

Seismic Design of Facilities for the Oil and Gas Industry, Risk Based Seismic Design Criteria and Upgrading of Existing Facilities

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ABSTRACT: *The design of facilities to resist seismic loads requires selection of an appropriate safety level. This paper will discuss the requirements of different international standards and will suggest that the criteria might be established on the basis of a quantitative risk analysis. The paper will, furthermore, discuss the experience oil companies have gained through working in Norway and North Western Europe in designing facilities to withstand the relevant seismic loads. Although this area of the world is an intraplate area with relatively low seismicity, it is suggested that the experience gained in using risk based seismic design criteria and quantitative risk analysis could be of value to those working in more seismic regions of the world. The paper will mainly refer to onshore terminal facilities on the Western Coast of Norway, which is the area of the North Western Europe with highest seismic hazard, and to offshore platforms in the Northern North Sea. Finally, the paper will present considerations related to upgrading of existing facilities with particular emphasis on facilities in the oil and gas industry.*

Keywords: Oil and gas industry; Safety level for design; International standards; Risk based seismic criteria; Upgrading of existing facilities; Introduction of barriers

1. Introduction

Use of risk based seismic design criteria allows for selection of the most appropriate design criteria for oil and gas facilities with respect to the facilities' impact on safety for humans, protection of the environment and protection of the company's investments. It is standard practice to apply different "importance factors" for the seismic resistant design of different kind of facilities (Ductility Level Earthquake design analysis), using an importance factor larger than 1,0 as multiplier on the seismic force for the most important facilities in accordance with the appropriate standard. It should be noted that the use of an importance factor larger than one is equivalent to selection of a higher safety level for the facilities, which again is equivalent to a lower annual probability of structural failure or a longer return period for the seismic load. A refinement of this practice could,

however, be considered in order to obtain the optimum criteria for the facilities in mind.

The refinement could be based on the results of a Quantitative Risk Analysis (*QRA*) where an estimate of the probability of failure of certain facilities and an analysis of the consequences of failure for personnel, damage to the environment and loss of investments would provide a complete risk picture. In this respect, it should be noted that safeguarding of personnel is given the absolutely highest priority while concern about environmental pollution and damage has been given increased attention over the last years. Defining an earthquake design level where the facilities could be operated safely after an earthquake and a level where safe shut down is possible ensures the safety for the investments. In areas where seismicity represents the governing design load, the facilities causing high

consequence failures can be identified and the safety level (for example the selected earthquake acceleration values) can be increased for such facilities that could cause high consequence failures.

Such facilities could be process facilities, LPG tanks, toxic storage tanks etc., which possibly could cause unacceptable hazard to nearby settlements or industrial facilities. Alternatively, the distance between facilities or the distance to nearby settlements could be increased in the design phase in order for nearby facilities or settlements to withstand loads from explosions or fires, which often results from earthquake loading. In seismic active regions there is, furthermore, considerable discussion as to need to upgrade existing facilities designed to older codes, in order for these facilities to fulfil the requirements of the present code. This subject is of particular interest for investors considering investments or economic participation in existing facilities.

2. Selection of Codes (Standards) for the Seismic Resistant Design of Onshore Facilities and Offshore Platforms

The laws and regulations in the country where a development is taking place determine the selection of codes and standards for the development of hydrocarbon facilities. In Norway the Norwegian Petroleum Directorate (*NPD*) is the governing body for all offshore developments. *NPD* refers as much as possible to Norwegian Standards for the construction industry and to industry standards ("Norsok" standards) that have been developed by the oil industry in close cooperation with the *NPD*. For offshore structures, particular reference should be made to Norsok Standard *N-003* [7]. This standard does also include recommendations as to earthquake resistant design of offshore platforms.

The rules and regulations of *NPD* will in the future be further developed to comply with the standards of the International Organization for Standardization (*ISO*) and the approach suggested in the latest *ISO* code [4] will be adapted, although selection of the safety level will be decided at the national level. Norwegian specialists will prepare the seismic hazard map [5].

