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APPLICATION OF DESIGN OF EXPERIMENTS (DOE) TO ANALYZE SENSITIVITY OF POSITION OF THE IN-LINE TENSION READER INTER-M PULSE IN A MOORING LINE

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Abstract

The Inter-M Pulse (IMP) is an instrumented mooring link designed to measure mooring line tension in real-time. The link is able to measure the load and acoustically transmit the information to a single receiver in the water underneath the floating unit. A set of tension/compression strain gauges transforms minuscule link deformations into electrical signals, which are interpreted by a calibrated linear co-relation with tension. The equipment was developed to be used in water depths ranging from 50 up to 3000 meters.

It is well known that the maximum tension in a mooring line is located on the top end of the catenary. However, considering operational issues, it is not feasible to install the IMP in this location. The equipment does not pass through the fairlead or any similar interface between mooring line and offshore unit; additionally, the harsh conditions in the splash zone mean that this is not a desirable region to position the sensor and the acoustic transmitter. For this reason, the Inter-M Pulse should be installed at the optimum position to measure the critical tension.

An engineering technique called Design of Experiments (DoE) is widely used in different industries but not often applied in the oil and gas industry. This paper uses the DoE approach to study the influence of different factors in the mooring line measurement and the optimization of Inter-M Pulse location.

1. Introduction

There is a growing consensus in the offshore oil and gas industry that done additional studies and actions need to take place to improve mooring system integrity. The Inter-M Pulse is an instrumented H-link solution for monitoring the mooring line tension in real time, providing information on stress values and fatigue life. It should be installed in a minimum water depth of 50 meters, due ROV limitations, down to when the mooring line load is over 50 ton, as previous calibration tests have shown this to be the minimum Inter M-Pulse accurate tension.

As previously mentioned, the purpose of this paper is to use (DoE) technique to understand the contribution of different factors involved in the Inter-M Pulse installation. The first step was to consider the main parameters that can influence the load in the mooring line. Those factors, found below, were initially investigated for two different mooring line configurations:

- Location of Inter-M Pulse in the mooring line.
- Anchor horizontal distance, caused by vessel offset.
- Significant Wave Height.
- Mooring line properties.
- Water Depth.

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The mooring conditions analyzed were created through the combination of these inputs presented above. The range of each one was defined according to realistic permanent mooring designs with each combination representing a catenary geometry. When combining these inputs, an impossible catenary configuration may be created. For example, if the line length is shorter than the water depth, no mooring line profile would fit this arrangement and, thus would not have a suitable result of this analysis. To avoid this issue, the horizontal distance and mooring line length were bonded to the corresponded water depth. Therefore to choose the two usual permanent mooring line configurations, a static analysis on the numbers of moored FPSOs was carried out. The histogram was divided into 4 classes of water depth, as shown in Figure 1.

