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Quantitative risk assessment & leak detection criteria for a subsea oil export pipeline

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Abstract: A quantitative risk assessment (QRA) based on leak detection criteria (LDC) for the design of a proposed subsea oil export pipeline is presented in this paper. The objective of this QRA/LDC study was to determine if current leak detection methodologies were sufficient, based on QRA results, while excluding the use of statistical leak detection; if not, an appropriate LDC for the leak detection system would need to be established. The famous UK PARLOC database was used for the calculation of pipeline failure rates, and the software POSVCM from MMS was used for oil spill simulations. QRA results revealed that the installation of a statistically based leak detection system (LDS) can significantly reduce time to leak detection, thereby mitigating the consequences of leakage. A sound LDC has been defined based on QRA study results and comments from various LDS vendors to assist the emergency response team (ERT) to quickly identify and locate leakage and employ the most effective measures to contain damage.

Keywords: QRA (quantitative risk assessment); risk; LDC (leak detection criteria); PARLOC database; pipeline

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1 Introduction

The Oil Export Pipeline is single 200.614 km×18” carbon steel pipeline transporting dry sales quality oil from offshore platform to onshore OGT. The pipeline transverses water depth from 1200 m to the shore – with approximately 160 km of the pipeline in the mid to shallow water area. The pipeline goes through near proximity to a marine park – which is regarded as a sensitive location. First of all, extensive data are supposed to be summarized in part 2 of this paper to do the pipeline QRA (quantitative risk assessment). The famous UK PARLOC database is used as a start point of the QRA study in part 3. Methods of QRA have referred to Ch. 40 of SPR book from Bai & Bai[1]. Then, a comparison of oil spill volumes with and without statistical LDS has been done to reveal the benefit of adopting appropriate statistical leak detection system. The QRA results recommend that the statistical LDS is necessary. Thus, a further job has been done in part 4 of this paper to define the LDC including the sensitivity, reliability, robustness and accuracy of LDS. At last, thoughtful conclusions are made in part 5.

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2 Data summary

Data and parameters used for the Oil Export Pipeline QRA in this report are quite rich. Reports, such as the pipeline design, operating study as well as Marine Hazards Study are referred. Because of the confidentiality consideration, the pipeline design and operating parameters are omitted here.

3 QRA study

3.1 General

This part is to predict the risk of oil spills from the oil export pipeline and to determine the frequency of leaks, leak volume, response time. Since the objective of this study is related to leak detection during operating phase, we shall focus on operating risks. The UK PARLOC 2001 database [2] will be used as a starting point of the following risk assessment.

The most significant environmental impact from oil spills occurs when the spill reaches sensitive shallow waters area and the K. Bay. Sensitive coastal resources potentially affected by the oil spills in the region include marine parks and coral clusters. Several hard bottom areas exist along the coastline. Although the pipeline has been routed to avoid live coral areas near the coast, an oil spill from the shallow water pipeline segment could impact several areas of live corals, including a designated Marine Park within hours of the spill or leakage.

In the following, specific risk assessment will be performed for the Oil Export Pipeline and three hypothetical leak sites will be studied: Mid Portion (KP 100), near Marine Park (KP 170) and Near Shore (KP 198). These sites are selected based on their sensitivity and the high potential of impact if leak occurs.

3.2 General of PoF assessment

The OPR in-house quantitative risk assessment (QRA) program has a series of quantitative probability of failure (PoF) judgment forms for different failure causes by using the UK PARLOC database mainly (see Table 1). Generally speaking, the PARLOC database is just a start point of PoF calculation. If there are more information available (inspection, operating and events records etc.), detailed modification should be done by risk analyzers.

Table 1 Trawling failure rates by PARLOC database 2001

Trawling density class	Trawler impact dent assessment result	
	Tolerable	Intolerable
H (>100 per km-yr)	Low bound	Best estimate
M (1-100 per km-yr)	0	Low bound
L (<1 per km-yr)	0	0
PoF evaluation	The analyzer can do the PoF modification	
Comments	Explanation of the PoF modification above	

Table 1 is an example of trawling failure rates judgment forms and similar forms have been designed for other pipeline failure causes (Anchor, Internal/External Corrosion, Material Defects and Grounding/Sinking etc).

