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Testing the Linearity Assumption in Leak Frequencies for Offshore Process Equipment

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Offshore QRAs normally assume that an installation's annual leak frequency depends linearly on its equipment count. This assumption is embedded in all generic leak frequency data for specific equipment items. To our knowledge, it has never been validated.

In this paper, we examine whether the relationship between leak frequency and the number of equipment items on an installation really is linear. Our chosen dataset is the UK offshore hydrocarbon release database. By accessing the original equipment population data, we have been able to calculate leak frequencies for individual installations varying widely in total equipment counts. Our results show significant deviations from the linear model.

After considering various possible interpretations, we conclude that lower frequencies are typically observed on small normally-unattended installations (NUIs), and also on large installations which have more opportunity to learn from experience and more incentive to invest in reliability. Excluding NUIs, there is a consistent decline in the leak frequency per equipment item as installation size increases.

Keywords: Risk assessment; leak frequencies; process equipment.

1. Introduction

1.1. *Background*

Quantitative risk analysis (QRA) necessarily involves simplification of reality. For example, complex non-linear relationships may be represented by simpler linear ones. It is good practice to list assumptions such as these so that they can be challenged and if necessary corrected. Yet some fundamental assumptions in QRA are rarely made explicit, and supporting evidence is rarely available. This paper addresses one such assumption.

Generic leak frequencies for process equipment are typically formed by dividing observed numbers of leaks by the equipment years in the exposed population to give frequencies in the form of "leaks per equipment item-year" (IOGP 2019). A QRA then multiplies these generic frequencies by the number of equipment items on the installation under study to estimate its annual leak frequency. This implicitly assumes that the generic leak frequency per equipment item is a constant, so that the installation's leak frequency is linearly proportional to the number of equipment items. The danger of over-confidence in this assumption has been pointed out in QRA guides (Spouge 1999 § 8.6.3) but few QRAs explicitly acknowledge it.

Recent technical guides (e.g. LR 2018, SNL 2022) and research literature (e.g. Xu et al 2020, Kaneko & Yuzui 2023) on offshore QRA have not addressed this issue, continuing with the embedded linearity assumption.

In this paper, we examine whether the relationship between leak frequency and the number of equipment items on an installation really is linear. To our knowledge, no previous study has addressed this. The obstacle is that the dataset needs to be able to show how the frequency varies on similar installations with different numbers of equipment items. This requires more detailed equipment population data than is normally available.

We believe the question is important in two main areas. First, for very large or very small offshore installations, the linear assumption may over-estimate or under-estimate the leak frequencies. Secondly, in other industries that use offshore leak frequencies for equipment made of many repeated items (e.g. multiple element gas containers), the linear assumption may over-estimate the leak frequencies. In either case, risk assessment and mitigation would be improved by better understanding the cause and extent of deviations from linearity.

1.2. *Objective*

Our objective is to explore how the process equipment leak frequency on an offshore installation varies with the number of equipment items present. Our hypothesis is that there may be some non-linearity in this relationship. We therefore try to quantify the relationship as accurately as possible using the available data and then investigate possible reasons for any deviation from linearity.

1.3. *Dataset*

Our chosen dataset is the hydrocarbon release database (HCRD) of the Health & Safety Executive (HSE), which covers oil and gas leaks from installations in the United Kingdom Continental Shelf (UKCS). It was created as part of the response to the *Piper Alpha* accident, and we believe it to be the world's largest and most comprehensive leak database. By accessing the original equipment population data that contributed to the latest update of the generic frequencies from this source (Bain 2017), we have been able to calculate leak frequencies for installations varying widely in size, and hence demonstrate the validity of the linearity assumption.

2. Method

2.1. *Leak data*

The UK offshore industry has reported leaks since 1 October 1992. HSE (2016) published a version of the database containing 4656 leaks in the UKCS between 1 October 1992 and 31 December 2015. After some changes to reporting requirements, HSE (2024) published a further 622 leaks during 2016-21. Since 1 October 2015, HSE (2025) has released quarterly reports but no collected database. We have collected the available data for the period 1992-2019 in an enhanced version of HCRD containing 5101 leaks.