For onshore facilities, the standards being developed by the European Committee for Standardisation will apply to Norway and these will gradually be adapted. As to earthquake resistant design, reference is made to Eurocode 8 [2] and to the Norwegian standard 3491-12 [6].

Having the general standards of the country in mind, the company can select stricter criteria (higher safety

level) should health, safety or environmental concerns (*HSE*-concerns) require so. For a company working in the international environment, the international standards prepared by *ISO* and *CEN* will normally constitute minimum requirements to the design. These are expected to gradually replace internationally the different *US* codes presently in use, such as the International Building Code ([3], formerly the Uniform Building Code) and other American National Standards (such as, for example [1]).

3. Experiences from Norway in Relation to Seismic Resistant Design of Facilities for the Oil and Gas Industry

Norway is part of the Fenno-Scandinavian shield and an intraplate region where earthquakes of Richter magnitude 5 and above occasionally occur. The seismic hazard is generally considered to be at the level of *US* Seismic Zone 1 (Eastern Part) and Zone 2 (along the Western Coast). Due to the large value of the investments in facilities for the oil and gas industry, typically being in the order of up to 2-3 Billion *US* \$ for single large offshore platforms and plants, it has been recognized that earthquake resistant design with a very low probability of collapse must be secured. In this respect, a ductility earthquake level (level where progressive collapse shall be avoided) has been selected at the 10 annual probability of exceedance level. This level coincides with the general level of safety required for the oil and gas industry on the Norwegian Continental Shelf in the North Sea. A similar approach has so far been taken for major onshore oil and gas facilities. Note that an importance factor of 1,0 is applied when using this exceedance level.

This again, has lead to a careful collection of seismic data and seismic sources as well as of the development of seismic attenuation relations for the area, leading eventually to the latest seismic hazard map(s) [5] for Norway and its continental shelf, see Figure (1). Of particular concern have been the completeness of the database and the low attenuation of the Norwegian bedrock.

Following the preparation of the map and the development of Eurocode 8 for Seismic Resistant Design of Buildings in the European Union [2], a Norwegian standard has been developed [6] for the seismic resistant design of buildings. The standard's approach to safety is based on use of a return period for ductile design of 475 years (10% probability of exceedance in 50 years) combined with importance factors as given in Table (1). The seismic importance

