

In this case, the summation mechanism results in probabilistic values that are very different from deterministic ones for medium and high risk. The shape of distribution can be the cause for the high risk difference, but the major peak corresponds with the deterministic value.

The last point is the global risk, presented in Figure 5.14.

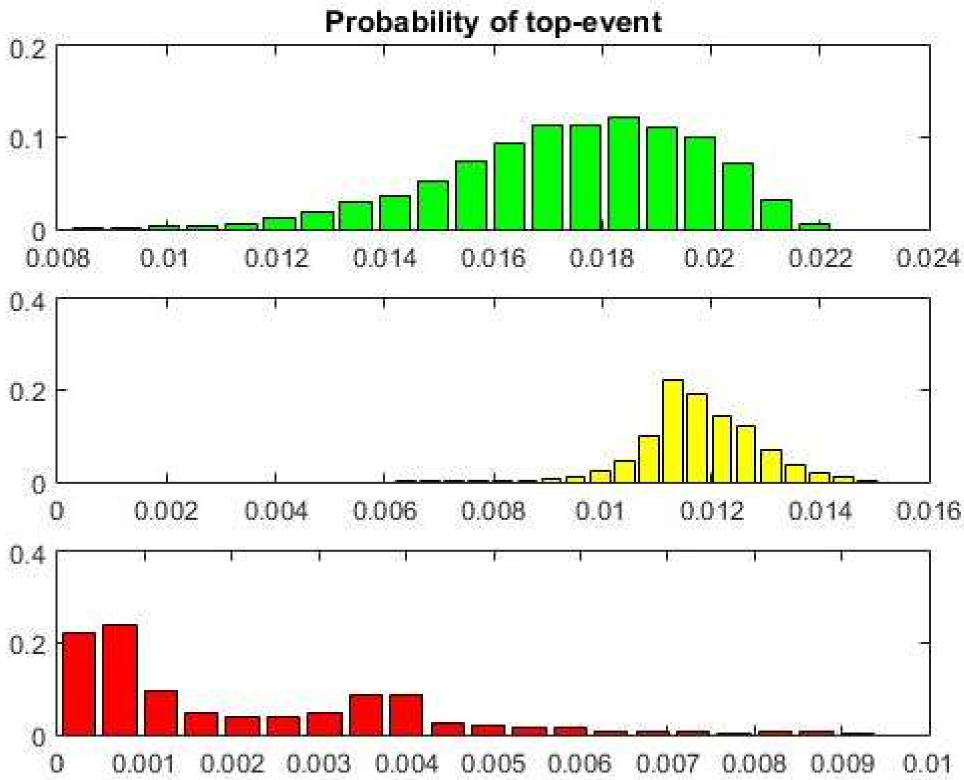


Figure 5.14: *probability of top event for a pressurized tank in Falconara Marittima (AN). On the x-axis are reported the value of probability distribution, in the y-axis the probability of a result to verify.*

In this case, the seismic contribution overwhelms the mechanical one. The Table 5.10 below resumes the results and show this phenomenon when compared with Table 5.9. There are some little differences, derived by mechanical influence, but they are negligible in the risk analysis.

Table 5.10: *risk analysis for a pressurized tank in Falconara Marittima (AN) calculated using a probabilistic approach (mean is reported) and a deterministic one.*

Risk level	Probabilistic value	Deterministic value
Low	$1.75\ 10^{-2}$	$2.09\ 10^{-2}$
Medium	$1.18\ 10^{-2}$	$8.1030\ 10^{-4}$
High	$2.0\ 10^{-3}$	$5.5442\ 10^{-4}$

5.2.1 Risk comparison

In these case studies, it is possible to see how the choice of the location where perform the analysis is fundamental: choosing an area with low seismic risk allows to appreciate the combination between mechanical and seismic failures.

Priolo, as expected, results the area with the highest seismic risk, too high that the mechanical contribution becomes negligible.

5.3 Final considerations

In order to resume the results, in Table 5.11 are reported the final values for the risk for each case study.

Table 5.11: *resume of results for release probability of tanks in different locations. The comparison between the probabilistic results (mean is reported) and deterministic one is possible. In (a) result of the floating roof tank in Osoppo (UD) are reported, in (b) the ones of the floating roof tank in Falconara Marittima (AN).*

Risk level	Probabilistic value	Deterministic value
Low	$1.33\ 10^{-2}$	$1.48\ 10^{-2}$
Medium	$2.7\ 10^{-3}$	$3.2\ 10^{-3}$
High	$2.9\ 10^{-3}$	$1.2\ 10^{-3}$

(a)

Risk level	Probabilistic value	Deterministic value
Low	$1.93\ 10^{-2}$	$2.13\ 10^{-2}$
Medium	$3.5\ 10^{-3}$	$4.0\ 10^{-3}$
High	$3.5\ 10^{-3}$	$1.3\ 10^{-3}$

(b)

Results of the pressurized tank in Priolo Gargallo (SR) are in table (c) and in Falconara maritime (AN) in table (d).

Risk level	Probabilistic value	Deterministic value
Low	0.1684	0.2101
Medium	$3.03\ 10^{-2}$	$4.25\ 10^{-2}$
High	$4.70\ 10^{-2}$	$3.38\ 10^{-2}$

(c)

Risk level	Probabilistic value	Deterministic value
Low	$1.75\ 10^{-2}$	$2.09\ 10^{-2}$
Medium	$1.18\ 10^{-2}$	$8.1030\ 10^{-4}$
High	$2.0\ 10^{-3}$	$5.5442\ 10^{-4}$

(d)

It is also possible to make some general considerations:

- In a highly seismic area as Priolo Gargallo (SR), final results for the risk are at least one order of magnitude higher than other locations.
- Falconara Marittima (AN) presents results that are much higher than expected. This fact is due to the presence of different seismic zones in the area surrounding the tank. It results a sum of various contribution that reaches a probability one and a half higher than Osoppo (UD).
- In general, it is possible to state that mechanical risk causes only little variations in risk calculation. In the analysis both mechanical and seismic risk were overestimate, so it is possible to assess that with a more rigorous analysis this disproportion won't change.
- In general, for the low risk case deterministic and probabilistic values are comparable. In other cases, the shape of the distribution generates the difference between these two values. In fact, if the value of the main peak were reported, it will be similar to the deterministic one.

- When the difference between deterministic and probabilistic values are too high and also the peak doesn’t correspond, it is due to the simplification adopted to avoid double counting.

In this way, a combination of natural risk and chemical one is possible. This first try could be a beginning in the integration of natural events in the calculation of risk, as “Seveso II Directive” states.

Conclusions

The aim of this work was to evaluate the risk for some chemical equipment located in seismic areas, as requested in “Seveso III Directive”.

The main problem that arose during the risk analysis was how to combine deterministic values derived by mechanical risk assessment and probabilistic distribution of earthquakes. The main assumption was to transform mechanical values in a probabilistic way. It was possible tanks to the presence of upper and lower values of failure frequencies that allow to reach a probability distribution one the average and the standard deviation are calculated. This choice was made because failure frequencies are derived by a structural analysis with a well-established procedure. Years of accidental data collection and innovation gave reliable results. On the other hand, in terms of seismic analysis, data are derived by historical series. These studies analyse all earthquakes with quantitative instrumental data starting only one hundred years ago, so they are based on few events. Their values are more general.

In order to reach a unique result, a fault tree analysis was performed to highlight all critical issues of a floating roof tank and a pressurized one. Furthermore, the seismic component was added to these trees to obtain a more general representation. Thanks to this method the risk became a sum of single contribution that can be analysed using a Matlab code specially developed.

First of all, it was important to study seismic data of the three location chosen: Osoppo (UD), Priolo Gargallo (SR) and Falconara Marittima (AN). In the firs case it was found that the risk associated to seismic events had a medium value; in Priolo the seismic risk is one of the highest of Italy; Falconara Marittima represents a peculiar case. In fact, it isn’t a highly seismic area, but it is surrounded by location that are subject to a high seismic risk. This fact results in the possibility that also far earthquakes can have consequences on this site. Floating roof tank was placed in Osoppo and Falconara Marittima, the pressurized one in Priolo Gargallo and again in Falconara Marittima. So Falconara represent the comparison terms for risk associated with atmospheric and pressurized tank.

The designed code summed results of the seismic analysis with the one of the mechanical failure probability: as stated above, a distribution cure of frequencies is obtained. The result expresses the probability of a top-event in each of the four case studies.

It was possible to compare the results obtained with a probabilistic analysis to that obtained with the deterministic one. In tables of Chapter 5 the results show the mean value of two methodologies and they are comparable.

In general, the preliminary results are promising and further studies are recommended in order to perform an analysis that takes into account all these safety equipment that are common in tank design.

In this work they were not considered because the aim was to combine two aspects of the risk and to see if this approach could be useful. Also liquid shaking wasn’t considered in this analysis.