For the current analysis, we need to know the size of the installation, and for this we need to identify them. HCRD has only included installation names since 2016. Before this, HCRD provided the installation start-up date and certain key features (e.g. whether fixed or mobile, production or non-production etc.). In our enhancement of HCRD we deduced the installation names so that they are known for the whole period 1992-2019. In 43 cases this was not possible, so we have 5058 leaks in which the installation is known.

The available equipment populations only cover fixed production installations during 1992-2016. Excluding mobile, subsea and non-production installations, and leaks since 31 December 2016, there are 4572 relevant leaks used in the analysis.

2.2. *Installations*

This analysis covers fixed installations involved in oil and gas production. In the UKCS these are mainly steel jacket platforms, but they also include a few concrete base platforms, oil storage units and floating production storage and offloading (FPSO) vessels, and one tension leg platform. Mobile drilling platforms are excluded.

To count the installations, we need to define what "installation" means. Several comprise bridge-linked pairs or complexes of multiple jackets. In this paper, we use the term "platform" to count individual jacket (or other) structures, while the term "installation" counts bridge-linked pairs or complexes of platforms. In other words, an installation may contain several bridge-linked platforms.

HSE provided a database of 715 platforms (according to the definition above) that operated in the UKCS at some point between 1 October 1992 and 31 December 2016, of which 315 were fixed production platforms. Including missing platforms and excluding duplicates, we have a total of 327 platforms, of which 114 are bridge-linked. They form 256 separate fixed production installations, including 43 that are bridge-linked.

2.3. *Equipment data*

HSE (2017) published estimates of the population of systems and equipment on fixed production platforms in the UKCS between 1 October 1992 and 31 December 2016. No updates have been published, and so it is currently impractical to estimate leak frequencies since 2016.

For the current analysis, we need to break down these estimates by the size of the installation. To do this, we accessed the original equipment population data ("parts counts") that DNV GL gathered to produce the estimates published by HSE (Bain 2017). This included comprehensive parts counts for 141 fixed production platforms. To simplify the analysis, we only used the parts counts from 2014/15, which covered 121 platforms. This is justifiable since the parts counts were not updated as the platforms aged.

DNV GL estimated the missing data as follows:

- System augmentation: On 86 platforms, some systems had no parts counts, and DNV GL estimated these using average parts counts in these systems on other platforms. In the present study, which compares large and small installations, the use of average parts counts is undesirable. Therefore, we have excluded these platforms from our analysis.
- Surrogate platforms: On 88 other platforms, no parts counts were available and DNV GL estimated these using similar platforms as surrogates, with scaling factors to adjust for the relative size of platform. In the present study, we have included these platforms where available in the 2014/15 parts count.

As a result, including surrogates, we have equipment data for 175 out of 256 installations.

The parts count for 2014/15 includes a total of 1.4 million equipment items (or metres of pipe) and including surrogates we estimate a total of 1.6 million equipment items. Taking account of each platform's production start and (where relevant) end dates, we estimate a total exposure during the period 1 October 1992 and 31 December 2016 of 36.5 million equipment item-years. This is 14% below the HSE's total for this period of 42.7 million equipment item-years, mainly due to the omission of system augmentation.

2.4. *Installation size groups*

To help investigate the effect of installation size on the leak frequencies, we categorise them by their total number of equipment items, as shown in Table 1.

Table 1. Installation size groups.

Group	Equipment items	Installations	Million equipment item-years	Mean items
Very large	>30,000	11	10.05	40,815
Large	20,001-30,000	17	9.56	24,916
Medium	10,001-20,000	27	8.29	14,238
Small	5,001-10,000	24	3.95	7,176
Very small	≤5,000	96	4.70	2,357
Unknown		81	6.15	
Total		256	42.70	6,467

2.4. *Frequency calculations*

From the data, we calculate two types of frequencies:

- Leak frequency per installation-year, i.e. the number of leaks divided by the number of installation-years.
- Leak frequency per item-year, i.e. the number of leaks divided by the number of equipment item-years.