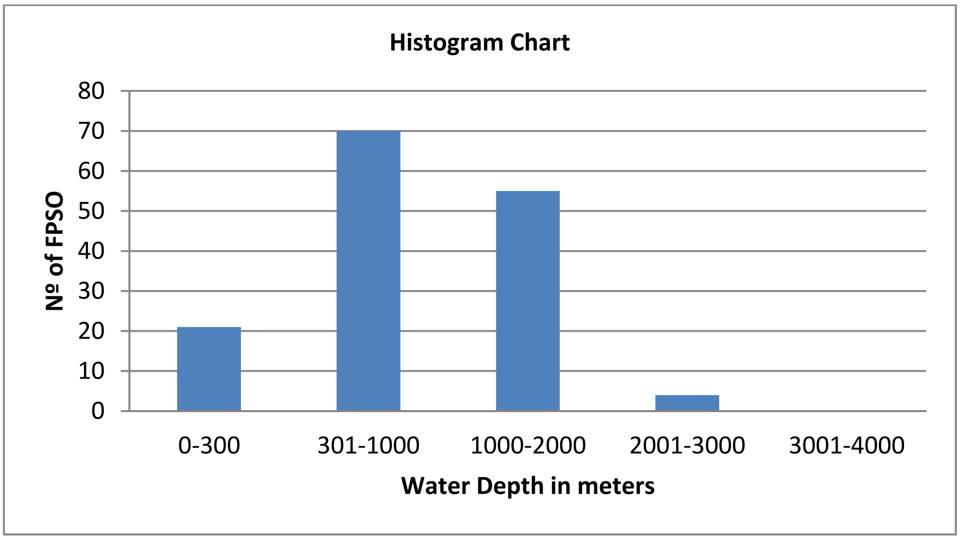

Figure 1. Histogram, from http://www.rigzone.com/

According to Figure 1, the most common water depth for a permanently moored unit is between 300 meters to 1000 meters. Based on this, a hypothetic mooring line configuration was chosen from a permanent unit in 776 m water depth, as well as an outlier in water depth of 2150 m.

After the recognition of these inputs, the outputs desired variables must be defined. They represent which evaluation criteria will be the focus of the DoE study and used to establish Inter-M Pulse installation zones. In other words, the DoE method will evaluate the output chosen, based on the all inputs considered. The evaluation criterion is listed below:

- Measurement Ratio (MR) between IMP Tension and Top Tension.

This output is the ratio used as a factor to transform the measured IMP tension to the maximum mooring line tension (top tension), as presented on the equation 1, below:

- MR = IMP Tension (IMPT) / Top Tension (TT) (1)

The maximum value of the MR is 1 and occurs when the IMPT is equal to TT, indicates that the Inter-M Pulse is installed in the interface between mooring line and offshore unit.

Initially a simplistic mooring line model was considered to select which parameters (inputs) are more important (influent) for the Inter-M Pulse reliability on fatigue assessment. At this stage it was possible to identify the level of influence of each input on the mooring line model.

With the initial investigation of the inputted parameters, made possible to understand the behavior the output chosen Measurement Ratio and to recognize the main effect. The quantification of influence of each input parameter is useful to show that some are negligible for the Inter-M Pulse reading.

In this study, the DoE was fed by a group of numerical analysis carried out using the software “Orcaflex 9.7” and results of these analyses were post-processed within the software “R i386”.

2. DOE Methodology

One of the main ways to improve the understanding and knowledge about any process, product or service is to analyze experimental data to create a correlation and predict results.

Currently the most common approach applied in the oil and gas industry is the experiment known as One-Variable-At-a-Time (OVAT). This concept involves inspecting each variable at a time, whilst maintaining all other variables fixed, thus relying on guesswork, luck, experience and/or intuition. Therefore OVAT requires a huge amount of resources to conduct the experiment, obtaining a restricted amount of data and conclusion about the factors influencing the process, product or service. In order to reduce the amount of experiments, and obtain a reliable and predictable effect of the factors and relationship between them, it is really important to vary the factors simultaneously, which is not addressed by the OVAT analysis.

The Design of Experiments (DoE) was developed in the early 1920's by Sir Ronald Fisher, to determinate the effects of the various fertilizers on different soils. He used DoE which could differentiate the effect of the fertilizer as well as other factors, such as underlying soil condition, moisture content of the soil etc. Since this initial experiment several worldwide manufacturers have reported improvements using this technique.
According to Antony (2003), DoE requires a sequence of activities to be applied:

A. Hypothesis: an assumption that motivates the experiment by changing two or more factors, in two levels, conveniently named as "-1" and "+1".
B. Experiment: a series of tests conducted to investigate the hypothesis.
C. Analysis: involves understanding the nature of data and performing statistical analysis of the data collected from the experiment.
D. Interpretation: is about understanding the results of experimental analysis.
E. Conclusion: involves determining whether or not the originally set hypothesis is true or false. Very often more experiments are required to test the hypothesis or new hypothesis.