During the PoF Evaluation scenario, the experienced user has an opportunity to alter the PoF values in order to quantitatively account for additional information. For altering the calculated PoF values, certain quantitative calculations are supposed to be performed for different failure modes normally.

3.3 Hole sizes & failure rates based on PARLOC database

For the Oil Export Pipeline here is a proposed one, there are no records of pipeline inspection available for QRA study, the PARLOC database will be used to predict pipeline failure rates based on the following two assumptions:

- The development of failure rates is coherent with the historical statistic results in PARLOC database.
- PARLOC database from the North Sea is applicable to pipeline maritime space analysis.

It is reasonable to take the PARLOC database as a start point of pipeline hazards identification, leaking hole sizes prediction and probability of failure (PoF) calculation. The following Table 2 is exactly derived form the UK PARLOC database. Representative leaking hole sizes, say 5 mm, 10 mm 20 mm, 50 mm, 80 mm, and 200 mm, are considered for the entire pipeline. These holes' sizes have been selected to provide easy comparison with the hole sizes considered in the database PARLOC 2001.

The data contained in the PARLOC database is used as a starting point in the identification of potential hazards and provide initial indications of the likely levels of the loss of containment frequency for an individual pipeline. For different leak causes, the lower bound, best and upper estimate failure frequencies of the 200.614 km long oil export pipeline derived from PARLOC 2001 (Table 5-7 and Table 5-8) are listed in Table 2.

Table 2 Relative failure frequencies

Cause	Frequency per km-yr		
	Lower bound	Best estimate	Upper estimate
Trawl	2.93E-09	5.85E-08	2.78E-07
Wreck	4.88E-10	9.75E-09	4.63E-08
Anchor	9.76E-10	1.95E-08	9.26E-08
Internal corrosion	2.83E-07	4.91E-07	7.94E-07
External corrosion	1.06E-07	1.84E-07	2.98E-07
Material- weld defect	3.54E-08	6.14E-08	9.93E-08

3.4 Failure rates modification to PARLOC based on specific analysis

The failure rates above are exactly statistic results deduced from PARLOC database. However, it should be noted that individual pipelines may have quite different histories, properties, characteristics and functions, these values require further modification based on the special conditions of the Oil Export Pipeline. The following sections are detailed analysis of the failure rates modification due to different damage causes.

3.4.1 Fishing interaction

Referring to the Marine Hazards Study Report of the Oil Export Pipeline, the results of trawler impact dent assessment indicate that the permanent dent depth of the non-concrete coated section (See Fig.1) of the oil export pipeline is within allowable limit based on a medium impact frequency. For the concrete coated section, however, no dent is permitted due to the high impact frequency. However, the impact strength of 50 mm thick concrete offers sufficient protection against the trawl impact. Thus, the trawling caused failure frequency is considered to be negligible.

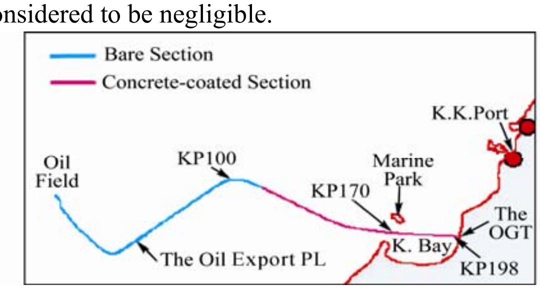

Fig.1 The 18' Oil Export Pipeline (200.614 km).

3.4.2 Merchant vessels

A shipping lane survey and a risk impact assessment have been performed in the Marine Hazard Study Report. A typical cargo vessel route map figure has shown that the typical commercial cargo vessel traveling is confined within waters on the continental shelf and goes across the Oil Export Pipeline at about KP 140. The impact of drop anchor from commercial cargo vessels on the oil export pipeline was assessed based on the methodology outlined in DNV-RP-F107. Combining the calculated energy level at each damage category with the results from Table 4.14 of Marine Hazards Study Report and the conditional probability in Table 4.15 yields a failure frequency of 9.6×10^{-6} per year. This is within the acceptance criteria of 1.0×10^{-5} for high safety class. And the average failure frequency of the whole pipeline (200.614 km) is 4.79×10^{-8} per km-yr. The near shore part of the pipeline is neither near any port nor crossed by any cargo route. Thus, anchor risk is negligible for this section.