We also express frequencies per item-year relative to the average of 4572/42.7 million = 1.1×10^{-4} per equipment item-year. This is the "linear model" as we represent it in this paper, equivalent to the average of HCRD results for all equipment types during 1992-2016. In practice QRAs use separate linear models for each equipment type.

2.5. *Non-linear model*

To better interpret the data, we develop a non-linear model as follows:

- Illustrate the trend of frequency with equipment quantity using a locally-weighted regression (LOESS), which depends on a smoothing parameter defined as the fraction of the data used at each point.
- Investigate the significance and possible causes of the observed variation using data segmented into size groups (Table 1).

- Choose a non-linear fit with the lowest residual standard error.

3. Results

3.1. *Leak frequency per installation year*

Figure 1 shows the leak frequency per year for installations that had equipment data and at least one leak, compared to the linear model and LOESS regression (with smoothing parameter 0.4).

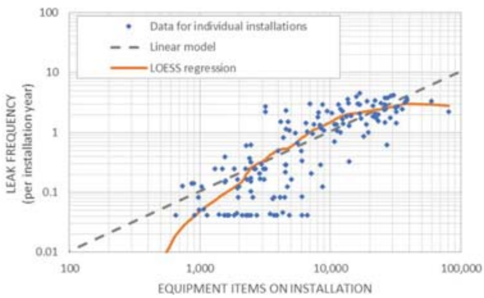

Fig. 1. Leak frequency for each installation.

It is immediately apparent that there is a lot of variation in leak frequency between installations, and that the linear model captures only a small part of this variation.

The small numbers of leaks on individual installations make their individual frequency estimates uncertain. When confidence ranges are estimated based purely on the numbers of leaks, the linear model passes within the 90% confidence range of only 97 of the 175 installations with equipment data (55%).

Another important cause of the scatter is uncertainty in the estimation of equipment data. This may partly explain the poor performance of the linear model. At present this uncertainty is unquantified.

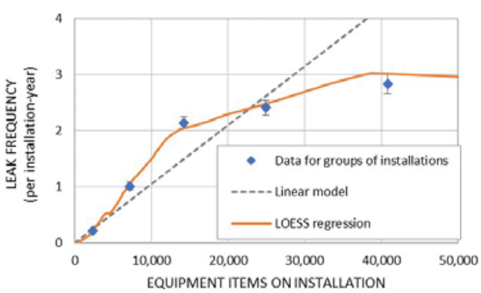

Fig. 2. Leak frequency for installation size groups.

Figure 2 shows the same models on a linear scale. It also includes the leak frequencies for each installation size group, plotted on a base of their average number of equipment items. Because there are many leaks in each group, the 90% confidence ranges are small. This shows that, while there is a generally upward trend, there are significant deviations from the linear model.

3.2. *Relative leak frequency*

Figure 3 shows the leak frequency per equipment item-year expressed relative to the linear model.

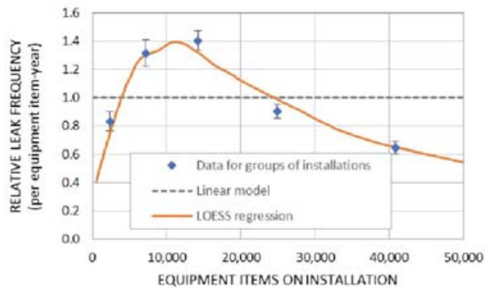

Fig. 3. Relative leak frequency.

Overall, the distribution follows an inverted U-shape. The 90% confidence ranges show that the frequencies for small and medium sized platforms are significantly higher than the linear model, while the frequencies for very large platforms are significantly lower.

To better understand the factors underlying this non-linearity, we consider several possible interpretations as follows.