The three basic principles to reduce or even remove experimental bias are randomization of the factors, replication and blocking. This is important especially on a large experiment where bias could result in wrong optimal settings or, in some cases, mask the effect of the really significant factors.

For the DoE study on the Inter-M Pulse, a regular factor experiment was applied, which consisted of changing each factor in two levels', -1 and +1. The interpretation of DoE analysis, were based in two charts: (1) standardized Pareto plot of effects, (2) Main Effects plot for the experiment. The Pareto plot of effects can be used to quantify the importance of each variable on the result, whereas the Main Effect plot allows visualization of the factor levels (-1,+1) impact on the result.

Based on the references (Antony J., and Kaye (2003); Benski, H.C (1989); Kumar, S. and Tobin, M (1990); Montgomery, D.C(2001)), the DoE analysis shall be conducted on the following phases (Figure 2) to achieve sustainable results;

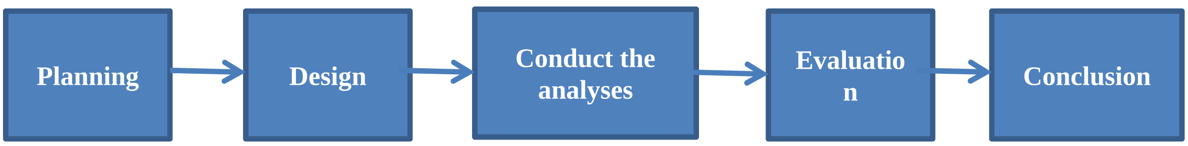

Figure 2 DoE Flowchart.

3. Planning Phase

The objective of this study, as mentioned before, is to understand the contribution of different factors involved in the Inter-M Pulse installation. In order to begin the planning phase, a clear definition of the physical model to be designed and studied is required. For that it was based on two proposed conventional mooring lines, chosen based on the FPSO histogram (Figure 1).

The first mooring proposed mooring line configuration was installed in 776 meters of water depth will be tagged as shallow configuration. Thereafter the second in 2150 meters water depth, will be tagged as deep configuration. Before moving to the next phase it is really important to detail the entire mooring line configuration, to choose the appropriate factors to be varied during the design and analysis phases. Table 1 shows all the components installed at the shallow and deep configurations. More detailed information can be found at Appendix A, Figure 4.

Table 1.Mooring lines configurations.

Components	Shallow configuration 776meters (Material/ diameter/ length)	Deep configuration 2150m (Material/ diameter/ length)
1	Chain/ Ø 95 mm/ 217 m	Chain/ Ø 120 mm/ 197 m
2	Polyester/ Ø 154 mm/ 13 m	Polyester/ Ø 207 mm/914 m
3	Chain/ Ø 95 mm/ 20 m	Chain/ Ø 120 mm/ 11.4 m
4	Polyester/ Ø 154 mm/174 m	Polyester/ Ø 207 mm/914 m
5	Chain/ Ø 95 mm/ 15 m	Chain/ Ø 120 mm/ 11.4 m
6	Polyester/ Ø 154 mm/578 m	Polyester/ Ø 207 mm/914 m
7	Chain/ Ø 95 mm/ 110 m	Chain/ Ø 120 mm/ 94.2 m
8	Wire/ Ø 88 mm/ 40 m	Chain/ Ø 120 mm/ 150 m

The possible variables that can be ranged for the design phase are detailed below and are illustrated at Appendix A, Figure 4:

- Water Depth.
- Vessel horizontal distance from the anchor, caused by the vessel off-set.
- Significant Wave Height.
- Inter-M Pulse position at the mooring line.
- Mooring line components properties.

The output value from DoE analysis will be the MR, calculated according to equation 1, mentioned in the introduction. Indeed, before beginning the design phase, it is important to emphasize that the mooring line from the shallow configuration does not fit on the deep configuration. This fact was considered during the design phase.

4. Design Phase

For any mooring design the water depth is a constraint. The designer must find the best solution to station keep a floating unit using a number of mooring lines must behave as catenaries. The solution for the catenary profile is based on: tension, horizontal distance and line length.