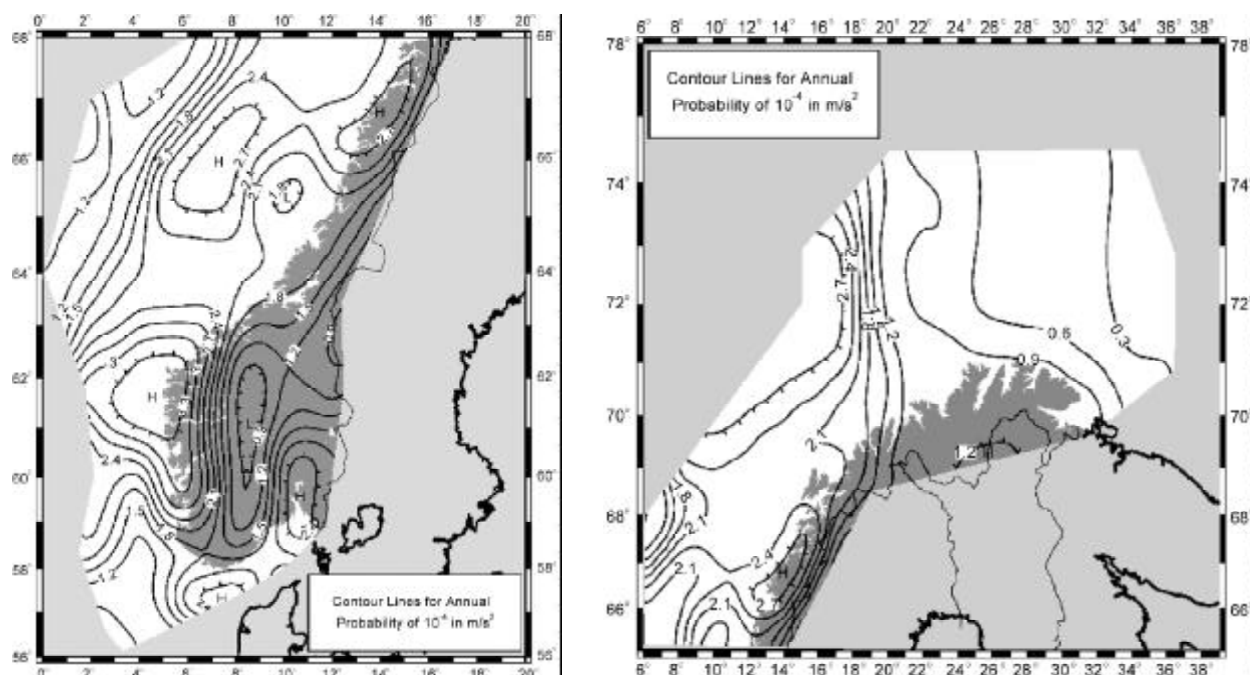


Figure 1. Seismic hazard maps for Norway and its continental shelf, peak ground acceleration at return period of 475 years.

factor is to be multiplied with the load found by applying the seismic hazard with a return period of 475 years. The selection of the return period associated with the different seismic classes should be noted, as this selection will lead to higher seismic factors for seismic classes *I* and *II* in regions with few high magnitude seismic events as compared to regions with more frequent high magnitude seismic events. This is exemplified by the *CEN* recommendation of using importance factors of 1,4 for seismic class *I* and 1,2 for seismic class *II*, respectively, noting that the Eurocode 8 (*CEN* standard) will have widest application in the more seismic regions of the Southern Europe as compared to the less Northern Europe.

4. The Safety Principles of the New Iso Standard (ISO 2001) for Offshore Structures

This standard presents a two level design procedure; design checks are to be made for the Serviceability Level Earthquake (*SLE*) and for the Ductility Level Earthquake (*DLE*). The *SLE* criteria should lead to a design that will meet the *DLE* criteria with minimum of changes:

- *SLE*: little or no damage accepted during frequent earthquakes.
- *DLE*: low probability of exceedance. Considerable damage accepted, collapse to be avoided.

For a structure we determine the Seismic Risk

Table 1. Importance factors according to the Norwegian seismic standard [6].

| Seismic Class | Seismic Importance Factor, γ_I | Consequences at Collapse | Associated Return Period (Years) |
|---------------|---------------------------------------|--------------------------|----------------------------------|
| I | 1,8 | Very large | 2 000 |
| II | 1,4 | Large | 1 000 |
| III | 1,0 | Average | 475 |
| IV | 0,7 | Small | 200 |

Category, *SCR* that is used to determine how the seismic design is carried out, depending on the exposure level (*L*) and the site seismic zone. *SLE* and *DLE* return periods depend on the “exposure level”. A structure’s exposure level, *L*, depends on the criticality of the structure, see Table (2).

For the different exposure levels, the standard sets the target annual probabilities of failures, p_f for the Ductility Level Earthquake, see Table (3). These probabilities of failure correspond to certain return periods.

Table 2. Different life safety categories for structures, i.e. different exposure levels (*L*) for structures according to the new offshore ISO Standard [4].

| Life Safety Category | High Consequences of Failure | Medium Consequences of Failure | Low Consequences of Failure |
|----------------------|------------------------------|--------------------------------|-----------------------------|
| Manned–Not evacuated | L 1 | L 1 | L 1 |
| Manned evacuated | L 1 | L 2 | L 2 |
| Unmanned | L 1 | L 2 | L 3 |

Table 3. The target annual probabilities of failures, p_f , for different exposure levels according to the offshore ISO Standard [4].

| Exposure level | p_f |
|----------------|------------------------------|
| L1 | $4 \times 10^{-4} = 1/2500$ |
| L2 | $1 \times 10^{-3} = 1/1000$ |
| L3 | $2,5 \times 10^{-3} = 1/400$ |