4. Interpretation

4.1. *Different equipment types*

One possible interpretation could be that the observed non-linearity results from different equipment types having different trends. The above results add together the 117 different equipment types distinguished by HCRD. While some of them experienced very few leaks, so that variations would be uncertain, other equipment types have many leaks, and so trends can be identified with more confidence for them. Figure 4 shows the relative leak frequency per item year on the 5 installation size groups for the 7 equipment types with more than 100 leaks. Although there are differences between the equipment types, they all have a similar trend, with lower frequencies on larger installations. The trends are less clear for small and very small installations. All have leak frequencies that are less than average on very large installations, and all except flanges have leak frequencies that are higher than average on small and medium installations.

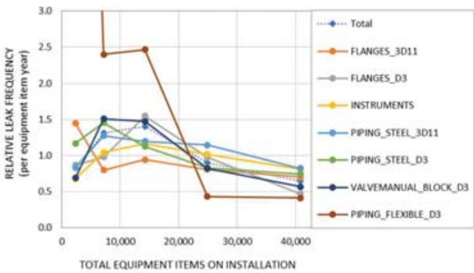

Fig. 4. Relative leak frequency for equipment types versus installation size.

Flexible piping (less than 3" diameter) stands out as having a much larger variation. Very small installations reported 12 such leaks (11% of the total) from 186 flexible pipe meter-years (0.8% of the total), giving a relative leak frequency of 14. Because only one very small platform reported flexible pipes in its parts counts, this result is considered very uncertain, which may explain why it is off the scale of the other results.

The above results are plotted on a base of the average number of all equipment items on installations in the size group, i.e. a measure of overall installation size. Figure 5 shows the relative leak frequency for the same 7 equipment types on a base of the average number of each equipment item on installations in the size group, i.e. a measure of the quantity of each equipment on the installation.

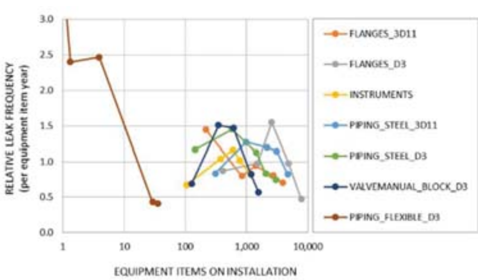

Fig. 5. Relative leak frequency for equipment types versus equipment quantity.

Although similar trends are apparent, it seems that the equipment quantity does not explain the variation as consistently as the installation size in Figure 4.

4.2. *Learning from experience*

A possible interpretation of the trend towards smaller leak frequencies on larger installations could be that they have greater opportunities to learn from experience. It is well established that task completion is more efficient for activities that are practiced more often (Newell & Rosenbloom 1981). It is likely that error rates are also lower in such cases. Large installations require more maintenance work, which gives their operators greater experience. Although the whole industry shares experience from incidents, which has probably contributed to the generally declining leak frequencies, it is inevitable that operators who have experienced the most leaks will also learn the most about how to prevent them. Since human error contributes to almost every leak, it is possible that the operators of larger installations will be better able to prevent leaks than the operators of smaller ones.

If this hypothesis was correct, the contribution of operational causes would be smaller on large installations. Table 2 shows the proportions of leaks with operational causes recorded by HCRD for each installation size group.

Table 2. Leak causes for installation size groups.

Group	Oper-ational failures	No oper-ational failures	Total
Very large	48%	52%	100%
Large	49%	51%	100%
Medium	50%	50%	100%
Small	53%	47%	100%
Very small	50%	50%	100%
Unknown	52%	48%	100%
Total	48%	52%	100%

As expected, operational failures make a lower contribution on larger installations, although the effect is quite small, so it cannot explain the leak frequency non-linearity by itself.

4.3. *Normally unattended installations*

A possible interpretation of the smaller leak frequencies on small and very small installations could be that many of these are normally unattended installations (NUIs). To avoid the need for human intervention, they may be designed to higher standards of reliability, which might produce lower leak frequencies.

To test this hypothesis, we have grouped NUIs separately from other installations. We identified 75 NUIs out of the 175 installations with equipment data. This is approximate because some installations were designated NUIs during the data collection period. Among normally attended installations, the small and very small groups have been combined.