As mentioned in the planning phase, the mooring line length was associated with the corresponding water depth, the latter being used to define nominal tension and length; the horizontal distance was changed according to the vessels typical offset. Usually the maximum off-set in rough water is 15% of the water depth and the vessel usually moves between 1% and 5% of the water depth.

The factors mentioned on the planning phase will be divided into two levels, high and low. These levels will be described on the following subsection. In the DoE model the high level of the chosen factors is represented as +1 and the low level of the chosen factors represented as -1.

4.1. Water Depth

The water depth is one of the main factors, with the mooring lines installed in two different water depths, with significant weight difference. For the DoE model the shallow mooring line (776 m) will be represented as -1 and the deep (2150m) as +1.

4.2. Horizontal distance

The permanent unit offset variation, due to environmental conditions, will be represented as a variation on horizontal distance from the anchor to the fairlead. This distance will be changed by the horizontal coordinates once the mooring line length is fixed and bonded to the water depth. The high level (+1) is the percentage of water depth added to the horizontal distance and the lower level (-1) is the percentage of water depth deducted from the horizontal distance. The variation considered for high and low level were ±1%, ±5% and ±15% of the water depth. However, for the DoE analysis to be acceptable just two levels are required, resulting in only one percentage of water depth. This study will analyze three horizontal distance, generating a total of six levels (±1). Due to this issue three DoE analysis were conducted, separated for each off-set. The DoE low level (-1) will be the short horizontal distance, and high level (+1) the longest horizontal distance.

4.3. Wave Height

Wave height is a consistent parameter in a mooring designer's mind. In this study the wave height is transformed into the fairlead height. As a generic model and for simplification reasons, an amplitude variation of 4 meters is used. For the DoE analysis the upper level (+1) was considered as 4 meters above sea level and the lower level (-1) 4 meters below sea level, meaning that during the analysis the coordinates from the fairlead will move upwards for upper level + 4 meters above the sea-level and downwards for lower level (-1) -4 meters.

4.4. Inter-M Pulse position at the mooring line

The location of the Inter-M Pulse is the main subject of this study; hence the first step is to understand how tension reading is impacted by its position in the mooring line. There are various factors that limit available locations for the IMP: some are operational whilst others are attributed to data quality requirements for mooring line fatigue life or further life extension.

The primary operational restriction is the battery replacement which is planned based on the quantity and period of the data transferred; usually the battery replacement is required every 3 years. Due to the risk involved in diving operations, ROVs are generally preferred for battery change out. The minimum water depth for a ROV operation is around 50 meters leading this depth to be selected as the minimum water depth for the study. While this primary restriction was considered from the start of the DoE study, other constraints will raise up from the analysis.

Once the length of the two chosen mooring line (shallow and deep configurations) have been decided, according to the water depth, the Inter M-Pulse install was positioned, based on mooring line length percentage. The 50 meter water depth, which represents 8% of the shallow mooring line (ML) configuration, was set as the low level (-1); the high level was set at the middle of the mooring line (ML), 50% of the length. These levels are illustrated on appendix A figure 3.

4.5. Mooring line properties

For a permanent unit at the two chosen water depths is almost impossible to reach a mooring line configuration using only one type of a material, such as: chain, wire and polyester. As shown at the planning phase, the mooring line configuration is basic: chain, polyester and wire cable. In order to analyze the influence of the mooring line properties, since the wire cable is heavier than polyester, polyester was set as a low level (-1) and wire as high level (+1).

4.6. Building the models

All factors compiled in Table 1 enable the start of the DoE study. A full factorial DoE analysis was run, which consisted of all possible combinations of the five factors, with the respective top and bottom levels. The number of physical cases to run a full factorial analysis are calculated by 2n, where n is the number of factors. In this case 32 calculations are required.

Table 2. Input factors.