Appendix

Matlab codes

A. Floating roof tank in Osoppo (UD)

```
clear all
close all
 rand=input('number of iterations')

% Earthquake

% seismic Matrix
R=xlsread('DistribuzioniOsoppo.xlsx', 'distanza', 'A1:A6');
M=xlsread('DistribuzioniOsoppo.xlsx', 'Magnitudo', 'A1:G1');
MP=xlsread('DistribuzioniOsoppo.xlsx', 'Matrice', 'A1:G6');
F=xlsread('DistribuzioniOsoppo.xlsx', 'Frequenza', 'A1:G1');

r=length(R);
m=length(M);
logPGA=[];
for i=1:r
    for j=1:m
        logPGA(i,j)=-3.37+(1.93-0.203*M(j)).*M(j)+(-
3.02+0.00744*M(j)^3)*log10(sqrt(R(i)^2+7.3^2));
    end
end

sigmashell=0.358; % % Shape value of LogPGA
mu2shell=0.38; % Mean value of Fragility Medium hole
sigma2shell=0.8; % shape value of Fragility Medium hole
mu3shell=1.18; % Mean value of Fragility large hole
sigma3shell=0.61;  % Shape value of Fragility large hole
PeqRS1shell=[];
PeqRS2shell=[];
PeqRS3shell=[];
PeqRS1shell=zeros(rand,1);
PeqRS2shell=zeros(rand,1);
PeqRS3shell=zeros(rand,1);

for i=1:rand
%     PGA1=10.^(logPGA+sigma);
    PGA1shell=random ('norm',logPGA,sigmashell);
    PGAshell=(10.^PGA1shell).*9.81;
    RS3eqshell= cdf('logn',PGAshell,mu3shell,sigma3shell);
    RS2eqshell=cdf('logn',PGAshell,mu2shell,sigma2shell);
    Prs1shell=(1-RS2eqshell).*(MP./100);
    Prs2shell=(RS2eqshell-RS3eqshell).*(MP./100);
    Prs3shell=RS3eqshell.*(MP./100);
    PfRS11shell=sum(Prs1shell).*F;
    PfRS1shell=sum(PfRS11shell(:));
    PfRS22shell=sum(Prs2shell).*F;
    PfRS2shell=sum(PfRS22shell(:));
    PfRS33shell=sum(Prs3shell).*F;
    PfRS3shell=sum(PfRS33shell(:));
```

```
    PeqRS1shell(i)=[PfRS1shell ];
    PeqRS2shell(i)=[PfRS2shell ];
    PeqRS3shell(i)=[PfRS3shell ];
    i=i+1;
end

PeqRSshell =[PeqRS1shell PeqRS2shell PeqRS3shell];
meaneqshell=mean(PeqRSshell);

% Deterministic approach
PGAdetshell=(10.^logPGA).*9.81;
RS3eqdetshell= cdf('logn',PGAdetshell,mu3shell,sigma3shell);
RS2eqdetshell=cdf('logn',PGAdetshell,mu2shell,sigma2shell);
Prs1detshell=(1-RS2eqdetshell).*(MP./100);
Prs2detshell=(RS2eqdetshell-RS3eqdetshell).*(MP./100);
Prs3detshell=RS3eqdetshell.*(MP./100);
PfRS11detshell= sum(Prs1detshell).*F;
PfRS1detshell=sum(PfRS11detshell(:));
PfRS22detshell= sum(Prs2detshell).*F;
PfRS2detshell=sum(PfRS22detshell(:));
PfRS33detshell= sum(Prs3detshell).*F;
PfRS3detshell=sum(PfRS33detshell(:));
PeqRSdetshell =[PfRS1detshell PfRS2detshell PfRS3detshell];

[countsa,centersa] = hist(PeqRS1shell,20);
[countsb,centersb] = hist(PeqRS2shell,20);
[countsc,centersc] = hist(PeqRS3shell,20);
[countspga,centerspga] = hist(PGA1shell,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));



figure (1)
subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Shell Failure Probability')
hold on
plot (meaneqshell(1),ya,'b',PeqRSdetshell(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneqshell(2),yb,'b',PeqRSdetshell(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneqshell(3),yc,'b',PeqRSdetshell(3),yc,'k')
hold off

% Pipes

sigma=0.358; % % Shape value of LogPGA
mu2=0.4522; % Mean value of Fragility Medium hole
sigma2=0.39; % shape value of Fragility Medium hole
mu3=0.7116; % Mean value of Fragility large hole
sigma3=0.20;  % Shape value of Fragility large hole
```

```
PeqRS1pipe=[];
PeqRS2pipe=[];
PeqRS3pipe=[];
PeqRS1pipe=zeros(rand,1);
PeqRS2pipe=zeros(rand,1);
PeqRS3pipe=zeros(rand,1);

for i=1:rand
%     PGA1=10.^(logPGA+sigma);
    PGA1pipe=random ('norm',logPGA,sigma);
    PGApipe=(10.^PGA1pipe).*9.81;
    RS3eqpipe= cdf('logn',PGApipe,mu3,sigma3);
    RS2eqpipe=cdf('logn',PGApipe,mu2,sigma2);
    Prs1pipe=(1-RS2eqpipe).*(MP./100);
    Prs2pipe=(RS2eqpipe-RS3eqpipe).*(MP./100);
    Prs3pipe=RS3eqpipe.*(MP./100);
    PfRS11pipe=sum(Prs1pipe).*F;
    PfRS1pipe=sum(PfRS11pipe(:));
    PfRS22pipe=sum(Prs2pipe).*F;
    PfRS2pipe=sum(PfRS22pipe(:));
    PfRS33pipe=sum(Prs3pipe).*F;
    PfRS3pipe=sum(PfRS33pipe(:));
    PeqRS1pipe(i)=[PfRS1pipe ];
    PeqRS2pipe(i)=[PfRS2pipe ];
    PeqRS3pipe(i)=[PfRS3pipe ];
    i=i+1;
end

PeqRSpipe =[PeqRS1pipe PeqRS2pipe PeqRS3pipe];
meaneqpipe=mean(PeqRSpipe);

% Deterministic approach
PGAdetpipe=(10.^logPGA).*9.81;
RS3eqdetpipe= cdf('logn',PGAdetpipe,mu3,sigma3);
RS2eqdetpipe=cdf('logn',PGAdetpipe,mu2,sigma2);
Prs1detpipe=(1-RS2eqdetpipe).*(MP./100);
Prs2detpipe=(RS2eqdetpipe-RS3eqdetpipe).*(MP./100);
Prs3detpipe=RS3eqdetpipe.*(MP./100);
PfRS11detpipe= sum(Prs1detpipe).*F;
PfRS1detpipe=sum(PfRS11detpipe(:));
PfRS22detpipe= sum(Prs2detpipe).*F;
PfRS2detpipe=sum(PfRS22detpipe(:));
PfRS33detpipe= sum(Prs3detpipe).*F;
PfRS3detpipe=sum(PfRS33detpipe(:));
PeqRSdetpipe =[PfRS1detpipe PfRS2detpipe PfRS3detpipe];

[countsa,centersa] = hist(PeqRS1pipe,20);
[countsb,centersb] = hist(PeqRS2pipe,20);
[countsc,centersc] = hist(PeqRS3pipe,20);
[countspga,centerspga] = hist(PGA1pipe,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));

figure (2)
subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Pipe Failure Probability')
hold on
plot (meaneqpipe(1),ya,'b',PeqRSdetpipe(1),ya,'k');
```

```
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneqpipe(2),yb,'b',PeqRSdetpipe(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneqpipe(3),yc,'b',PeqRSdetpipe(3),yc,'k')
hold off

% Sum seismic risk

%Probabilistic
PeqRS1= PeqRS1shell+PeqRS1pipe-(PeqRS1shell.*PeqRS1pipe);
PeqRS2= PeqRS2shell+PeqRS2pipe-(PeqRS2shell.*PeqRS2pipe);
PeqRS3= PeqRS3shell+PeqRS3pipe-(PeqRS3shell.*PeqRS3pipe);

PeqRS =[PeqRS1 PeqRS2 PeqRS3];
meaneq=mean(PeqRS);

%Deterministic
PeqRS1det= PfRS1detshell+PfRS1detpipe-(PfRS1detshell.*PfRS1detpipe);
PeqRS2det= PfRS2detshell+PfRS2detpipe-(PfRS2detshell.*PfRS2detpipe);
PeqRS3det= PfRS3detshell+PfRS3detpipe-(PfRS3detshell.*PfRS3detpipe);
PeqRSdet =[PeqRS1det PeqRS2det PeqRS3det];

[countsa,centersa] = hist(PeqRS1,20);
[countsb,centersb] = hist(PeqRS2,20);
[countsc,centersc] = hist(PeqRS3,20);
[countspga,centerspga] = hist(PGA1pipe,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));


figure (3)
subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Seismic Failure Probability')
hold on
plot (meaneq(1),ya,'b',PeqRSdet(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneq(2),yb,'b',PeqRSdet(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneq(3),yc,'b',PeqRSdet(3),yc,'k')
hold off
```

```
% Failure rate of mechanical component

%longnormal distribution
m= [0.0016 0.0009 0.0014 0.000000048 0.0000001 0.00000021]; %event/years
LB=[0.0011 0.0005 0.0009 0.00000002 0.000000024 0.000000038]; %event/years
UB=[0.0023 0.0014 0.002 0.000000112 0.00000041 0.00000053]; %event/years

ef=sqrt(UB./LB);
sig=log(ef)/1.645;
v=(m.^2).*(exp(sig.^2)-1);
sigmashell=sig;
mu = log((m.^2)./sqrt(v+m.^2));

T=50;
X=[];
for i=1:rand
    for j=1:length(m)
        X(i,j)=random ('logn',mu(j),sigmashell(j));
          if (X(j)<=UB(j) && X(j)>=LB(j))
            X(i,j)=X(i,j);
          else
              if (X(j)<UB(j))
                  X(i,j)=UB(j);
              end
              if (X(j)>LB(j))
                  X(i,j)=LB(j);
              end
          end
          P1(i,j) = X(i,j);
          RS1(i,j) = P1(i,j).*0.84;
          RS2(i,j) = P1(i,j).*0.08;
          RS3(i,j) = P1(i,j).*0.08;
    end
end
PmRS1=sum(RS1,2)-(RS1(:,1).*RS1(:,2))-(RS1(:,2).*RS1(:,3))-
(RS1(:,3).*RS1(:,1))-(RS1(:,4).*RS1(:,1))-(RS1(:,5).*RS1(:,1))-
(RS1(:,4).*RS1(:,2))-(RS1(:,5).*RS1(:,2))-(RS1(:,4).*RS1(:,3))-
(RS1(:,5).*RS1(:,3))-(RS1(:,4).*RS1(:,5))-(RS1(:,1).*RS1(:,6))-
(RS1(:,2).*RS1(:,6))-(RS1(:,3).*RS1(:,6))-(RS1(:,4).*RS1(:,6))-
(RS1(:,5).*RS1(:,6));
PmRS2=sum(RS2,2)-(RS2(:,1).*RS2(:,2))-(RS2(:,2).*RS2(:,3))-
(RS2(:,3).*RS2(:,1))-(RS2(:,4).*RS2(:,1))-(RS2(:,5).*RS2(:,1))-
(RS2(:,4).*RS2(:,2))-(RS2(:,5).*RS2(:,2))-(RS2(:,4).*RS2(:,3))-
(RS2(:,5).*RS2(:,3))-(RS2(:,4).*RS2(:,5))-(RS2(:,1).*RS2(:,6))-
(RS2(:,2).*RS2(:,6))-(RS2(:,3).*RS2(:,6))-(RS2(:,4).*RS2(:,6))-
(RS2(:,5).*RS2(:,6));
PmRS3=sum(RS3,2)-(RS3(:,1).*RS3(:,2))-(RS3(:,2).*RS3(:,3))-
(RS3(:,3).*RS3(:,1))-(RS3(:,4).*RS3(:,1))-(RS3(:,5).*RS3(:,1))-
(RS3(:,4).*RS3(:,2))-(RS3(:,5).*RS3(:,2))-(RS3(:,4).*RS3(:,3))-
(RS3(:,5).*RS3(:,3))-(RS3(:,4).*RS3(:,5))-(RS3(:,1).*RS3(:,6))-
(RS3(:,2).*RS3(:,6))-(RS3(:,3).*RS3(:,6))-(RS3(:,4).*RS3(:,6))-
(RS3(:,5).*RS3(:,6));

PmRS=[PmRS1 PmRS2 PmRS3];
meanm=mean(PmRS);

% Deterministic approach
P1det = m;
RS1det = P1det.*0.84;
RS2det = P1det.*0.08;
RS3det = P1det.*0.08;
```

```
PmRS1det=sum(RS1det,2)-(RS1det(:,1).*RS1det(:,2))-
(RS1det(:,2).*RS1det(:,3))-(RS1det(:,3).*RS1det(:,1))-
(RS1det(:,4).*RS1det(:,1))-(RS1det(:,5).*RS1det(:,1))-
(RS1det(:,4).*RS1det(:,2))-(RS1det(:,5).*RS1det(:,2))-
(RS1det(:,4).*RS1det(:,3))-(RS1det(:,5).*RS1det(:,3))-
(RS1det(:,4).*RS1det(:,5))-(RS1det(:,1).*RS1det(:,6))-
(RS1det(:,2).*RS1det(:,6))-(RS1det(:,3).*RS1det(:,6))-
(RS1det(:,4).*RS1det(:,6))-(RS1det(:,6).*RS1det(:,5));
PmRS2det=sum(RS2det,2)-(RS2det(:,1).*RS2det(:,2))-
(RS2det(:,2).*RS2det(:,3))-(RS2det(:,3).*RS2det(:,1))-
(RS2det(:,4).*RS2det(:,1))-(RS2det(:,5).*RS2det(:,1))-
(RS2det(:,4).*RS2det(:,2))-(RS2det(:,5).*RS2det(:,2))-
(RS2det(:,4).*RS2det(:,3))-(RS2det(:,5).*RS2det(:,3))-
(RS2det(:,4).*RS2det(:,5))-(RS2det(:,1).*RS2det(:,6))-
(RS2det(:,3).*RS2det(:,6))-(RS2det(:,3).*RS2det(:,6))-
(RS2det(:,4).*RS2det(:,6))-(RS2det(:,6).*RS2det(:,5));
PmRS3det=sum(RS3det,2)-(RS3det(:,1).*RS3det(:,2))-
(RS3det(:,2).*RS3det(:,3))-(RS3det(:,3).*RS3det(:,1))-
(RS3det(:,4).*RS3det(:,1))-(RS3det(:,5).*RS3det(:,1))-
(RS3det(:,4).*RS3det(:,2))-(RS3det(:,5).*RS3det(:,2))-
(RS3det(:,4).*RS3det(:,3))-(RS3det(:,5).*RS3det(:,3))-
(RS3det(:,4).*RS3det(:,5))-(RS3det(:,1).*RS3det(:,6))-
(RS3det(:,2).*RS3det(:,6))-(RS3det(:,3).*RS3det(:,6))-
(RS3det(:,4).*RS3det(:,4))-(RS3det(:,6).*RS3det(:,5));

PmRSdet =[PmRS1det PmRS2det PmRS3det];

[countsd,centersd] = hist(PmRS1,20);
[countse,centerse] = hist(PmRS2,20);
[countsf,centersf] = hist(PmRS3,20);

yd=linspace(0,(max(countsd/rand)+0.05),100);
ye=linspace(0,(max(countse/rand)+0.05),100);
yf=linspace(0,(max(countsf/rand)+0.05),100);

figure (4)

subplot(3,1,1)
bar(centersd,(countsd/rand),'g');
title ('Failure Probability of Mechanical Components ')
hold on
plot (meanm(1),yd,'b');
hold on
plot (PmRSdet(1),yd,'k');
hold off

subplot(3,1,2)
bar(centerse,(countse/rand),'y')
hold on
plot (meanm(2),ye,'b')
hold on
plot (PmRSdet(2),ye,'k')
hold off

subplot(3,1,3)
bar(centersf,(countsf/rand),'r')
hold on
plot (meanm(3),yf,'b')
hold on
plot (PmRSdet(3),yf,'k')
```

```
hold off

% Probability of release from atmospheric tank

PRS1=PeqRS1+PmRS1-(PeqRS1.*PmRS1);
PRS2=PeqRS2+PmRS2-(PeqRS2.*PmRS2);
PRS3=PeqRS3+PmRS3-(PeqRS3.*PmRS3);
P=[PRS1 PRS2 PRS3];
meanP=mean(P);

% Deterministic approach
PRS1det=PeqRS1det+PmRS1det-(PeqRS1det*PmRS1det);
PRS2det=PeqRS2det+PmRS2det-(PeqRS2det*PmRS2det);
PRS3det=PeqRS3det+PmRS3det-(PeqRS3det*PmRS3det);
PRSdet=[PRS1det PRS2det PRS3det];

[counts1,centers1] = hist(PRS1,20);
[counts2,centers2] = hist(PRS2,20);
[counts3,centers3] = hist(PRS3,20);

y1=linspace(0,(max(counts1/rand)+0.05),100);
y2=linspace(0,(max(counts2/rand)+0.05),100);
y3=linspace(0,(max(counts3/rand)+0.05),100);

figure (5)

subplot(3,1,1)
bar(centers1,(counts1/rand),'g')
title ('Probability of top-event')
hold on
plot (meanP(1),y1,'b')
hold on
plot (PRSdet(1),y1,'k')
hold off

subplot(3,1,2)
bar(centers2,(counts2/rand),'y')
hold on
plot (meanP(2),y2,'b')
hold on
plot (PRSdet(2),y2,'k')
hold off

subplot(3,1,3)
bar(centers3,(counts3/rand),'r')
hold on
plot (meanP(3),y3,'b')
hold on
plot (PRSdet(3),y3,'k')
hold off
```