We will then have to find the seismicity of the area to determine the seismic zone. This standard suggests that the zone is characterized by the value of the spectral acceleration at 1,0 second, $S_a(1,0$ second), where the 1000-year return period is used as reference. Seismic Zonation Maps for use in simplified analysis are presented the Standard. Separate maps also give $S_a(0,2 \text{ sec})$ for the 1000-year return period. The value of the spectral acceleration at a specific time, T , for a specific site is given by: $S_{a,site}(T) = (3T + 0,4) \times C_a S_{a,map}(0,2)$, where C_a is the site soil coefficient. The traditional peak ground acceleration level at bedrock for a site is found as $S_a = 0,4 \times S_{a,map}(0,2)$.

For the different seismic zones and exposure levels we thereafter find, according to the code the Seismic Risk Category (SCR), see Table (4) and decide on seismic design procedure/requirement; use of detailed or simplified design procedure, Table (5). This ISO standard thus puts forward a semi-probabilistic approach to the design, prescribing a minimum safety level to be applied for the design of offshore structures.

Table 4. Seismic risk category according to Table 11.2-3 of the offshore ISO Standard [4].

| Site Seismic Zone | Exposure Level | | |
|-------------------|----------------|-------|-------|
| | L3 | L2 | L1 |
| 0 | SCR 4 | SCR 4 | SCR 4 |
| 1 | SCR 3 | SCR 3 | SCR 2 |
| 2 | SCR 3 | SCR 3 | SCR 1 |
| 3 | SCR 3 | SCR 2 | SCR 1 |
| 4 | SCR 2 | SCR 1 | SCR 1 |

Table 5. Seismic design requirements according to Table 12.1-1 of the ISO standard [4].

| SCR | Seismic-Action Procedure | Evaluation of Seismic Activity | Non-Linear DLE Analysis |
|---------------------------------------------------------------------------------------------------------------------------------------|--------------------------|--------------------------------------------|-------------------------|
| 1 | Detailed | Site-Specific | Required |
| 2 | Detailed or Simplified | Site-Specific or ISO maps or regional maps | Recommended |
| 3 | Simplified | ISO Maps or Regional Maps | Permitted |
| 4 | None | None | None |
| Use SCR 3 rules for structures where the design lateral seismic action is less than 5% of total permanent action plus variable action | | | |

5. The Use of quantitative Risk Analysis (QRA) in Design of Onshore Facilities

5.1. Seismic Design Criteria for Onshore Facilities

The design of onshore facilities is normally undertaken by determining the horizontal base shear force. This force is dependent upon the following multipliers:

- Design base acceleration determined from seismic hazard analysis
- Response coefficient of the building to the load, taking into account the dynamics of the building and the soil dynamic amplification effects
- Importance factor of the building
- Behavioural factor of the building as determined by the building's structural system
- Weight of the building.

Through this approach, the safety level is inherent in the

- Selection of the return period for the design base acceleration
- Importance factor of the building.

The CEN code (the code of the European Union) applicable for the earthquake resistant design of buildings [2] recommends a return period of 475 years for ductile design, i.e. a design where collapse is avoided. The different member countries of the European Union will select the safety level, depending upon the safety level specified in the laws of the countries.

The importance factor, reflecting the importance category of the building, should be selected as dependent upon the variability in the seismic hazard at the site. The importance factors recommended in Eurocode 8 and the factors recommended in the Norwegian code, see Table (6), reflect the differences in earthquake variability between Southern European countries and in Norway as also discussed when presenting Table (1).

5.2. Application of Quantitative Risk Analysis for the Establishment of Risk Based Seismic Design Criteria

For a specific facility, it is suggested to select the

Table 6. Importance factors for seismic resistant design of buildings.

| Importance Category/Building Class | Large | Average | Small |
|------------------------------------|-------|---------|-------|
| CEN [2] | 1,2 | 1,0 | 0,8 |
| Norway [6] | 1,4 | 1,0 | 0,7 |
| Return Period (Years) | 1000 | 475 | 200 |

effective design acceleration (i.e. the design base acceleration times the importance factor) on the basis of a risk analysis where we compare the risk to personnel, to the environment and to nearby facilities with acceptance criteria set by the company. These acceptance criteria could be criteria for safeguarding the facilities or the environment and the personnel. Note that the acceptance criteria as a minimum must satisfy the requirements and laws of the country in which the facilities are installed.