Levels	Water Depth	Hor. Dist	Wave height	IMP	Material
-1	776 m	-5% *WD	-4 m	8% of ML	Poly
1	2140 m	5% *WD	4 m	50% of ML	Wire

Based on the input Table 2, it was possible to build the runs sequence through the “R i386” software, generating the total amount of 32 runs needed to be performed using “Orcaflex 9.7”. The run sequence can be found in Table 3, which also contains the details of the chosen factors in some of the runs.

Table 3.Runs sequence resume.

Runs	Water Depth	Horizontal Distance	Wave Height	IMP position	Material
1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	1
⋮	⋮	⋮	⋮	⋮	⋮
31	-1	1	1	1	1
32	1	1	1	1	-1

5. Conducting the analysis

As mentioned on the planning phase, the horizontal distance variation analyses were considered: ±1%, ±5% and ±15% of the water depth. However, as mentioned before, the horizontal distance is one of the DoE factors with just two levels. To analyze all horizontal distance variation, three DoE runs were required.

Through “R i386” software sequence of 32 runs were generated for each horizontal variation, adding to an amount of 96 runs. Once the runs sequence, was generated, the “Orcaflex 9.7”, built the models, solved the catenary equations, and saved the Measured Ratio (MR) of each run in a worksheet. Once all runs were done, the MR results from the worksheet were inputted as a result in the R software, which was then post-processed to achieve the DoE results.

6. Evaluation

The models response, MR, from the “Orcaflex 9.7” analysis was inputted on a new column, into the run sequence shown in Table 3, and analyzed using “R i386” software. From the DoE analysis using “R i386” it was possible to extract the linear model correlation and the factors influence.

Table 4 demonstrates the first output from the “R i386” software. The first column is the liner equation input, such as factor and interactions between them. The second is a simplification of the first column to reduce the equation length. Thereafter the third thru last column represent the linear equation coefficients for each percentage of the off-set variation.

Table 4. “R i386” output regression functions.

	Simp.	Coef. for ±15%WD	Coef .for ±5%WD	Coef .for ±1%WD
Constant	A	0.7032	0.6666	0.6441
Water Depth	B	-0.0272	-0.0827	-0.0861
Horizontal Distance	C	0.2277	0.1035	0.0152
Wave Height	D	0.0086	0.0117	0.0114
IMP position	E	-0.0713	-0.0694	-0.0744
Material	F	0.0816	0.1050	0.1014
Water Depth :Horizontal Distance	B*C	-0.0097	-0.0288	-0.0103
Water Depth :Wave Height	B*D	0.0073	0.0043	0.0030
Water Depth :IMP position	B*E	0.0490	0.0384	0.0401
Water Depth :Material	B*F	0.0195	0.0213	0.0321
Horizontal Distance :Wave Height	C*D	-0.0076	-0.0058	-0.0056
Horizontal Distance :IMP position	C*E	0.0568	0.0262	0.0004

Horizontal Distance :Material	C*F	-0.0290	-0.0002	0.0046
Wave Height :IMP position	D*E	0.0080	0.0084	0.0080
Wave Height :Material	D*F	-0.0078	-0.0075	-0.0062
IMP position :Material	E*F	0.0266	0.0343	0.0327
R^2		0.96	0.97	0.98

With table 4, above, it is possible to transpose the linear model from the correlation generated by "R i386" software to any other software. This is achieved, by simply using the coefficients and multiplies it by the factors and factors interaction. To reduce the equation length the factor names were replaced with the letters A to F, according to the second column of table 4. The equations below were generated for each off-set variation:

$$Measure_{Ratio\ 15\%} = A * 0.7032 - B * 0.0272 + C * 0.2277 \ldots\ldots + EF * 0.0266 \quad (2)$$

$$Measure_{Ratio\ 5\%} = A * 0.6666 - B * 0.0827 + C * 0.1035 \ldots\ldots + EF * 0.0343 \quad (3)$$

$$Measure_{Ratio\ 1\%} = A * 0.6441 - B * 0.0861 + C * 0.0152 \ldots\ldots + EF * 0.0327 \quad (4)$$

It's important to emphasize that standardizing all the equation coefficients (+1 or -1) means the factors can easily be compared one with another. In order to compare the factors influence for the Measure Factor (MF), a Pareto plot was made (illustrated in Figure 3) with the coefficients standardized on percentage.