B. Floating roof tank in Falconara Marittima (AN)

```
clear all
close all

rand=input('number of iterations')
```

```
% Earthquake

% Seismic Matrix
R=xlsread('DistribuzioniFalconara.xlsx', 'distanza', 'A1:A11');
M=xlsread('DistribuzioniFalconara.xlsx', 'Magnitudo', 'A1:H1');
MP=xlsread('DistribuzioniFalconara.xlsx', 'Matrice', 'A1:H11');
F=xlsread('DistribuzioniFalconara.xlsx', 'Frequenza', 'A1:H1');

r=length(R);
m=length(M);
logPGA=[];
for i=1:r
    for j=1:m
        logPGA(i,j)=-3.37+(1.93-0.203*M(j)).*M(j)+(-
3.02+0.00744*M(j)^3)*log10(sqrt(R(i)^2+7.3^2));
    end
end

sigmashell=0.358; % % Shape value of LogPGA
mu2shell=0.38; % Mean value of Fragility Medium hole
sigma2shell=0.8; % shape value of Fragility Medium hole
mu3shell=1.18; % Mean value of Fragility large hole
sigma3shell=0.61;  % Shape value of Fragility large hole
PeqRS1shell=[];
PeqRS2shell=[];
PeqRS3shell=[];
PeqRS1shell=zeros(rand,1);
PeqRS2shell=zeros(rand,1);
PeqRS3shell=zeros(rand,1);

for i=1:rand
    PGA1shell=random ('norm',logPGA,sigmashell);
    PGAshell=(10.^PGA1shell).*9.81;
    RS3eqshell= cdf('logn',PGAshell,mu3shell,sigma3shell);
    RS2eqshell=cdf('logn',PGAshell,mu2shell,sigma2shell);
    Prs1shell=(1-RS2eqshell).*(MP./100);
    Prs2shell=(RS2eqshell-RS3eqshell).*(MP./100);
    Prs3shell=RS3eqshell.*(MP./100);
    PfRS11shell=sum(Prs1shell).*F;
    PfRS1shell=sum(PfRS11shell(:));
    PfRS22shell=sum(Prs2shell).*F;
    PfRS2shell=sum(PfRS22shell(:));
    PfRS33shell=sum(Prs3shell).*F;
    PfRS3shell=sum(PfRS33shell(:));
    PeqRS1shell(i)=[PfRS1shell ];
    PeqRS2shell(i)=[PfRS2shell ];
    PeqRS3shell(i)=[PfRS3shell ];
    i=i+1;
end

PeqRSshell =[PeqRS1shell PeqRS2shell PeqRS3shell];
meaneqshell=mean(PeqRSshell);

% Deterministic approach
PGAdetshell=(10.^logPGA).*9.81;
RS3eqdetshell= cdf('logn',PGAdetshell,mu3shell,sigma3shell);
RS2eqdetshell=cdf('logn',PGAdetshell,mu2shell,sigma2shell);
Prs1detshell=(1-RS2eqdetshell).*(MP./100);
Prs2detshell=(RS2eqdetshell-RS3eqdetshell).*(MP./100);
Prs3detshell=RS3eqdetshell.*(MP./100);
PfRS11detshell= sum(Prs1detshell).*F;
```

```
PfRS1detshell=sum(PfRS11detshell(:));
PfRS22detshell= sum(Prs2detshell).*F;
PfRS2detshell=sum(PfRS22detshell(:));
PfRS33detshell= sum(Prs3detshell).*F;
PfRS3detshell=sum(PfRS33detshell(:));
PeqRSdetshell =[PfRS1detshell PfRS2detshell PfRS3detshell];

[countsa,centersa] = hist(PeqRS1shell,20);
[countsb,centersb] = hist(PeqRS2shell,20);
[countsc,centersc] = hist(PeqRS3shell,20);
[countspga,centerspga] = hist(PGA1shell,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));

figure (1)
subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Shell Failure Probability')
hold on
plot (meaneqshell(1),ya,'b',PeqRSdetshell(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneqshell(2),yb,'b',PeqRSdetshell(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneqshell(3),yc,'b',PeqRSdetshell(3),yc,'k')
hold off

% Pipes

sigma=0.358; % % Shape value of LogPGA
mu2=0.4522; % Mean value of Fragility Medium hole
sigma2=0.39; % shape value of Fragility Medium hole
mu3=0.7116; % Mean value of Fragility large hole
sigma3=0.20;  % Shape value of Fragility large hole
PeqRS1pipe=[];
PeqRS2pipe=[];
PeqRS3pipe=[];
PeqRS1pipe=zeros(rand,1);
PeqRS2pipe=zeros(rand,1);
PeqRS3pipe=zeros(rand,1);

for i=1:rand
    PGA1pipe=random ('norm',logPGA,sigma);
    PGApipe=(10.^PGA1pipe).*9.81;
    RS3eqpipe= cdf('logn',PGApipe,mu3,sigma3);
    RS2eqpipe=cdf('logn',PGApipe,mu2,sigma2);
    Prs1pipe=(1-RS2eqpipe).*(MP./100);
    Prs2pipe=(RS2eqpipe-RS3eqpipe).*(MP./100);
    Prs3pipe=RS3eqpipe.*(MP./100);
    PfRS11pipe=sum(Prs1pipe).*F;
    PfRS1pipe=sum(PfRS11pipe(:));
    PfRS22pipe=sum(Prs2pipe).*F;
```

```
    PfRS2pipe=sum(PfRS22pipe(:));
    PfRS33pipe=sum(Prs3pipe).*F;
    PfRS3pipe=sum(PfRS33pipe(:));
    PeqRS1pipe(i)=[PfRS1pipe ];
    PeqRS2pipe(i)=[PfRS2pipe ];
    PeqRS3pipe(i)=[PfRS3pipe ];
    i=i+1;
end

PeqRSpipe =[PeqRS1pipe PeqRS2pipe PeqRS3pipe];
meaneqpipe=mean(PeqRSpipe);

% Deterministic approach
PGAdetpipe=(10.^logPGA).*9.81;
RS3eqdetpipe= cdf('logn',PGAdetpipe,mu3,sigma3);
RS2eqdetpipe=cdf('logn',PGAdetpipe,mu2,sigma2);
Prs1detpipe=(1-RS2eqdetpipe).*(MP./100);
Prs2detpipe=(RS2eqdetpipe-RS3eqdetpipe).*(MP./100);
Prs3detpipe=RS3eqdetpipe.*(MP./100);
PfRS11detpipe= sum(Prs1detpipe).*F;
PfRS1detpipe=sum(PfRS11detpipe(:));
PfRS22detpipe= sum(Prs2detpipe).*F;
PfRS2detpipe=sum(PfRS22detpipe(:));
PfRS33detpipe= sum(Prs3detpipe).*F;
PfRS3detpipe=sum(PfRS33detpipe(:));
PeqRSdetpipe =[PfRS1detpipe PfRS2detpipe PfRS3detpipe];

[countsa,centersa] = hist(PeqRS1pipe,20);
[countsb,centersb] = hist(PeqRS2pipe,20);
[countsc,centersc] = hist(PeqRS3pipe,20);
[countspga,centerspga] = hist(PGA1pipe,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));

figure (2)

subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Pipe Failure Probability')
hold on
plot (meaneqpipe(1),ya,'b',PeqRSdetpipe(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneqpipe(2),yb,'b',PeqRSdetpipe(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneqpipe(3),yc,'b',PeqRSdetpipe(3),yc,'k')
hold off

% Sum seismic risk

%Probabilistic
PeqRS1= PeqRS1shell+PeqRS1pipe-(PeqRS1shell.*PeqRS1pipe);
```

```
PeqRS2= PeqRS2shell+PeqRS2pipe-(PeqRS2shell.*PeqRS2pipe);
PeqRS3= PeqRS3shell+PeqRS3pipe-(PeqRS3shell.*PeqRS3pipe);

PeqRS =[PeqRS1 PeqRS2 PeqRS3];
meaneq=mean(PeqRS);

%Deterministic
PeqRS1det= PfRS1detshell+PfRS1detpipe-(PfRS1detshell.*PfRS1detpipe);
PeqRS2det= PfRS2detshell+PfRS2detpipe-(PfRS2detshell.*PfRS2detpipe);
PeqRS3det= PfRS3detshell+PfRS3detpipe-(PfRS3detshell.*PfRS3detpipe);
PeqRSdet =[PeqRS1det PeqRS2det PeqRS3det];

[countsa,centersa] = hist(PeqRS1,20);
[countsb,centersb] = hist(PeqRS2,20);
[countsc,centersc] = hist(PeqRS3,20);
[countspga,centerspga] = hist(PGA1pipe,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));

figure (3)
subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Seismic Failure Probability')
hold on
plot (meaneq(1),ya,'b',PeqRSdet(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneq(2),yb,'b',PeqRSdet(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneq(3),yc,'b',PeqRSdet(3),yc,'k')
hold off

% Failure rate of mechanical component

%longnormal distribution
m= [0.0016 0.0009 0.0014 0.000000048 0.0000001 0.00000021]; %event/years
LB=[0.0011 0.0005 0.0009 0.00000002 0.000000024 0.000000038]; %event/years
UB=[0.0023 0.0014 0.002 0.000000112 0.00000041 0.00000053]; %event/years

ef=sqrt(UB./LB);
sig=log(ef)/1.645;
v=(m.^2).*(exp(sig.^2)-1);
sigmashell=sig;
mu = log((m.^2)./sqrt(v+m.^2));

T=50;
X=[];
for i=1:rand
    for j=1:length(m)
        X(i,j)=random ('logn',mu(j),sigmashell(j));
          if (X(j)<=UB(j) && X(j)>=LB(j))
```

```
            X(i,j)=X(i,j);
          else
              if (X(j)<UB(j))
                  X(i,j)=UB(j);
              end
              if (X(j)>LB(j))
                  X(i,j)=LB(j);
              end
          end
          P1(i,j) = X(i,j);
          RS1(i,j) = P1(i,j).*0.84;
          RS2(i,j) = P1(i,j).*0.08;
          RS3(i,j) = P1(i,j).*0.08;
    end
end
PmRS1=sum(RS1,2)-(RS1(:,1).*RS1(:,2))-(RS1(:,2).*RS1(:,3))-
(RS1(:,3).*RS1(:,1))-(RS1(:,4).*RS1(:,1))-(RS1(:,5).*RS1(:,1))-
(RS1(:,4).*RS1(:,2))-(RS1(:,5).*RS1(:,2))-(RS1(:,4).*RS1(:,3))-
(RS1(:,5).*RS1(:,3))-(RS1(:,4).*RS1(:,5))-(RS1(:,1).*RS1(:,6))-
(RS1(:,2).*RS1(:,6))-(RS1(:,3).*RS1(:,6))-(RS1(:,4).*RS1(:,6))-
(RS1(:,5).*RS1(:,6));
PmRS2=sum(RS2,2)-(RS2(:,1).*RS2(:,2))-(RS2(:,2).*RS2(:,3))-
(RS2(:,3).*RS2(:,1))-(RS2(:,4).*RS2(:,1))-(RS2(:,5).*RS2(:,1))-
(RS2(:,4).*RS2(:,2))-(RS2(:,5).*RS2(:,2))-(RS2(:,4).*RS2(:,3))-
(RS2(:,5).*RS2(:,3))-(RS2(:,4).*RS2(:,5))-(RS2(:,1).*RS2(:,6))-
(RS2(:,2).*RS2(:,6))-(RS2(:,3).*RS2(:,6))-(RS2(:,4).*RS2(:,6))-
(RS2(:,5).*RS2(:,6));
PmRS3=sum(RS3,2)-(RS3(:,1).*RS3(:,2))-(RS3(:,2).*RS3(:,3))-
(RS3(:,3).*RS3(:,1))-(RS3(:,4).*RS3(:,1))-(RS3(:,5).*RS3(:,1))-
(RS3(:,4).*RS3(:,2))-(RS3(:,5).*RS3(:,2))-(RS3(:,4).*RS3(:,3))-
(RS3(:,5).*RS3(:,3))-(RS3(:,4).*RS3(:,5))-(RS3(:,1).*RS3(:,6))-
(RS3(:,2).*RS3(:,6))-(RS3(:,3).*RS3(:,6))-(RS3(:,4).*RS3(:,6))-
(RS3(:,5).*RS3(:,6));

PmRS=[PmRS1 PmRS2 PmRS3];
meanm=mean(PmRS);

% Deterministic approach
P1det = m;
RS1det = P1det.*0.84;
RS2det = P1det.*0.08;
RS3det = P1det.*0.08;

PmRS1det=sum(RS1det,2)-(RS1det(:,1).*RS1det(:,2))-
(RS1det(:,2).*RS1det(:,3))-(RS1det(:,3).*RS1det(:,1))-
(RS1det(:,4).*RS1det(:,1))-(RS1det(:,5).*RS1det(:,1))-
(RS1det(:,4).*RS1det(:,2))-(RS1det(:,5).*RS1det(:,2))-
(RS1det(:,4).*RS1det(:,3))-(RS1det(:,5).*RS1det(:,3))-
(RS1det(:,4).*RS1det(:,5))-(RS1det(:,1).*RS1det(:,6))-
(RS1det(:,2).*RS1det(:,6))-(RS1det(:,3).*RS1det(:,6))-
(RS1det(:,4).*RS1det(:,6))-(RS1det(:,6).*RS1det(:,5));
PmRS2det=sum(RS2det,2)-(RS2det(:,1).*RS2det(:,2))-
(RS2det(:,2).*RS2det(:,3))-(RS2det(:,3).*RS2det(:,1))-
(RS2det(:,4).*RS2det(:,1))-(RS2det(:,5).*RS2det(:,1))-
(RS2det(:,4).*RS2det(:,2))-(RS2det(:,5).*RS2det(:,2))-
(RS2det(:,4).*RS2det(:,3))-(RS2det(:,5).*RS2det(:,3))-
(RS2det(:,4).*RS2det(:,5))-(RS2det(:,1).*RS2det(:,6))-
(RS2det(:,3).*RS2det(:,6))-(RS2det(:,3).*RS2det(:,6))-
(RS2det(:,4).*RS2det(:,6))-(RS2det(:,6).*RS2det(:,5));
PmRS3det=sum(RS3det,2)-(RS3det(:,1).*RS3det(:,2))-
(RS3det(:,2).*RS3det(:,3))-(RS3det(:,3).*RS3det(:,1))-
(RS3det(:,4).*RS3det(:,1))-(RS3det(:,5).*RS3det(:,1))-
```

```
(RS3det(:,4).*RS3det(:,2))-(RS3det(:,5).*RS3det(:,2))-
(RS3det(:,4).*RS3det(:,3))-(RS3det(:,5).*RS3det(:,3))-
(RS3det(:,4).*RS3det(:,5))-(RS3det(:,1).*RS3det(:,6))-
(RS3det(:,2).*RS3det(:,6))-(RS3det(:,3).*RS3det(:,6))-
(RS3det(:,4).*RS3det(:,4))-(RS3det(:,6).*RS3det(:,5));

PmRSdet =[PmRS1det PmRS2det PmRS3det];

[countsd,centersd] = hist(PmRS1,20);
[countse,centerse] = hist(PmRS2,20);
[countsf,centersf] = hist(PmRS3,20);

yd=linspace(0,(max(countsd/rand)+0.05),100);
ye=linspace(0,(max(countse/rand)+0.05),100);
yf=linspace(0,(max(countsf/rand)+0.05),100);

figure (4)

subplot(3,1,1)
bar(centersd,(countsd/rand),'g');
title ('Failure Probability of Mechanical Components ')
hold on
plot (meanm(1),yd,'b');
hold on
plot (PmRSdet(1),yd,'k');
hold off

subplot(3,1,2)
bar(centerse,(countse/rand),'y')
hold on
plot (meanm(2),ye,'b')
hold on
plot (PmRSdet(2),ye,'k')
hold off

subplot(3,1,3)
bar(centersf,(countsf/rand),'r')
hold on
plot (meanm(3),yf,'b')
hold on
plot (PmRSdet(3),yf,'k')
hold off

% Probability of release from atmospheric tank

PRS1=PeqRS1+PmRS1-(PeqRS1.*PmRS1);
PRS2=PeqRS2+PmRS2-(PeqRS2.*PmRS2);
PRS3=PeqRS3+PmRS3-(PeqRS3.*PmRS3);
P=[PRS1 PRS2 PRS3];
meanP=mean(P);

% Deterministic approach
PRS1det=PeqRS1det+PmRS1det-(PeqRS1det*PmRS1det);
PRS2det=PeqRS2det+PmRS2det-(PeqRS2det*PmRS2det);
PRS3det=PeqRS3det+PmRS3det-(PeqRS3det*PmRS3det);
PRSdet=[PRS1det PRS2det PRS3det];

[counts1,centers1] = hist(PRS1,20);
[counts2,centers2] = hist(PRS2,20);
[counts3,centers3] = hist(PRS3,20);
```

```
y1=linspace(0,(max(counts1/rand)+0.05),100);
y2=linspace(0,(max(counts2/rand)+0.05),100);
y3=linspace(0,(max(counts3/rand)+0.05),100);

figure (5)

subplot(3,1,1)
bar(centers1,(counts1/rand),'g')
title ('Probability of top-event')
hold on
plot (meanP(1),y1,'b')
hold on
plot (PRSdet(1),y1,'k')
hold off

subplot(3,1,2)
bar(centers2,(counts2/rand),'y')
hold on
plot (meanP(2),y2,'b')
hold on
plot (PRSdet(2),y2,'k')
hold off

subplot(3,1,3)
bar(centers3,(counts3/rand),'r')
hold on
plot (meanP(3),y3,'b')
hold on
plot (PRSdet(3),y3,'k')
hold off
```