Figure 6 shows the resulting leak frequency per item-year for the 4 normally attended installation size groups with NUIs counted separately. The frequencies are expressed relative to the linear model.

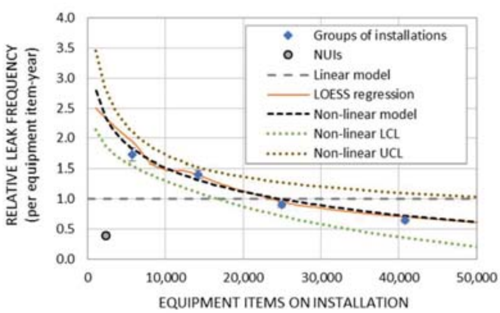

Fig. 6. Relative leak frequency with NUI separated

This confirms that NUIs caused the reduction in leak frequency for small and very small installations. Once they are removed, there is a consistent decline in leak frequency with installation size shown by both the installation size groups and the LOESS regression. Similar analysis of NUIs shows no significant influence of size on their leak frequencies.

Compared to the average leak frequency per equipment item-year (F) for all installations, the relative leak frequency (RF) for an installation with N equipment items can be approximated by the following non-linear model:

For normally attended installations:

$$RF = \frac{F(N)}{F} = 6.722 - 0.566 \ln N$$

For normally unattended installations:

$$RF = \frac{F(N)}{F} = 0.39$$

This non-linear model has R^2=0.13 and standard error of residuals 1.18. Its lower (5%) and upper (95%) confidence limits are included in Figure 6. It passes within the 90% confidence range of 114 of the 175 installations with equipment data (65%). This is better than the linear model (standard error 1.26), although it still does not explain all the variation between installations. The confidence limits show that the differences are only significant for installations with less than 16,000 or more than 50,000 equipment items.

4.3 *Economic incentives*

If designing NUIs for greater reliability has achieved a reduction in leak frequency, it is possible that similar design choices may also have affected other installations. In general, larger installations have greater production and hence greater incentive to avoid downtime. This might justify investment in reliability that also contributes to reducing their leak frequency. This might explain why the reduction seems consistent across all equipment types and depends less on the numbers of the specific leaking equipment.

4.4. *Under-reporting of leaks*

An important potential confounding factor of any frequency data is under-reporting of incidents. The UK offshore industry has made unusual efforts to obtain consistent reporting within HCRD. Nevertheless, a possible interpretation of the trend towards smaller leak frequencies on larger installations could be that they have reported leaks less consistently than smaller installations. Furthermore, a possible cause of smaller leak frequencies on NUIs could be a failure to detect or report incidents with no consequences.

This hypothesis can be tested using the relative frequency of different severities of leaks, based on the assumption that more severe leaks are more likely to be reported comprehensively. Table 3 shows the proportions of major, significant and minor leaks for each installation size group. High proportions of major leaks or low proportions of minor leaks are considered indicative of possible under-reporting.

Although there is some variation between the installation size groups, there are no consistent trends, and hence no indication that the results above could have been caused by under-reporting of leaks.

Table 3. Leak severity for installation size groups.

Group	Major leaks	Signif leaks	Minor leaks	Total
Very large	3.5%	46%	50%	100%
Large	5.4%	48%	47%	100%
Medium	3.2%	47%	50%	100%
Small	4.6%	41%	54%	100%
Very small	6.0%	44%	50%	100%
Unknown	4.8%	45%	50%	100%
Total	4.4%	46%	50%	100%

4.5. *Under-estimation of equipment*

Another possible confounding factor could be errors in the parts counts or estimation of equipment data on surrogate platforms. At present this uncertainty is unquantified. It is a possible cause of the scatter in Figure 1, and hence of the relatively poor performance of both linear and non-linear models.

However, while inconsistency between installations might be expected, such errors would be random and would tend to cancel out in the large population groups used here. The most likely bias would be incomplete parts counts. This might be expected on very large installations, where equipment counting is more onerous. However, if it had occurred its effect would be to increase the leak frequency for them, potentially concealing a greater reducing trend with installation size.