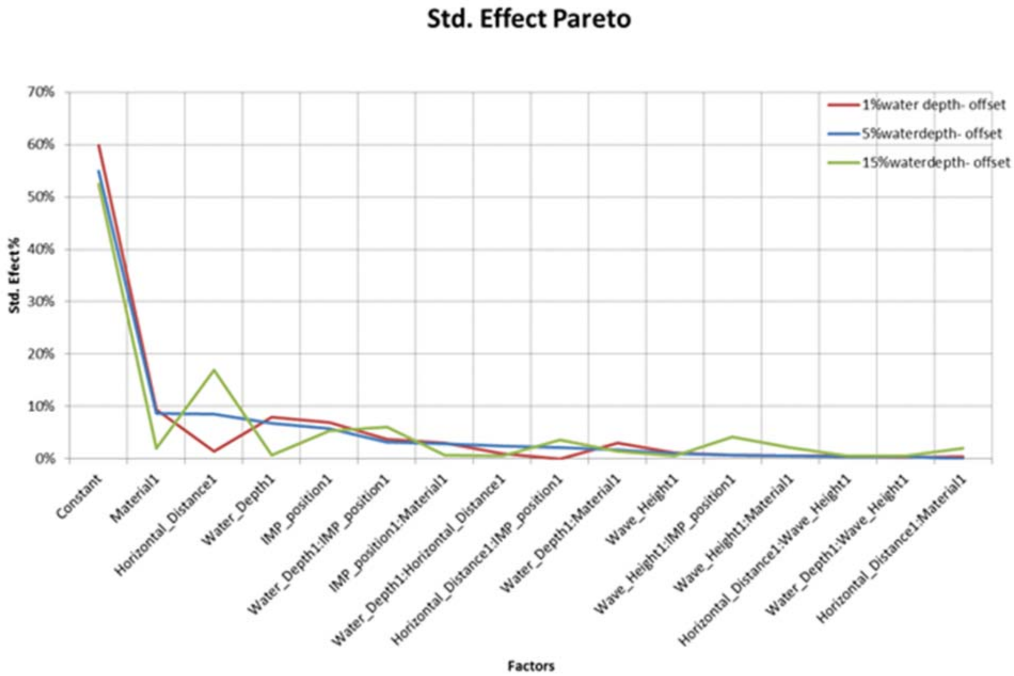

Figure 3.Standardized Pareto Effect for different offset.

It is clean from figure 3, that the influence of the material (polyester and wire) is significant for the MR for off-sets with ±1% and ±5% of the water depth and not so important, for off-set with ±15% of water depth. Similar result is observed for the Water depth coefficient, as the off-set is increased, the coefficient is reduced. On the other hand, the horizontal distance coefficient has the opposite behavior, increasing in importance as the offset, percentage of the water depth, is increased.

The Inter-M Pulse position still has significant impact on the MR for all offsets measured, as the coefficient did not show any significant change. The wave height coefficient did not show any change either, but with less significant importance for the measure ratio.

For a better understanding of how the MR change due to the input change, factors ±1, figure 5 (in Appendix A) shows a chart plotting the main effects. From this, it is possible to visualize the coefficient effect as the MR result. The figure 5 shows that the maximum measure variation, difference between the minimum values to maximum, is 0.5, which ranges from 0.45 to 0.95 for the ±15% of water depth offset (horizontal distance), but the MR variation is reduced as reduced the offset, reaching a minimum variation of 0.20, from minimum of 0.58 to maximum of 0.78 at ±1% of water depth offset.