C. Pressurized tank in Priolo (SR)

```
clear all
close all

rand=input('number of iterations')

% Earthquakes

% Seismic Matrix
R=xlsread('DistribuzioniPriolo.xlsx', 'distanza', 'A1:A9');
M=xlsread('DistribuzioniPriolo.xlsx', 'Magnitudo', 'A1:I1');
MP=xlsread('DistribuzioniPriolo.xlsx', 'Matrice', 'A1:I9');
F=xlsread('DistribuzioniPriolo.xlsx', 'Frequenza', 'A1:I1');

r=length(R);
m=length(M);
logPGA=[];
for i=1:r
    for j=1:m
        logPGA(i,j)=-3.37+(1.93-0.203*M(j)).*M(j)+(-
3.02+0.00744*M(j)^3)*log10(sqrt(R(i)^2+7.3^2));
    end
end

sigmashell=0.358; % % Shape value of LogPGA
mu1shell=0.83; %Mean value of Fragility Small hole
```

```
sigma1shell=0.99;  %shape value of Fragility Small hole
mu2shell=1.85; % Mean value of Fragility Medium hole
sigma2shell=0.85; % shape value of Fragility Medium hole
mu3shell=4.91; % Mean value of Fragility large hole
sigma3shell=0.84;  % Shape value of Fragility large hole
PeqRS1shell=[];
PeqRS2shell=[];
PeqRS3shell=[];
PeqRS1shell=zeros(rand,1);
PeqRS2shell=zeros(rand,1);
PeqRS3shell=zeros(rand,1);

for i=1:rand
    PGA1shell=random ('norm',logPGA,sigmashell);
    PGAshell=(10.^PGA1shell).*9.81;
    RS1eqshell= cdf('logn',PGAshell,mu1shell,sigma1shell);
    RS3eqshell= cdf('logn',PGAshell,mu3shell,sigma3shell);
    RS2eqshell= cdf('logn',PGAshell,mu2shell,sigma2shell);
    Prs1shell=(1-RS1eqshell).*(MP./100);
    Prs2shell=(RS2eqshell-RS3eqshell).*(MP./100);
    Prs3shell=RS3eqshell.*(MP./100);
    PfRS11shell=sum(Prs1shell).*F;
    PfRS1shell=sum(PfRS11shell(:));
    PfRS22shell=sum(Prs2shell).*F;
    PfRS2shell=sum(PfRS22shell(:));
    PfRS33shell=sum(Prs3shell).*F;
    PfRS3shell=sum(PfRS33shell(:));
    PeqRS1shell(i)=[PfRS1shell ];
    PeqRS2shell(i)=[PfRS2shell ];
    PeqRS3shell(i)=[PfRS3shell ];
    i=i+1;
end

PeqRSshell =[PeqRS1shell PeqRS2shell PeqRS3shell];
meaneqshell=mean(PeqRSshell);

% Deterministic approach
PGAdetshell=(10.^logPGA).*9.81;
RS3eqdetshell= cdf('logn',PGAdetshell,mu3shell,sigma3shell);
RS2eqdetshell=cdf('logn',PGAdetshell,mu2shell,sigma2shell);
Prs1detshell=(1-RS2eqdetshell).*(MP./100);
Prs2detshell=(RS2eqdetshell-RS3eqdetshell).*(MP./100);
Prs3detshell=RS3eqdetshell.*(MP./100);
PfRS11detshell= sum(Prs1detshell).*F;
PfRS1detshell=sum(PfRS11detshell(:));
PfRS22detshell= sum(Prs2detshell).*F;
PfRS2detshell=sum(PfRS22detshell(:));
PfRS33detshell= sum(Prs3detshell).*F;
PfRS3detshell=sum(PfRS33detshell(:));
PeqRSdetshell =[PfRS1detshell PfRS2detshell PfRS3detshell];

[countsa,centersa] = hist(PeqRS1shell,20);
[countsb,centersb] = hist(PeqRS2shell,20);
[countsc,centersc] = hist(PeqRS3shell,20);
[countspga,centerspga] = hist(PGA1shell,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));

figure (2)
```

```
subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Shell Failure Probability')
hold on
plot (meaneqshell(1),ya,'b',PeqRSdetshell(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneqshell(2),yb,'b',PeqRSdetshell(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneqshell(3),yc,'b',PeqRSdetshell(3),yc,'k')
hold off

% Pipes

sigma=0.358; % % Shape value of LogPGA
mu2=0.4522; % Mean value of Fragility Medium hole
sigma2=0.39; % shape value of Fragility Medium hole
mu3=0.7116; % Mean value of Fragility large hole
sigma3=0.20;  % Shape value of Fragility large hole
PeqRS1pipe=[];
PeqRS2pipe=[];
PeqRS3pipe=[];
PeqRS1pipe=zeros(rand,1);
PeqRS2pipe=zeros(rand,1);
PeqRS3pipe=zeros(rand,1);

for i=1:rand
    PGA1pipe=random ('norm',logPGA,sigma);
    PGApipe=(10.^PGA1pipe).*9.81;
    RS3eqpipe= cdf('logn',PGApipe,mu3,sigma3);
    RS2eqpipe=cdf('logn',PGApipe,mu2,sigma2);
    Prs1pipe=(1-RS2eqpipe).*(MP./100);
    Prs2pipe=(RS2eqpipe-RS3eqpipe).*(MP./100);
    Prs3pipe=RS3eqpipe.*(MP./100);
    PfRS11pipe=sum(Prs1pipe).*F;
    PfRS1pipe=sum(PfRS11pipe(:));
    PfRS22pipe=sum(Prs2pipe).*F;
    PfRS2pipe=sum(PfRS22pipe(:));
    PfRS33pipe=sum(Prs3pipe).*F;
    PfRS3pipe=sum(PfRS33pipe(:));
    PeqRS1pipe(i)=[PfRS1pipe ];
    PeqRS2pipe(i)=[PfRS2pipe ];
    PeqRS3pipe(i)=[PfRS3pipe ];
    i=i+1;
end

PeqRSpipe =[PeqRS1pipe PeqRS2pipe PeqRS3pipe];
meaneqpipe=mean(PeqRSpipe);

% Deterministic approach
PGAdetpipe=(10.^logPGA).*9.81;
RS3eqdetpipe= cdf('logn',PGAdetpipe,mu3,sigma3);
RS2eqdetpipe=cdf('logn',PGAdetpipe,mu2,sigma2);
```

```
Prs1detpipe=(1-RS2eqdetpipe).*(MP./100);
Prs2detpipe=RS3eqdetpipe.*(MP./100);
Prs3detpipe=Prs2detpipe;
PfRS11detpipe= sum(Prs1detpipe).*F;
PfRS1detpipe=sum(PfRS11detpipe(:));
PfRS22detpipe= sum(Prs2detpipe).*F;
PfRS2detpipe=sum(PfRS22detpipe(:));
PfRS33detpipe= sum(Prs3detpipe).*F;
PfRS3detpipe=sum(PfRS33detpipe(:));
PeqRSdetpipe =[PfRS1detpipe PfRS2detpipe PfRS3detpipe];

[countsa,centersa] = hist(PeqRS1pipe,20);
[countsb,centersb] = hist(PeqRS2pipe,20);
[countsc,centersc] = hist(PeqRS3pipe,20);
[countspga,centerspga] = hist(PGA1pipe,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));

figure (3)

subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Pipe Failure Probability')
hold on
plot (meaneqpipe(1),ya,'b',PeqRSdetpipe(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneqpipe(2),yb,'b',PeqRSdetpipe(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneqpipe(3),yc,'b',PeqRSdetpipe(3),yc,'k')
hold off

% Sum seismic risk

%Probabilistic
PeqRS1= PeqRS1shell+PeqRS1pipe-(PeqRS1shell.*PeqRS1pipe);
PeqRS2= PeqRS2shell+PeqRS2pipe-(PeqRS2shell.*PeqRS2pipe);
PeqRS3= PeqRS3shell+PeqRS3pipe-(PeqRS3shell.*PeqRS3pipe);

PeqRS =[PeqRS1 PeqRS2 PeqRS3];
meaneq=mean(PeqRS);

%Deterministic
PeqRS1det= PfRS1detshell+PfRS1detpipe-(PfRS1detshell.*PfRS1detpipe);
PeqRS2det= PfRS2detshell+PfRS2detpipe-(PfRS2detshell.*PfRS2detpipe);
PeqRS3det= PfRS3detshell+PfRS3detpipe-(PfRS3detshell.*PfRS3detpipe);
PeqRSdet =[PeqRS1det PeqRS2det PeqRS3det];

[countsa,centersa] = hist(PeqRS1,20);
[countsb,centersb] = hist(PeqRS2,20);
[countsc,centersc] = hist(PeqRS3,20);
```

```
[countspga,centerspga] = hist(PGA1pipe,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));

figure (4)

subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Seismic Failure Probability')
hold on
plot (meaneq(1),ya,'b',PeqRSdet(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneq(2),yb,'b',PeqRSdet(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneq(3),yc,'b',PeqRSdet(3),yc,'k')