For a selected part of the facilities, for example a building, a tank, or a gas centre, the probability of failure, P_f , is determined through the selection of the effective design acceleration. Furthermore, the consequences of failure to nearby facilities, the environment or the personnel (including personnel living in nearby settlements) are dependent upon the distance of the selected part to the nearby facility and the structural strength of the nearby facility.

For a situation with a prevailing wind direction one obtains, for example, “risk contours” as shown in Figure (2) (possibly resulting in consequences that could cause failure of the nearby facilities, like the gas ratio in the spreading of a gas cloud, heat/ temperature

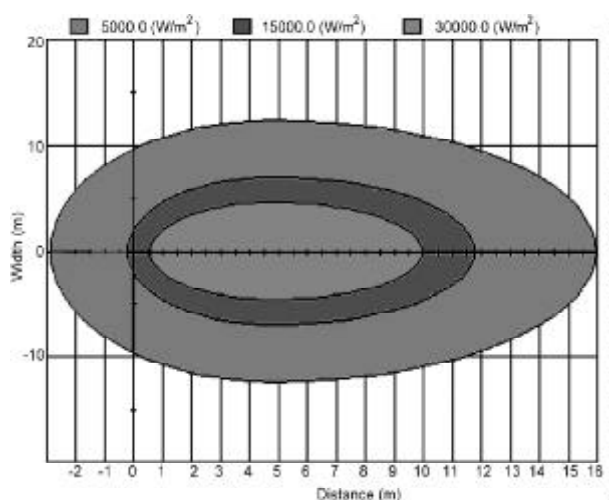


Figure 2. Conceptual drawing of the spreading of hazard (as represented by the maximum heating value, W/m^2) in the case of an explosion of a small volume of explosive material located at coordinate (4,0). “Risk consequence contours” near a high-risk facility given wind direction from left to right.

contours that could cause explosion of the nearby facility, etc.). Note that in the case of larger amounts of gas release, the scales in Figure (2) may be increased one or several orders of magnitude.

In relation to the established risk contour lines, we can compare the calculated risk with the acceptance criteria noting that the risk to nearby facilities/environment and personnel can be lowered by:

- Increasing the effective design acceleration level, which is equivalent to increasing the return period of the seismic load
- Introducing safety measures like: structural strengthening, shut down measures or physical distance to nearby facilities or settlements.

In this respect we will emphasis on the possibility of introducing safety by distance. This measure is particularly important with respect to 3rd party personnel (i.e. for personnel not working directly at the facility). The use of a larger distance to the nearby facilities to provide safety or the use of an increased strength of the nearby facility can be considered as alternatives to an increased return period of the seismic design load.

This qualitative risk analysis will provide us with an exact picture of the safety level for the nearby facilities, the environment and personnel and will serve as a tool to select the correct combination of effective design seismic acceleration, distance to other facilities/settlements and the structural strength of the nearby facilities. The analysis could be used for a review of the requirements of the code, in order to evaluate whether the code’s suggested safety level satisfies the basic acceptance criteria of the company. It could also serve as a particularly important tool in selecting criteria and layout of the facilities in cases where new technologies are considered to be utilized in an area, for example in the case of use of technologies that may have a larger consequence to nearby facilities than use of conventional technologies. This could, for example, be when considering the application of larger storage tanks than traditionally used in an area or traditionally used as basis for the code’s selection of safety levels.

It should be noted that the design of major facilities in the oil and gas industry always should be based on a site-specific seismic hazard analysis, and a site-specific analysis of the geotechnical data (soils data) at the site.