4.6. *Excluded installations*

The analysis excludes 81 installations whose equipment counts were based on system augmentation. They were 58% NUIs, compared to 43% of installations in the analysis, and had an average of 3000 equipment items. Their relative leak frequency was 1.1. Further analysis would be needed to confirm that their exclusion did not bias the results.

4.7. *Progressive improvement*

HCRD shows a distinct downward trend in leak frequencies since 2005 (Bain 2017), presumed to result from progressive improvement in safety management. If there was also a trend in installation size, it is possible that the above results might misrepresent the trend with time as a trend with installation size. This hypothesis can be tested using the most recent data, as shown in Table 4, which also separates NUIs and combines the small and very small groups.

Table 4. Leak data for installation size groups.

Group	1992-2016		2016	
	leaks	million item-yrs	leaks	million items
Very large	697	10.05	10	0.413
Large	924	9.56	17	0.368
Medium	1246	8.29	24	0.358
Small	790	4.27	12	0.182
NUI	182	4.37	5	0.185
Unknown	733	6.15	13	0.380
Total	4572	42.70	81	1.886

Figure 7 compares the relative leak frequencies above to equivalent results derived from 2016 data alone. The 2016 dataset is much smaller and hence more uncertain, but is consistent with the full 1992-2016 dataset. There is no evidence that the non-linearity has changed during this period.

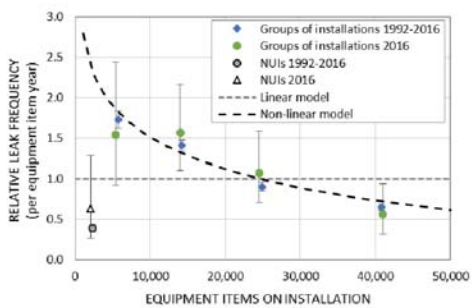

Fig. 7. Relative leak frequency in different time periods

5. Conclusions

This paper has tested the conventional assumption that leak frequency depends linearly on the number of equipment items and found that the real picture is more complex.

Our results show that there is a lot of variation in leak frequency between installations, and the linear model captures only a small part of this variation. Individual equipment types show similar patterns so the unknown influence is probably not equipment type. Uncertainty in equipment populations may explain some of the variation. Fully understanding the influences is a topic for future research.

Excluding NUIs, there is a consistent decline in leak frequency with installation size. We have measured installation size using its total number of hydrocarbon equipment items, as defined in HCRD. A non-linear model, relating leak frequency to this measure of installation size, produces a better fit to the data than the linear model.

One possible interpretation of this result could be that larger installations have greater opportunities to learn from experience. Another interpretation could be that they have greater economic incentive to avoid downtime and hence reduce leaks. Similarly, NUIs may be designed to higher standards to avoid the need for human intervention.

We have considered possible confounding factors such as under-reporting of leaks, under-estimation of equipment, exclusion of installations with unsuitable equipment counts and downward trends due to progressive safety improvement. None of these factors seem to have affected the results.

6. Way ahead

While leak frequencies based on the linear assumption are well-established, our study suggests that the non-linear model could be used to adjust the frequencies in QRAs of offshore installations, reflecting the average effect of installation size. These are significant increases for small installations and significant reductions for very large installations and NUIs. At present, we recommend using these factors for sensitivity tests, so as not to undermine the consistency that HCRD has achieved in QRAs.

We believe that greater discussion and more extensive research is needed on the factors underlying the non-linear effect that we have uncovered. There is also a need to investigate other factors that might explain the variation in leak frequency between installations.

Our analysis also implies that better and larger data collections are needed to fully capture the non-linearity. In particular, the equipment data for HCRD should be updated alongside the leak data collection.

For other industries that use offshore leak frequencies, our results suggest that the linear assumption may over-estimate leaks from equipment made of many repeated items (e.g. multiple element gas containers) but under-estimate leaks for organisations with little experience (e.g. small operators or new industries). However, there is at present no simple way of applying the adjustment factors from the offshore results to other industries. This might be facilitated once the causes of the non-linearity are better understood.

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