hold off

%Mechanical failure probability

mmec= [0.000000048 0.0000001 0.00000021]; %event/years
LBmec=[0.00000002 0.000000024 0.000000038]; %event/years
UBmec=[0.000000112 0.00000041 0.00000053]; %event/years

efmec=sqrt(UBmec./LBmec);

sigmec=log(efmec)/1.645;
vmec=(mmec.^2).*(exp(sigmec.^2)-1);
sigmamec=sigmec;
mumec = log((mmec.^2)./sqrt(vmec+mmec.^2));

T=50;
X=[];
for i=1:rand
    for j=1:length(mmec)
        X(i,j)=random ('logn',mumec(j),sigmamec(j));
          if (X(j)<=UBmec(j) && X(j)>=LBmec(j))
            X(i,j)=X(i,j);
          else
              if (X(j)<UBmec(j))
                  X(i,j)=UBmec(j);
              end
              if (X(j)>LBmec(j))
                  X(i,j)=LBmec(j);
              end
          end
          P1mec(i,j) = X(i,j);
          RS1mec(i,j) = P1mec(i,j).*0.84;
          RS2mec(i,j) = P1mec(i,j).*0.08;
          RS3mec(i,j) = P1mec(i,j).*0.08;
    end
end
```

```
PmRS1mec=sum(RS1mec,2)-(RS1mec(:,1).*RS1mec(:,2))-
(RS1mec(:,1).*RS1mec(:,3))-(RS1mec(:,3).*RS1mec(:,2));
PmRS2mec=sum(RS2mec,2)-(RS2mec(:,1).*RS2mec(:,2))-
(RS2mec(:,1).*RS2mec(:,3))-(RS2mec(:,3).*RS2mec(:,2));
PmRS3mec=sum(RS3mec,2)-(RS3mec(:,1).*RS3mec(:,2))-
(RS3mec(:,1).*RS3mec(:,3))-(RS3mec(:,3).*RS3mec(:,2));

PmRSmec =[PmRS1mec PmRS2mec PmRS3mec];
meanmmec=mean(PmRSmec);

% deterministic approach

P1detmec = mmec;
RS1detmec = P1detmec.*0.84;
RS2detmec = P1detmec.*0.08;
RS3detmec = P1detmec.*0.08;
PmRS1detmec=sum(RS1detmec)-(RS1detmec(:,1).*RS1detmec(:,2))-
(RS1detmec(:,1).*RS1detmec(:,3))-(RS1detmec(:,3).*RS1detmec(:,2));
PmRS2detmec=sum(RS2detmec,2)-(RS2detmec(:,1).*RS2detmec(:,2))-
(RS2detmec(:,1).*RS2detmec(:,3))-(RS2detmec(:,3).*RS2detmec(:,2));
PmRS3detmec=sum(RS3detmec,2)-(RS3detmec(:,1).*RS3detmec(:,2))-
(RS3detmec(:,1).*RS3detmec(:,3))-(RS3detmec(:,3).*RS3detmec(:,2));

PmRSdetmec =[PmRS1detmec PmRS2detmec PmRS3detmec];

[countsd,centersd] = hist(PmRS1mec,20);
[countse,centerse] = hist(PmRS2mec,20);
[countsf,centersf] = hist(PmRS3mec,20);

yd=linspace(0,(max(countsd/rand)+0.05),100);
ye=linspace(0,(max(countse/rand)+0.05),100);
yf=linspace(0,(max(countsf/rand)+0.05),100);

figure (5)

subplot(3,1,1)
bar(centersd,(countsd/rand),'g');
title ('Mechanical Failure Probability of Pipes and Valves')
hold on
plot (meanmmec(1),yd,'b');
hold on
plot (PmRSdetmec(1),yd,'k');
hold off

subplot(3,1,2)
bar(centerse,(countse/rand),'y')
hold on
plot (meanmmec(2),ye,'b')
hold on
plot (PmRSdetmec(2),ye,'k')
hold off

subplot(3,1,3)
bar(centersf,(countsf/rand),'r')
hold on
plot (meanmmec(3),yf,'b')
hold on
plot (PmRSdetmec(3),yf,'k')
hold off
```

```
%Pressure shell

mshell= [0.000081 0.000052 0.0000097]; %event/years
LBshell=[0.000046 0.000025 0.0000014]; %event/years
UBshell=[0.00013 0.000095 0.000036]; %event/years

efshell=sqrt(UBshell./LBshell);

sigshell=log(efshell)/1.645;
vshell=(mshell.^2).*(exp(sigshell.^2)-1);
sigmashell=sigshell;
mushell = log((mshell.^2)./sqrt(vshell+mshell.^2));

T=50;
X=[];
for i=1:rand
    for j=1:length(mshell)
        X(i,j)=random ('logn',mushell(j),sigmashell(j));
    end
end
PmRS1shell=P1shell(:,1);
PmRS2shell=P1shell(:,2);
PmRS3shell=P1shell(:,3);

PmRSshell =[PmRS1shell PmRS2shell PmRS3shell];
meanmshell=mean(PmRSshell);

% Deterministic approach
P1detshell = mshell;
PmRS1detshell=P1detshell(1,1);
PmRS2detshell=P1detshell(1,2);
PmRS3detshell=P1detshell(1,3);

PmRSdetshell =[PmRS1detshell PmRS2detshell PmRS3detshell];

[countsd,centersd] = hist(PmRS1shell,20);
[countse,centerse] = hist(PmRS2shell,20);
[countsf,centersf] = hist(PmRS3shell,20);

yd=linspace(0,(max(countsd/rand)+0.05),100);
ye=linspace(0,(max(countse/rand)+0.05),100);
yf=linspace(0,(max(countsf/rand)+0.05),100);

figure (6)

subplot(3,1,1)
bar(centersd,(countsd/rand),'g');
title ('Mechanical Failure Shell')
hold on
plot (meanmshell(:,1),yd,'b');
hold on
plot (PmRSdetshell(1),yd,'k');
hold off

subplot(3,1,2)
bar(centerse,(countse/rand),'y')
hold on
plot (meanmshell(:,2),ye,'b')
hold on
plot (PmRSdetshell(2),ye,'k')
```

```
hold off

subplot(3,1,3)
bar(centersf,(countsf/rand),'r')
hold on
plot (meanmshell(:,3),yf,'b')
hold on
plot (PmRSdetshell(3),yf,'k')
hold off

%Summation

PmRS1=PmRSmec(:,1)+PmRSshell(1,1)-(PmRSmec(:,1).*PmRSshell(1,1));
PmRS2=PmRSmec(:,2)+PmRSshell(1,2)-(PmRSmec(:,2).*PmRSshell(1,2));
PmRS3=PmRSmec(:,3)+PmRSshell(1,3)-(PmRSmec(:,3).*PmRSshell(1,3));
PmRS= [PmRS1 PmRS2 PmRS3];
meanm=mean(PmRS);

PmRSdet=PmRSdetmec+PmRSdetshell-(PmRSdetmec.*PmRSdetshell);
PmRS1det=PmRSdet(:,1);
PmRS2det=PmRSdet(:,2);
PmRS3det=PmRSdet(:,3);

[countsd,centersd] = hist(PmRS1,20);
[countse,centerse] = hist(PmRS2,20);
[countsf,centersf] = hist(PmRS3,20);

yd=linspace(0,(max(countsd/rand)+0.05),100);
ye=linspace(0,(max(countse/rand)+0.05),100);
yf=linspace(0,(max(countsf/rand)+0.05),100);

figure (7)

subplot(3,1,1)
bar(centersd,(countsd/rand),'g');
title ('Failure Probability due to Mechanical Components')
hold on
plot (meanm(1),yd,'b');
hold on
hold off

subplot(3,1,2)
bar(centerse,(countse/rand),'y')
hold on
plot (meanm(2),ye,'b')
hold on
hold off

subplot(3,1,3)
bar(centersf,(countsf/rand),'r')
hold on
plot (meanm(3),yf,'b')
hold on
hold off

% Probability of release from pressurized tank

PRS1=PeqRS1+PmRS1-(PeqRS1.*PmRS1);
PRS2=PeqRS2+PmRS2-(PeqRS2.*PmRS2);
PRS3=PeqRS3+PmRS3-(PeqRS3.*PmRS3);
```

```
P=[PRS1 PRS2 PRS3];
meanP=mean(P);

% Deterministic approach
PRS1det=PeqRS1det+PmRS1det-(PeqRS1det*PmRS1det);
PRS2det=PeqRS2det+PmRS2det-(PeqRS2det*PmRS2det);
PRS3det=PeqRS3det+PmRS3det-(PeqRS3det*PmRS3det);
PRSdet=[PRS1det PRS2det PRS3det];

[counts1,centers1] = hist(PRS1,20);
[counts2,centers2] = hist(PRS2,20);
[counts3,centers3] = hist(PRS3,20);

y1=linspace(0,(max(counts1/rand)+0.05),100);
y2=linspace(0,(max(counts2/rand)+0.05),100);
y3=linspace(0,(max(counts3/rand)+0.05),100);

figure (8)

subplot(3,1,1)
bar(centers1,(counts1/rand),'g')
title ('Probability of top-event')
hold on
plot (meanP(1),y1,'b')
hold on
plot (PRSdet(1),y1,'k')
hold off

subplot(3,1,2)
bar(centers2,(counts2/rand),'y')
hold on
plot (meanP(2),y2,'b')
hold on
plot (PRSdet(2),y2,'k')
hold off

subplot(3,1,3)
bar(centers3,(counts3/rand),'r')
hold on
plot (meanP(3),y3,'b')
hold on
plot (PRSdet(3),y3,'k')
hold off
```