5.3. Application of QRA for the Establishment of Risk Based Seismic Design Criteria for Gas Systems

The alternative of using shut down valves or other

means of automatic shut down systems based on the level of acceleration could be particularly useful in case of gas facilities/gas pipelines. The acceptable inventory of gas in a pipeline system could be identified as a function of the seismic hazard and the consequences a leak would have. Thereafter, optimisation can be carried out to find the most optimum way to provide the acceptable safety level, either by introducing a lower probability of failure (increasing the return period of the seismic load) or by decreasing the consequences of a failure by decreasing the gas inventory (for example by increasing the number of shut down valves that are reacting to a certain earthquake acceleration level).

6. Examples

For onshore facilities in Norway, reference for design purposes in the past normally has been given to different versions of the Uniform Building Code [3]. The *DLE* safety level has typically been set to having an annual probability of exceedance of 10^{-4} (10.000 year return period). Site-specific seismic hazard analyses have been carried out to determine the associated acceleration levels. The selection of such a strict safety levels might not be warranted from a risk based point of view and the new Norwegian Code, see Table (1) calls for the selection of more balanced return periods for design of facilities, depending on the importance of the buildings/facilities.

For some specific facilities (like the Mongstad refinery and the Snøhvit LNG plant) in the vicinity of areas with population, the risk to personnel living outside the facilities (3rd party personnel) has been considered through quantitative risk analyses in order to satisfy the requirement that the Fatal Accidental Ratio value should be around one for those living outside the facilities (meaning that the fatality ratio should not be more than 1 in the case of 108 exposed hours). As a result of these analyses, the administration buildings have been moved away from the main facilities or away from the downstream side of the prevailing wind direction.

7. Considerations Related To Seismic Strengthening of Facilities and Lifelines in the Oil and Gas Industry

7.1. Introduction to Discussion on Risk Assessment

The most important characteristics of facilities and lifelines in the oil and gas industry are that they are normally built to stringent national and international code requirements, that they represent large investments

and that they contain large inventories of explosive and toxic materials.

In view of the risk these facilities represent, we are concerned about the risk to people (which includes first party risk, that is risk to those directly involved in operating the facilities, and third party, that is risk to persons outside the facilities that are not involved in the operations of the facilities). Furthermore, we are concerned about possible pollution to the environment and the possible loss of facilities and investments in case of damages to the facilities, as for example caused by a fire.

Due to the high risk, the oil and gas industry provides acceptance criteria to safeguard people, environment and facilities. These criteria will take construction activities as well as operations into account:

- In regards to safety of personnel, acceptance criteria relates to *FAR* value, Fatal accidental value (Probability of loss in 10^8 man hours of exposure):
 - For personnel working on offshore platforms the *FAR* value is in the range of 5 to 10
 - For 3rd party personnel, the acceptable *FAR* value is considerably less.
- In relation to ensuring a clean environment, acceptance criteria relates to amount of release of hydrocarbons and the consequences of the releases.
- Regarding safety for the investments (the facilities), the acceptance criteria relates to satisfying the requirements of international and national codes and to company criteria (if stricter):
 - In this respect it should be noted that rebuilding and retrofitting normally is “tax deductible” so that there will be a loss for the host country in case of loss of assets. Even if the facilities could be fully insured, there is a considerable loss to the society in case of a major loss of facilities in the oil and gas industry.
 - Company criteria will, furthermore, take possible “loss of reputation” and loss of production into account.

7.2. Retrofit and Upgrading Needs for Facilities in the Oil and Gas Industry

For retrofitting after an earthquake, standard civil and mechanical engineering strengthening methods apply. To invest in new-built facilities designed in accordance with the latest version of the code may, however, be more economical. This could also ensure that more

economical operation procedures may be applied in the running of the facilities.

Our present concern should focus on possible needs to upgrade older facilities to be able to resist the consequences of future earthquakes. This will involve the following evaluation:

- A re-evaluation of the seismic hazard at the site of the facilities
- A site investigation to check whether the general conditions of the facilities are acceptable
- An analysis of whether the structure is designed for the appropriate exposure level.