7. Conclusion

This approach to understand the factors influencing the MR has shown influence of: water depth, Inter-M Pulse position, mooring line material and horizontal off-set. The wave height coefficient was found to be irrelevant when compared to the others factors. Therefore to achieve accurate mooring line tension measurement through the Inter M Pulse, are required:

- Accurate mooring line as-built, controlling: installation water depth, mooring line materials length, density and mechanical properties.
- At minimum off set (Horizontal distance), in case of -15% water depth which means close to the anchor/ pile position, locate the Inter-M Pulse between 50 meter of water depth down to when the mooring line load is 50 ton (minimum Inter M-Pulse accurate tension)
- The MR dependency for offset greater than ±1% water depth, is higher, making it necessary to control the off-set.
- The MR is not constant, thereon is necessary to have a transfer function with; Inter-M Pulse tension and off set as an input and mooring line top tension as an output.

8. Appendix A

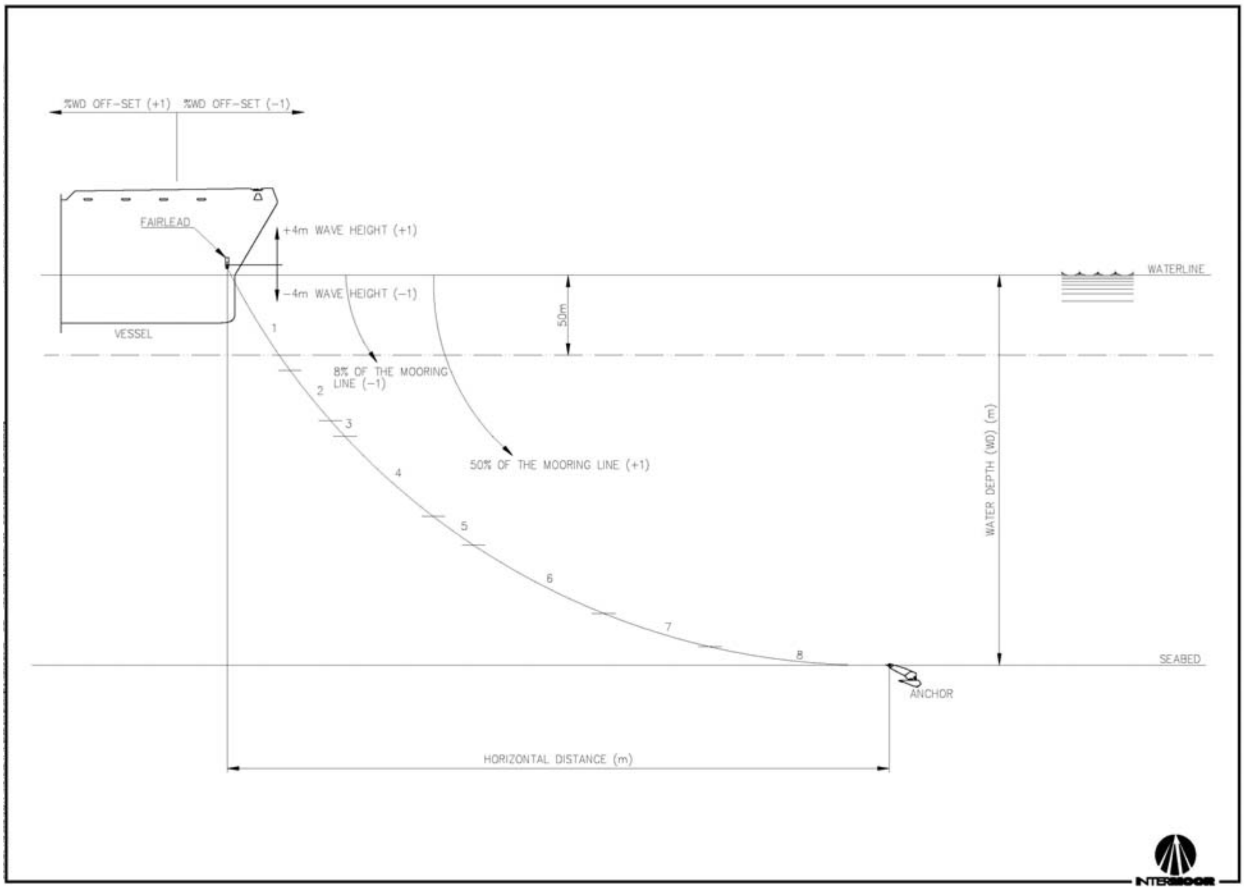

Figure 4. Detailed Mooring line, for the DoE Study.

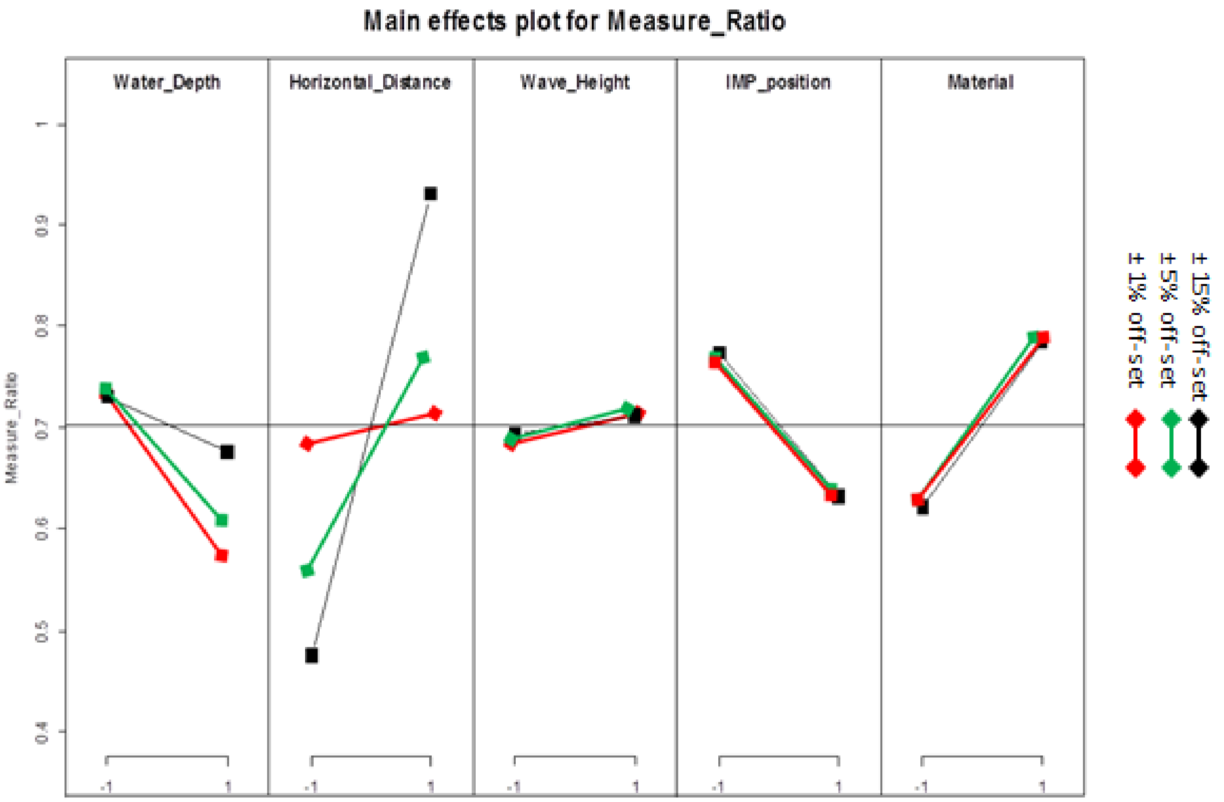

Figure 5. Main Effect for Measure ratio (MR).

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