D. Pressurized tank in Falconara Marittima (AN)

```
clear all
close all

rand=input('number of iterations')


% seismic Matrix
R=xlsread('DistribuzioniFalconara.xlsx', 'distanza', 'A1:A11');
M=xlsread('DistribuzioniFalconara.xlsx', 'Magnitudo', 'A1:H1');
MP=xlsread('DistribuzioniFalconara.xlsx', 'Matrice', 'A1:H11');
F=xlsread('DistribuzioniFalconara.xlsx', 'Frequenza', 'A1:H1');
```

```
r=length(R);
m=length(M);
logPGA=[];
for i=1:r
    for j=1:m
        logPGA(i,j)=-3.37+(1.93-0.203*M(j)).*M(j)+(-
3.02+0.00744*M(j)^3)*log10(sqrt(R(i)^2+7.3^2));
    end
end

sigmashell=0.358; % % Shape value of LogPGA
mu1shell=0.83; %Mean value of Fragility Small hole
sigma1shell=0.99;  %shape value of Fragility Small hole
mu2shell=1.85; % Mean value of Fragility Medium hole
sigma2shell=0.85; % shape value of Fragility Medium hole
mu3shell=4.91; % Mean value of Fragility large hole
sigma3shell=0.84;  % Shape value of Fragility large hole
PeqRS1shell=[];
PeqRS2shell=[];
PeqRS3shell=[];
PeqRS1shell=zeros(rand,1);
PeqRS2shell=zeros(rand,1);
PeqRS3shell=zeros(rand,1);

for i=1:rand
    PGA1shell=random ('norm',logPGA,sigmashell);
    PGAshell=(10.^PGA1shell).*9.81;
    RS1eqshell= cdf('logn',PGAshell,mu1shell,sigma1shell);
    RS3eqshell= cdf('logn',PGAshell,mu3shell,sigma3shell);
    RS2eqshell= cdf('logn',PGAshell,mu2shell,sigma2shell);
    Prs1shell=(1-RS1eqshell).*(MP./100);
    Prs2shell=(1-RS2eqshell).*(MP./100);
    Prs3shell=RS3eqshell.*(MP./100);
    PfRS11shell=sum(Prs1shell).*F;
    PfRS1shell=sum(PfRS11shell(:));
    PfRS22shell=sum(Prs2shell).*F;
    PfRS2shell=sum(PfRS22shell(:));
    PfRS33shell=sum(Prs3shell).*F;
    PfRS3shell=sum(PfRS33shell(:));
    PeqRS1shell(i)=[PfRS1shell ];
    PeqRS2shell(i)=[PfRS2shell ];
    PeqRS3shell(i)=[PfRS3shell ];
    i=i+1;
end

PeqRSshell =[PeqRS1shell PeqRS2shell PeqRS3shell];
meaneqshell=mean(PeqRSshell);

% Deterministic approach
PGAdetshell=(10.^logPGA).*9.81;
RS3eqdetshell= cdf('logn',PGAdetshell,mu3shell,sigma3shell);
RS2eqdetshell=cdf('logn',PGAdetshell,mu2shell,sigma2shell);
Prs1detshell=(1-RS2eqdetshell).*(MP./100);
Prs2detshell=(RS2eqdetshell-RS3eqdetshell).*(MP./100);
Prs3detshell=RS3eqdetshell.*(MP./100);
PfRS11detshell= sum(Prs1detshell).*F;
PfRS1detshell=sum(PfRS11detshell(:));
PfRS22detshell= sum(Prs2detshell).*F;
PfRS2detshell=sum(PfRS22detshell(:));
PfRS33detshell= sum(Prs3detshell).*F;
PfRS3detshell=sum(PfRS33detshell(:));
PeqRSdetshell =[PfRS1detshell PfRS2detshell PfRS3detshell];
```

```
[countsa,centersa] = hist(PeqRS1shell,20);
[countsb,centersb] = hist(PeqRS2shell,20);
[countsc,centersc] = hist(PeqRS3shell,20);
[countspga,centerspga] = hist(PGA1shell,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));

figure (2)

subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Shell Failure Probability')
hold on
plot (meaneqshell(1),ya,'b',PeqRSdetshell(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneqshell(2),yb,'b',PeqRSdetshell(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneqshell(3),yc,'b',PeqRSdetshell(3),yc,'k')
hold off

% Pipes

sigma=0.358; % % Shape value of LogPGA
mu2=0.4522; % Mean value of Fragility Medium hole
sigma2=0.39; % shape value of Fragility Medium hole
mu3=0.7116; % Mean value of Fragility large hole
sigma3=0.20;  % Shape value of Fragility large hole
PeqRS1pipe=[];
PeqRS2pipe=[];
PeqRS3pipe=[];
PeqRS1pipe=zeros(rand,1);
PeqRS2pipe=zeros(rand,1);
PeqRS3pipe=zeros(rand,1);

for i=1:rand
    PGA1pipe=random ('norm',logPGA,sigma);
    PGApipe=(10.^PGA1pipe).*9.81;
    RS3eqpipe= cdf('logn',PGApipe,mu3,sigma3);
    RS2eqpipe=cdf('logn',PGApipe,mu2,sigma2);
    Prs1pipe=(1-RS2eqpipe).*(MP./100);
    Prs2pipe=(RS2eqpipe-RS3eqpipe).*(MP./100);
    Prs3pipe=RS3eqpipe.*(MP./100);
    PfRS11pipe=sum(Prs1pipe).*F;
    PfRS1pipe=sum(PfRS11pipe(:));
    PfRS22pipe=sum(Prs2pipe).*F;
    PfRS2pipe=sum(PfRS22pipe(:));
    PfRS33pipe=sum(Prs3pipe).*F;
    PfRS3pipe=sum(PfRS33pipe(:));
    PeqRS1pipe(i)=[PfRS1pipe ];
    PeqRS2pipe(i)=[PfRS2pipe ];
```

```
    PeqRS3pipe(i)=[PfRS3pipe ];
    i=i+1;
end

PeqRSpipe =[PeqRS1pipe PeqRS2pipe PeqRS3pipe];
meaneqpipe=mean(PeqRSpipe);

% Deterministic approach
PGAdetpipe=(10.^logPGA).*9.81;
RS3eqdetpipe= cdf('logn',PGAdetpipe,mu3,sigma3);
RS2eqdetpipe=cdf('logn',PGAdetpipe,mu2,sigma2);
Prs1detpipe=(1-RS2eqdetpipe).*(MP./100);
Prs2detpipe=RS3eqdetpipe.*(MP./100);
Prs3detpipe=Prs2detpipe;
PfRS11detpipe= sum(Prs1detpipe).*F;
PfRS1detpipe=sum(PfRS11detpipe(:));
PfRS22detpipe= sum(Prs2detpipe).*F;
PfRS2detpipe=sum(PfRS22detpipe(:));
PfRS33detpipe= sum(Prs3detpipe).*F;
PfRS3detpipe=sum(PfRS33detpipe(:));
PeqRSdetpipe =[PfRS1detpipe PfRS2detpipe PfRS3detpipe];

[countsa,centersa] = hist(PeqRS1pipe,20);
[countsb,centersb] = hist(PeqRS2pipe,20);
[countsc,centersc] = hist(PeqRS3pipe,20);
[countspga,centerspga] = hist(PGA1pipe,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));

figure (3)

subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Pipe Failure Probability')
hold on
plot (meaneqpipe(1),ya,'b',PeqRSdetpipe(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneqpipe(2),yb,'b',PeqRSdetpipe(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneqpipe(3),yc,'b',PeqRSdetpipe(3),yc,'k')
hold off

% Sum seismic risk

%Probabilistic
PeqRS1= PeqRS1shell+PeqRS1pipe-(PeqRS1shell.*PeqRS1pipe);
PeqRS2= PeqRS2shell+PeqRS2pipe-(PeqRS2shell.*PeqRS2pipe);
PeqRS3= PeqRS3shell+PeqRS3pipe-(PeqRS3shell.*PeqRS3pipe);

PeqRS =[PeqRS1 PeqRS2 PeqRS3];
```

```
meaneq=mean(PeqRS);

%Deterministic
PeqRS1det= PfRS1detshell+PfRS1detpipe-(PfRS1detshell.*PfRS1detpipe);
PeqRS2det= PfRS2detshell+PfRS2detpipe-(PfRS2detshell.*PfRS2detpipe);
PeqRS3det= PfRS3detshell+PfRS3detpipe-(PfRS3detshell.*PfRS3detpipe);
PeqRSdet =[PeqRS1det PeqRS2det PeqRS3det];

[countsa,centersa] = hist(PeqRS1,20);
[countsb,centersb] = hist(PeqRS2,20);
[countsc,centersc] = hist(PeqRS3,20);
[countspga,centerspga] = hist(PGA1pipe,20);

ya=linspace(0,(max(countsa/rand)+0.05));
yb=linspace(0,(max(countsb/rand)+0.05));
yc=linspace(0,(max(countsc/rand)+0.05));


figure (4)

subplot(3,1,1)
bar(centersa,(countsa/rand),'g');
title ('Seismic Failure Probability')
hold on
plot (meaneq(1),ya,'b',PeqRSdet(1),ya,'k');
hold off

subplot(3,1,2)
bar(centersb,(countsb/rand),'y')
hold on
plot (meaneq(2),yb,'b',PeqRSdet(2),yb,'k')
hold off

subplot(3,1,3)
bar(centersc,(countsc/rand),'r')