Such an evaluation should be carried out when new information about a possible higher seismic hazard than originally considered in the original design becomes available or when the facilities are being upgraded for larger throughput or when it for other reasons becomes apparent that the facilities might need a check of whether the safety level is appropriate. In the case the risk is found to be too high, actions should be taken.

The actual upgrading of facilities for the oil and gas industry could involve:

- Structural “strengthening” (to reduce the probability of damage caused by a future earthquake):
 - This solution will apply for pipelines crossing active faults in the case the pipeline has not been designed for fault movements.
 - This will also apply to particular sensitive equipment, possibly having to be put on base isolators. A particular problem may be connections between equipment and piping inside a plant.
 - New-built might, however, be more economical.
- The alternative way to upgrade facilities not satisfying the risk acceptance criteria is to reduce the consequences of any earthquake damage. This is an alternative way to reduce the risk caused by the seismicity and it could be achieved by introducing new barriers in existing facilities:
 - For the wells might shut in valves acting on a certain level of accelerations be an efficient means to reduce the consequences of an earthquake.
 - For pipelines might introduction of additional shut down valves acting on the acceleration levels be introduced at locations where leakages could cause loss of lives or high level of environmental pollution or damage.
 - For onshore plants could construction of safety

walls be considered. Furthermore, the distance between facilities with high risk could be increased. Control room facilities could, for example, be moved away from large risk facilities. 3rd party personnel or workers’ camps could be moved. For the operational safety of hydrocarbon plants, quantitative risk analysis would be suggested.

- For offshore platforms are wells and piping systems of particular concern, potentially generating leaks. Additional shut down systems reacting on acceleration levels might be suggested. Safety walls might be installed to limit any escalation of fires or one could consider to downgrade the platforms to unmanned mode.
- Unsafe support structures might eventually have to be shut down and be replaced by sub sea systems.
- Of some concern is the large number of developments on potentially unstable sloping sea bottom where barriers in the wells are required.

7.3. Cost Benefit Analysis

In relation to safety for investments, cost benefit analysis are normally carried out to guide in determining cost benefit of upgrading. These will include:

- Estimating the value of the facilities (Direct consequences of a loss with inclusion of any consequential losses)
- Determining the annual probability of loss (or severe damage)
- Estimating the annual costs of a loss of existing facilities as the product of probability and consequence
- Calculating in a similar way the annual costs of a loss of the upgraded facilities. Note that the probability of a loss of upgraded facilities will be less than the probability of a loss of the existing facilities
- The expected annual savings associated with upgrading is found as the difference between the calculated costs of losses
- The net present value of the expected savings is estimated as sum of net present value of saving in future years (over the future expected lifetime of the facilities):
 - Sum over the number, n , of years {the expected annual savings/ $(1 + \text{interest rate in } \%)^i$ } where i is the i -th year.
 - In the case the net present value of the savings is larger than the investments in upgrading; there

is an incentive to upgrade.

- Controversial aspects for the use of cost benefit analysis are, however, the choice of interest rate and the value of the consequential losses.

There is some concern that a cost benefit analysis might be used to document that the code gives too strict requirements. Cost benefit analysis could, however, be an efficient tool to identify “hot spots” where it will be beneficially from a cost point of view to increase the safety beyond the requirements of the code or standard. It is not the intention to suggest that the safety should be less than the requirements of the national and/or appropriate international codes or standards.

8. Conclusions

The safety requirements of the different international design codes in relation to earthquake resistant design have been reviewed. The new *ISO* code for offshore structures [4] and the new Eurocode 8 for onshore buildings [2] represent well balanced codes. It is suggested, however, that a quantitative risk analysis could be well suited to confirm that the safety obtained through the use of the codes, is adequate for the facilities to be designed. This relates in particular to facilities in the oil and gas industry as these facilities often contain large amounts of highly flammable and toxic materials.

Furthermore, considerations related to seismic strengthening of facilities and lifelines in the Oil and Gas Industry have been presented with a view on implementation of realistic strengthening means and introduction of barriers to reduce consequences to

personnel, environment and assets.

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