3.4.3 Construction and material defects

The verification of the integrity of the pipeline after construction is completed – it can be obtained through the gauging plate and pressure testing at pre-commissioning stage. These steps and the overall technical integrity verification plan will significantly reduce the frequency of failure due to material or construction defects for this project. Therefore, the frequency of failure due to material and construction defects can be anticipated to be well below 10^{-6} per km-yr and the best estimated results of 1.23×10^{-7} per km-yr from PARLOC 2001 is taken for further assessment.

3.4.4 Sinking and grounding vessels

Two other potential causes of shipping damage to pipelines are: foundering–which involves a vessel sinking exactly on top of the pipeline or grounding–where a vessel drifts to the shore due to the occurrence of mechanical failure and impacts the pipeline. The rate of geometric interference (ship footprint on pipeline trench) from ship sinking is less than 10^{-6} per year. The best estimated wreck damage frequency 9.75×10^{-9} per km-yr from PARLOC database is taken for further calculation.

3.4.5 Corrosion

An elaborate study has been done in the “Oil Field Facilities Corrosion, Materials and Inspection Report”.

At a level of 1900 ppm bicarbonate and with corrosion inhibitor availability in the export pipeline of 99.4%, the predicted actual corrosion rate is 0.15 mm/yr (6.1 mpy). Over a 20-year period, this results in 3 mm corrosion loss just within the corrosion allowance. In addition to water removal and corrosion inhibition, internal corrosion in the export pipeline will be managed with an appropriate cleaning pigging program and corrosion monitoring. It is conservative to take the best estimated internal corrosion failure frequency 4.91×10^{-7} per km-yr.

What’s more, the Oil Export Pipeline is 50mm concrete coated and there are external anti-corrosion coating and cathodic protection all along the pipeline, together with the low risk of external interference – resulting in that the best estimated failure frequency 1.84×10^{-7} per km-yr from PARLOC is employed in this report.

Thus we get the oil export pipeline failure rate of 6.75×10^{-7} per km-yr for corrosion considering both internal and external corrosion effects. These corrosion failure frequencies above are largely empirical judgment, incorporating comments from workshop with many experts’ attendance.

3.4.6 Conclusion & summary of modification results

The failure rates’modification results from detailed analysis above are listed in Table 3. The total pipeline failure frequency for the whole length (200.614 km) of the pipeline is found to be less than 1.72×10^{-4} per-yr. This failure frequency is shown to be low and comparable to industry standard.

Table 3 Modification results of failure frequencies by causes /per km-yr

Cause	Failure frequency		
	Mid portion	Near marine park	Near shore
Trawl	0	0	0
Anchor	4.79E-08	4.79E-08	0.00E+00
Wreck	9.75E-09	9.75E-09	9.75E-09
Corrosion	6.75E-07	6.75E-07	6.75E-07
Material defects	1.23E-07	1.23E-07	1.23E-07
TOTAL	8.56E-07	8.56E-07	8.08E-07

3.5 Oil spill with and without LDS

3.5.1 Oil spill model

An oil spill model POSVCM [3] from MMS has been employed to simulate the oil export pipeline leakages at various situations.

The Pipeline Oil Spill Volume Computer Model (POSVCM) provides a methodology to determine worst-case discharges from seafloor pipelines. Inputs to POSVCM are parameters describing the configuration and characteristics of the pipeline system, the fluid it contains, and the sizes of leakages. Key outputs are the evolution of the release rate over time, the total mass of oil released.

The Oil Export Pipeline has been soundly modeled in the POSVCM as illustrated in Fig. 2. The entire oil export pipeline has been divided into three sections, and the mean internal diameter 0.4211 m has been used to simplify the model.