hold on
plot (meaneq(3),yc,'b',PeqRSdet(3),yc,'k')
hold off

%Mechanical failure probability

mmec= [0.000000048 0.0000001 0.00000021]; %event/years
LBmec=[0.00000002 0.000000024 0.000000038]; %event/years
UBmec=[0.000000112 0.00000041 0.00000053]; %event/years

efmec=sqrt(UBmec./LBmec);

sigmec=log(efmec)/1.645;
vmec=(mmec.^2).*(exp(sigmec.^2)-1);
sigmamec=sigmec;
mumec = log((mmec.^2)./sqrt(vmec+mmec.^2));

T=50;
X=[];
for i=1:rand
    for j=1:length(mmec)
        X(i,j)=random ('logn',mumec(j),sigmamec(j));
          if (X(j)<=UBmec(j) && X(j)>=LBmec(j))
            X(i,j)=X(i,j);
          else
```

```
                if (X(j)<UBmec(j))
                    X(i,j)=UBmec(j);
                end
                if (X(j)>LBmec(j))
                    X(i,j)=LBmec(j);
                end
            end
            P1mec(i,j) = X(i,j);
            RS1mec(i,j) = P1mec(i,j).*0.84;
            RS2mec(i,j) = P1mec(i,j).*0.08;
            RS3mec(i,j) = P1mec(i,j).*0.08;
    end
end
PmRS1mec=sum(RS1mec,2)-(RS1mec(:,1).*RS1mec(:,2))-
(RS1mec(:,1).*RS1mec(:,3))-(RS1mec(:,3).*RS1mec(:,2));
PmRS2mec=sum(RS2mec,2)-(RS2mec(:,1).*RS2mec(:,2))-
(RS2mec(:,1).*RS2mec(:,3))-(RS2mec(:,3).*RS2mec(:,2));
PmRS3mec=sum(RS3mec,2)-(RS3mec(:,1).*RS3mec(:,2))-
(RS3mec(:,1).*RS3mec(:,3))-(RS3mec(:,3).*RS3mec(:,2));

PmRSmec =[PmRS1mec PmRS2mec PmRS3mec];
meanmmec=mean(PmRSmec);

% Deterministic approach
P1detmec = mmec;
RS1detmec = P1detmec.*0.84;
RS2detmec = P1detmec.*0.08;
RS3detmec = P1detmec.*0.08;
PmRS1detmec=sum(RS1detmec)-(RS1detmec(:,1).*RS1detmec(:,2))-
(RS1detmec(:,1).*RS1detmec(:,3))-(RS1detmec(:,3).*RS1detmec(:,2));
PmRS2detmec=sum(RS2detmec,2)-(RS2detmec(:,1).*RS2detmec(:,2))-
(RS2detmec(:,1).*RS2detmec(:,3))-(RS2detmec(:,3).*RS2detmec(:,2));
PmRS3detmec=sum(RS3detmec,2)-(RS3detmec(:,1).*RS3detmec(:,2))-
(RS3detmec(:,1).*RS3detmec(:,3))-(RS3detmec(:,3).*RS3detmec(:,2));

PmRSdetmec =[PmRS1detmec PmRS2detmec PmRS3detmec];

[countsd,centersd] = hist(PmRS1mec,20);
[countse,centerse] = hist(PmRS2mec,20);
[countsf,centersf] = hist(PmRS3mec,20);

yd=linspace(0,(max(countsd/rand)+0.05),100);
ye=linspace(0,(max(countse/rand)+0.05),100);
yf=linspace(0,(max(countsf/rand)+0.05),100);

figure (5)

subplot(3,1,1)
bar(centersd,(countsd/rand),'g');
title ('Mechanical Failure Probability of Pipes and Valves')
hold on
plot (meanmmec(1),yd,'b');
hold on
plot (PmRSdetmec(1),yd,'k');
hold off

subplot(3,1,2)
bar(centerse,(countse/rand),'y')
hold on
plot (meanmmec(2),ye,'b')
hold on
```

```
plot (PmRSdetmec(2),ye,'k')
hold off

subplot(3,1,3)
bar(centersf,(countsf/rand),'r')
hold on
plot (meanmmec(3),yf,'b')
hold on
plot (PmRSdetmec(3),yf,'k')
hold off

%Pressure shell

mshell= [0.000081 0.000052 0.0000097]; %event/years
LBshell=[0.000046 0.000025 0.0000014]; %event/years
UBshell=[0.00013 0.000095 0.000036]; %event/years

efshell=sqrt(UBshell./LBshell);

sigshell=log(efshell)/1.645;
vshell=(mshell.^2).*(exp(sigshell.^2)-1);
sigmashell=sigshell;
mushell = log((mshell.^2)./sqrt(vshell+mshell.^2));

T=50;
X=[];
for i=1:rand
    for j=1:length(mshell)
        X(i,j)=random ('logn',mushell(j),sigmashell(j));
    end
end
PmRS1shell=P1shell(:,1);
PmRS2shell=P1shell(:,2);
PmRS3shell=P1shell(:,3);

PmRSshell =[PmRS1shell PmRS2shell PmRS3shell];
meanmshell=mean(PmRSshell);

% Deterministic approach
P1detshell = mshell;
PmRS1detshell=P1detshell(1,1);
PmRS2detshell=P1detshell(1,2);
PmRS3detshell=P1detshell(1,3);

PmRSdetshell =[PmRS1detshell PmRS2detshell PmRS3detshell];

[countsd,centersd] = hist(PmRS1shell,20);
[countse,centerse] = hist(PmRS2shell,20);
[countsf,centersf] = hist(PmRS3shell,20);

yd=linspace(0,(max(countsd/rand)+0.05),100);
ye=linspace(0,(max(countse/rand)+0.05),100);
yf=linspace(0,(max(countsf/rand)+0.05),100);

figure (6)

subplot(3,1,1)
bar(centersd,(countsd/rand),'g');
title ('Mechanical Failure Shell')
hold on
```

```
plot (meanmshell(:,1),yd,'b');
hold on
plot (PmRSdetshell(1),yd,'k');
hold off

subplot(3,1,2)
bar(centerse,(countse/rand),'y')
hold on
plot (meanmshell(:,2),ye,'b')
hold on
plot (PmRSdetshell(2),ye,'k')
hold off

subplot(3,1,3)
bar(centersf,(countsf/rand),'r')
hold on
plot (meanmshell(:,3),yf,'b')
hold on
plot (PmRSdetshell(3),yf,'k')
hold off

%Summation

PmRS1=PmRSmec(:,1)+PmRSshell(1,1)-(PmRSmec(:,1).*PmRSshell(1,1));
PmRS2=PmRSmec(:,2)+PmRSshell(1,2)-(PmRSmec(:,2).*PmRSshell(1,2));
PmRS3=PmRSmec(:,3)+PmRSshell(1,3)-(PmRSmec(:,3).*PmRSshell(1,3));
PmRS= [PmRS1 PmRS2 PmRS3];
meanm=mean(PmRS);

PmRSdet=PmRSdetmec+PmRSdetshell-(PmRSdetmec.*PmRSdetshell);
PmRS1det=PmRSdet(:,1);
PmRS2det=PmRSdet(:,2);
PmRS3det=PmRSdet(:,3);

[countsd,centersd] = hist(PmRS1,20);
[countse,centerse] = hist(PmRS2,20);
[countsf,centersf] = hist(PmRS3,20);

yd=linspace(0,(max(countsd/rand)+0.05),100);
ye=linspace(0,(max(countse/rand)+0.05),100);
yf=linspace(0,(max(countsf/rand)+0.05),100);

figure (7)

subplot(3,1,1)
bar(centersd,(countsd/rand),'g');
title ('Failure Probability due to Mechanical Components')
hold on
plot (meanm(1),yd,'b');
hold on
plot (PmRSdet(1),yd,'k');
hold off

subplot(3,1,2)
bar(centerse,(countse/rand),'y')
hold on
plot (meanm(2),ye,'b')
hold on
plot (PmRSdet(2),ye,'k')
hold off
```

```
subplot(3,1,3)
bar(centersf,(countsf/rand),'r')
hold on
plot (meanm(3),yf,'b')
hold on
plot (PmRSdet(3),yf,'k')
hold off

% Probability of release from pressurized tank

PRS1=PeqRS1+PmRS1-(PeqRS1.*PmRS1);
PRS2=PeqRS2+PmRS2-(PeqRS2.*PmRS2);
PRS3=PeqRS3+PmRS3-(PeqRS3.*PmRS3);
P=[PRS1 PRS2 PRS3];
meanP=mean(P);

% Deterministic approach
PRS1det=PeqRS1det+PmRS1det-(PeqRS1det*PmRS1det);
PRS2det=PeqRS2det+PmRS2det-(PeqRS2det*PmRS2det);
PRS3det=PeqRS3det+PmRS3det-(PeqRS3det*PmRS3det);
PRSdet=[PRS1det PRS2det PRS3det];

[counts1,centers1] = hist(PRS1,20);
[counts2,centers2] = hist(PRS2,20);
[counts3,centers3] = hist(PRS3,20);

y1=linspace(0,(max(counts1/rand)+0.05),100);
y2=linspace(0,(max(counts2/rand)+0.05),100);
y3=linspace(0,(max(counts3/rand)+0.05),100);

figure (8)

subplot(3,1,1)
bar(centers1,(counts1/rand),'g')
title ('Probability of top-event')
hold on
plot (meanP(1),y1,'b')
hold on
plot (PRSdet(1),y1,'k')
hold off

subplot(3,1,2)
bar(centers2,(counts2/rand),'y')
hold on
plot (meanP(2),y2,'b')
hold on
plot (PRSdet(2),y2,'k')
hold off

subplot(3,1,3)
bar(centers3,(counts3/rand),'r')
hold on
plot (meanP(3),y3,'b')
hold on
plot (PRSdet(3),y3,'k')
hold off
```

Bibliography

Azzuni, E., & Guzey, S. (2015). Comparison of the shell design methods for cylindrical liquid storage tanks. *Engineering Structures*. http://doi.org/10.1016/j.engstruct.2015.07.050

Azzuni, E., & Guzey, S. (2015). Comparison of the shell design methods for cylindrical liquid storage tanks. *Engineering Structures*, *101*, 621–630. http://doi.org/10.1016/j.engstruct.2015.07.050

Carluccio, A. Di. (n.d.). Structural Characterisation and Seismic Evaluation of Steel Structural Characterisation and Seismic Evaluation of Steel Equipments in Industrial Plants Structural Characterisation and Seismic Evaluation of Steel Equipments in Industrial Plants.

Casamirra, M., Castiglia, F., Corchia, L., Giardina, M., Lombardo, C., & Messina, G. (n.d.). RISK ANALYSIS OF THE STORAGE UNIT IN A HYDROGEN REFUELLING STATION.

Chiara, V., Zanini, M., & Maschio, G. (n.d.). VALUTAZIONE DELL'EFFETTO SISMICO NELLA STIMA DELLE FREQUENZE DI UN IMPIANTO INDUSTRIALE.

Di Carluccio, A. (n.d.). Dottorato di Ricerca in Rischio Sismico Structural Characterisation and Seismic Evaluation of Steel Equipments in Industrial Plants.

Di, T., Per, S., Noto, S. E., Decanini, L., Mollaioli, F., Panza, G. F., … Vaccari, F. (n.d.). 6. pericolosità sismica della sicilia sud orientale. terremoti di scenario per augusta, siracusa e noto.

Ennis, T. (n.d.). PRESSURE RELIEF CONSIDERATIONS FOR LOW-PRESSURE (ATMOSPHERIC) STORAGE TANKS.

Farahani, H. J., Peterson, G. A., & Westfall, D. G. (1998). This Page Intentionally Left Blank. *Advances in Agronomy*. http://doi.org/10.1016/S0065-2113(08)60505-2

Kirchsteiger, C. (1999). On the use of probabilistic and deterministic methods in risk analysis. *Journal of Loss Prevention in the Process Industries*, *12*, 399–419. Retrieved from www.elsevier.com/locate/jlp

Lanzano, G., Salzano, E., Santucci De Magistris, F., & Fabbrocino, G. (2013). Seismic vulnerability of natural gas pipelines. *Reliability Engineering and System Safety*, *117*, 73–80. http://doi.org/10.1016/j.ress.2013.03.019

Limin, W. (n.d.). Fault Tree Analysis for Oil Tank Fire and Explosion.

Petroleum Institute, A. (n.d.). By Authority Of THE UNITED STATES OF AMERICA Legally Binding Document.

Pg&e, N. A. (n.d.). Deterministic and Probabilistic Assessments.

Rajakarunakaran, S., Maniram Kumar, A., & Arumuga Prabhu, V. (2015). Applications of fuzzy faulty tree analysis and expert elicitation for evaluation of risks in LPG refuelling station. *Journal of Loss Prevention in the Process Industries*. http://doi.org/10.1016/j.jlp.2014.11.016

Salzano, E., Agreda, A. G., Di Carluccio, A., & Fabbrocino, G. (2009). Risk assessment and early warning systems for industrial facilities in seismic zones. *Reliability Engineering and System Safety*, *94*, 1577–1584. http://doi.org/10.1016/j.ress.2009.02.023

Salzano, E., Agreda, A. G., Di Carluccio, A., & Fabbrocino, G. (2009). Risk assessment and early warning systems for industrial facilities in seismic zones. *Reliability Engineering and System Safety*, *94*, 1577–1584. http://doi.org/10.1016/j.ress.2009.02.023

Shi, L., Shuai, J., & Xu, K. (2014). Fuzzy fault tree assessment based on improved AHP for fire and explosion accidents for steel oil storage tanks. *Journal of Hazardous Materials*. http://doi.org/10.1016/j.jhazmat.2014.06.034

Shi, L., Shuai, J., & Xu, K. (2014). Fuzzy fault tree assessment based on improved AHP for fire and explosion accidents for steel oil storage tanks. *Journal of Hazardous Materials*, *278*, 529–538. http://doi.org/10.1016/j.jhazmat.2014.06.034

Determinism vs. Probabilism, Introduction to Basic Methods and Structure of Probabilistic Risk Assessments (PRA) Scope of Probabilistic Risk Assessment (PRA). (n.d.).

DESIGN AND ANALYSIS OF PRESSURE VESSEL. (n.d.). *International Journal of Innovative Research in Technology & Science(IJIRTS) INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN TECHNOLOGY & SCIENCE*, *28*(3), 2321–1156.

DESIGN RECOMMENDATION FOR STORAGE TANKS AND THEIR SUPPORTS WITH EMPHASIS ON SEISMIC DESIGN. (2010).

Ringraziamenti

Voglio ringraziare tutti coloro che hanno permesso il raggiungimento di questo obiettivo. In primis la mia famiglia ed Ylenia che sono sempre stati al mio fianco facendomi sentire il loro sostegno incondizionato. Grazie alla loro presenza ho potuto vivere serenamente questi cinque anni di impegno e coronarli con questo risultato. Un grazie ai miei colleghi e compagni di università per essere riusciti a rendere leggere anche le lezioni più pesanti e i compiti più ingrati. In ambito accademico, ringrazio il Prof. Giuseppe Maschio per avermi fatto scoprire un ramo dell'ingegneria chimica che non conoscevo e che ora mi appassiona, e l'Ing. Chiara Vianello per l'aiuto che mi ha dato durante questi mesi di lavoro. Grazie anche a tutti coloro che in un modo o nell'altro sono entrati a far parte della mia vita in questi anni: anche con un solo gesto o una parola avete contribuito a farmi crescere ed arrivare fino a qui.