3.5.2 Emergency Response

Discounting the leaking size and pressure, two components of a release volume from the oil pipeline are: (a) the continued pumping that occurs before the line can be shut down and (b) the liquid that drains from the pipe after the line has been shut down.

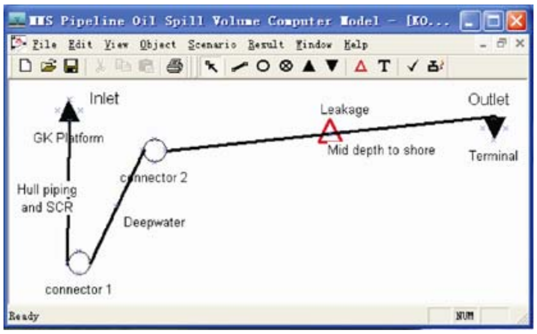

Fig.2 The Oil Export Pipeline model

Table 4 Emergency response with/without LDS for leakage near Marine Park

Hole sizes /mm	LD /min	DoS /min	Conf. /min	Shut-in /min	Simulation /min
Near Marine Park leakage with LDS					
5	40	90	360	5	495
10	40	90	360	5	495
20	7	90	60	5	162
50	7	90	60	5	162
80	3	0	0	5	8
200	3	0	0	5	8
Near Marine Park leakage without LDS					
5	980	90	480	5	1555
10	980	90	480	5	1555
20	540	90	45	5	680
50	540	90	45	5	680
80	5	0	0	5	10
200	5	0	0	5	10

A timely detection and confirmation of a leak will initiate a quick pipeline shut-down response. Depending on the routine nature/schedule of the visual observation, the leak detection could vary significantly from hours to days. For computational leak detection system, the detection time can vary from minutes to hours depending on leak sizes, transient operations and the flow rates. Although the leak detection may need to be confirmed with visual observation, the total response time (with computational leak detection system) should be reduced significantly in particular – with regard to smaller leak sizes (from potentially days to hours). The normal emergency response sequence to a leakage should be like this:

- Step 1: Leak is detected (LD) - leak continues;
- Step 2: Deployment of surveillance (DoS) to ascertain the detected leak signal- leak continues;
- Step 3: Leak confirmation- leak continues;
- Step 4: Pump shut-down and inlet valve shut-in to isolate the leak, the outlet valve at OGT to be left open to help reducing the pressure in the pipeline after confirming the leak- leak continues;
- Step 5: Mechanical recovery using booms/nets and skimmers will be deployed to site immediately, e.g. Split Mechanical Pipeline Repair Clamps are designed to encapsulate leaking or damaged pipe sections in a fast and effective means.

Assumptions of emergency response time before pipeline shut-in with and without statistical LDS (herein, it means without LDS third tier as the description above) have been made based on the comments of a conference with several experts' attendance from Emergency Response Team (ERT). Thus, only the leaking process before shut-in is able to be modeled to figure out the oil spill volume, which is the main part of spilling quantity. As the Marine Park is the most environment sensitive area along the export pipeline, emergency response time with/without LDS for leakage near Marine Park is given in Table 4. The interval of emergency response depends on the capability of LDS.

3.5.3 Modeling results

Based on the entire precondition above, three representative leaking hole sizes have been modeled by POSVCM at two different scenarios: operating pressure scenario (from 121bar* at host to 7bar at the OGT) and design pressure scenario (from 241bar at host to 90bar at the OGT).

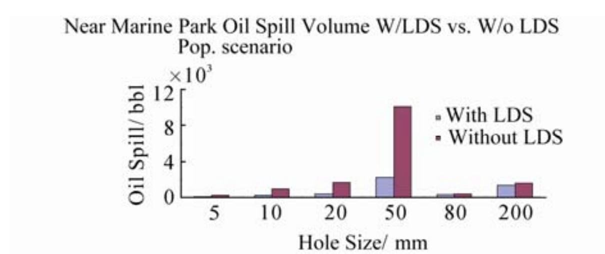

Fig.3 Operating pressure scenario-oil leakage near Marine Park

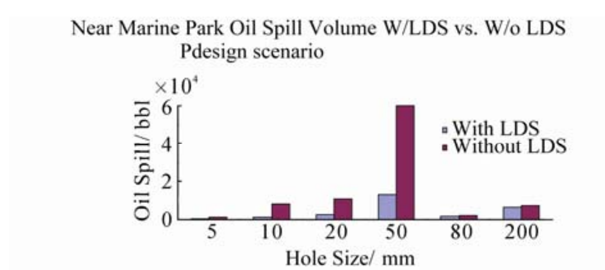

Fig.4 Design pressure scenario- oil leakage near Marine Park

（*1 bar=100 kPa）

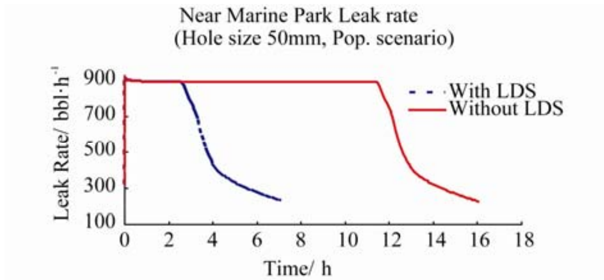

Fig.5 Operating pressure scenario- leak rate near Marine Park (hole size: 50 mm)

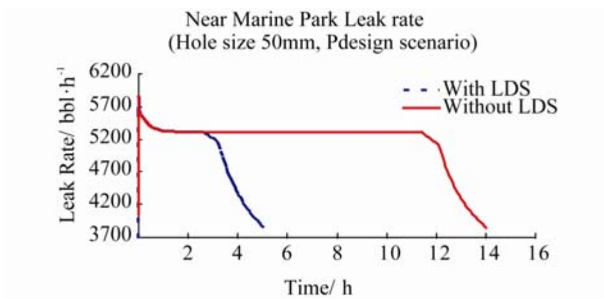

Fig.6 Design pressure scenario - leak rate near Marine Park (hole size: 50 mm)

The oil spill models run from the very beginning of the leak and the spill rates tend to be constant before the pipeline shut-in. However, the leak rate will decline sharply once the inlet valve of the pipeline is shut in to mitigate the leakage. The oil spill calculation results illustrated above from Fig.3 to Fig.6 have revealed that the installation of statistical LDS can large reduce the time of leak detection, thereby mitigating the consequence of leakage.

3.5.4 Oil dispersion assessment

The most environment sensitive area has been considered for oil dispersion assessment: Near Marine Park. The nearest section of pipeline to Marine Park is located between KP 168 and KP 171 (See Fig.1), for approx. 2000 m. At this location, as with the remaining section of the shallow water section, the pipeline will be coated with 50 mm of concrete coating as additional mechanical protection.

The leak scenario near Marine Park has been modeled in an EIA report for the oil export pipeline to the OGT. This study further models the oil spill dispersion based on the potential leak sizes in the pipeline at near Marine Park scenario of both the NE and SW monsoon seasons. During the NE monsoon season, the model predicts a maximum of 90% to 100% probability of shoreline oiling southeast of the release site, due to the close distance of the release location to the shoreline. During the SW monsoon season, the model predicts a maximum of 60% to 70% probability of shoreline oiling, which would decrease with increasing distance of release from the shoreline. And the oil spills are supposed to infect the Marine Park shoreline in one or two hours.

Extensive discussion on how the oil spill may impact the marine and coastal environment can be found in EIA. Combined with the oil spill volume modeling results in last section of this report, there are several conclusions that can be drawn:

- Any oil spill may have significant impact on the environment at both near shore and Marine Park.
- Statistical LDS will provide greater benefits for small to medium size leaks.
- For large leakages, LDS will provide limited values as the response time will be similar for both with or without LDS.
- The capability of proposed statistical LDS (See Table 4) is acceptable to detect oil leakage before the shoreline is infected.

At the marine park or near shore, the LDS will provide limited value due to rapid dispersion especially during monsoon seasons.

4 Leak detection criteria (LDC) design

QRA results reveal that the oil spill impact on the Marine Park and Shoreline at the scenario without statistical LDS is much severer than that with statistical LDS, so it is significant for us to establish a system to assist the Emergency Response Team (ERT) to quickly identify, locate and employ a mitigation measure to contain the damage in case a leak incident occurs.

DEP 31.40.60.11 [4] identified that LDC should be the requirement of the LDS, which is the outcome of a Quantitative Risk Assessment (QRA). The oil dispersion study has revealed that the spilled oil is supposed to infect the Marine Park shoreline in one or two hours. However, according to the emergency response presented in Table 4, the proposed statistical LDS is able to detect the oil spill before the Marine Park shoreline is infected.

Actually, if the oil dispersion study has proved that the proposed statistical LDS in emergency response assessment is unacceptable, the redesign of a much more strict emergency response scheme is necessary. This means a better LDS is needed. Thus, the LDC design is an interactive process between the QRA study Team and the Emergency Response Team (ERT).

Selecting of the LDS is the responsibility of the operating company based on the performance criteria established according to the API 1130[5] recommendation. The recommended acceptance limit for each of the performance criteria for the selection of LDS is provided in Table 5, which has incorporated QRA study results and comments from various LDS vendors.

Table 5 LDS Performance indicator criteria according to API 1130

Performance metric	Specific performance criteria	Steady state	Transient state
Sensitivity	Minimum detectable leak rate /%	0.50	2.00
	Response time for 100% leak / min	4	2
	Response time for 50% leak/ min	4	2
	Response time for 10% leak/ min	7	8
	Response time for 5% leak/ min	16	27
	Response time for 1% leak/ min	80	400
Reliability	Incorrect leak alarm declarations rate overall	1 time/ annum	2 times/ annum
Robustness	Loss of function due to pressure outages	NO	NO
	Loss of function due to temperature outages	NO	NO
	Loss of function due to flow outages	YES	YES
	Loss of function due to pump state change	NO	NO
	Loss of function due to valve state change	NO	NO
	Start-up stabilization period	NO	NO
Accuracy	Leak location for 100% leak /%	6	6
	Leak location for 15% leak /%	7	8
	Leak location for 2% leak /%	21	17
	Leak location for 1% leak /%	27	30
	Leak rate error /%	1	50

5 Conclusions

Table 3 has shown different causes of failure frequencies at the three representative leak sites. And the total pipeline failure frequency for the whole length (200.614 km) of the pipeline is found to be less than 1.72×10^{-4} per annum. This failure frequency is shown to be low and comparable to industry standard. From the QRA, it can also be concluded that there are little, if any, opportunities for further reduction to the failure frequency. The benefit of LDS has been shown in the figures of oil spill modeling results, which have indicated that the installation of LDS can largely reduce the oil spill volume. Thus, suitable LDS is recommended to be installed to reduce the impact of oil spill consequences. The oil spill dispersion assessment has proved that the capability of proposed statistical LDS by Emergency Response Team is acceptable to detect oil leakage before the shoreline is infected.

The LDC design is an interactive process between the QRA study Team and the Emergency Response Team (ERT). The acceptance limit for each of the performance criteria for the selection of LDS has been defined in Table 5 based on QRA study results and comments from various LDS vendors.

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一条海底输油管道的定量风险评估其检测标准设计

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摘　要：该报告描述一条预设海底管道的基于定量风险分析（QRA）的泄漏检测标准（LDC）设计问题. 定量风险分析的结

果会反映出统计泄漏检测方法是否必要.如果必要，恰当的泄漏检测标准必须建立.在分析中，著名的英国 PARLOC 2001 数据库将会用来估算管道实效概率。而来自 MMS 的 POSVCM 模型则用来做泄漏模拟计算.定量风险分析的结果说明，统计方法的泄露检测系统能打幅度地减少泄漏检测所需时间，从而减轻泄露的事故后果.根据 QRA 的分析结果，以及许多泄漏检测系统买主的建议，合理的西漏检测标准被设计出来.一旦泄漏事故产生，它可以帮助紧急事故相应组（ERT）快速检测，定位以及采取方法减轻泄漏.

关键词：定量风险分析；风险；泄露检测标准；PARLOC 数据库；管道