Study of Effect of Trawl Gear on Submarine Pipeline in the Persian Gulf

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Abstract
This paper presents a novel strategy based on the finite element method for prediction of fishing gear interference loads on submarine pipelines. Trawl gear is one of the main factors in the failure of the submarine pipelines. In this paper, the influence of trawl gear on submarine pipeline in the 19th South Pars gas field is located in the Persian Gulf which is having 32” diameter is considered. The FE model is performed using OrcaFlex software includes modeling of seabed, pipeline and trawl gear parameters. To modeling soil and reinforced concrete, non-linear parameters are considered and to validating the models, DNV-RP-F111 and results of modeling by SAGE Profile software is used. The results indicated that by increasing free span height, pipeline response is increased but by increasing free span length, only lateral displacement has shown considerable increment. Finally, maximum time of meeting design acceptance criteria was determined for the trawl gear.

Keywords: Submarine pipeline, Pull-over load, Finite Element Model, OrcaFlex.

Introduction
Submarine Pipelines failures lead to oil spills in water and may even lead to explosion that will result in heavy financial and environmental damages. Interaction between fishing gear and subsea pipelines is a crucial challenge for the co-existence of fisheries and offshore hydrocarbon exploitation. The most comprehensive database of offshore pipeline failure is available in the report of the UK Health and Safety Executive PARLOC 2001 [1]. The PARLOC database indicate that about 53% of pipeline failures were caused from Accidental Limit State factors in the submarine pipelines include Trawling, Dropped object, Anchoring and Natural hazard [1-3]. The damage to the pipeline due to the fishing gear is very dependent on the type of fishing gear and the pipeline conditions, e.g. the weight and velocity of the fishing gear and the wall thickness, coating and flexibility of the pipeline [4]. Many different types of fishing gear are used in the commercial fishing industry around the world. There are three types of trawl systems is shown in Figure 1, based on how the opening of the trawl bag is maintained [5]:

a) Beam trawl by use of transverse beams
b) Twin trawl with clump weight
c) Otter trawl by use of trawl boards; which include V-Board, Polyvalent Board and Polyfoil Board.

Generally, assessment of the interaction between bottom trawl gears and pipelines divided into three phases, which include [5]:

i. **Impact phase:** In this phase focuses on energy absorption and denting of the cross-section due to the initial impact load and gives it a short impact.
ii. **Pull-over phase**: The “pull-over” phase is when the trawl gear drags over the pipeline on the seabed for some seconds. This response type is dynamic and requires use of nonlinear finite element (FE) methods due to large lateral displacements, seabed contact, axial force changes and possible elasto-plastic material response.
iii. **Hooking phase**: In some cases, the trawl gear may actually be hooked under the pipeline and move it along with the trawl equipment, leading to a very severe loading situation. Hooking design load effects may be obtained by static nonlinear FE analysis of the pipeline subjected to a prescribed vertical lifting height.

Pull-over loading seems to have the largest potential for improvements. The focus in this paper is therefore exclusively on prediction of loads and responses in the pull-over phase. Research addressing the pull-over phase was initially based on laboratory tests and full-scale tests. Extensive testing was carried out in a Norwegian joint industry project (JIP) in the1970s to study the interaction between pipelines and trawl gear [6-8]. Numerical methods for response prediction of pipelines subjected to prescribed pull-over loads were introduced in work carried out by Bergan and Mollestad [9] and Guijt and Horenberg [10] in the 1980s. Verley [11] is modelled the effect of free spans of up to 6 m height on trawl force. Results are presented for maximum warp force, maximum force applied to the pipeline and shape of the force-time trace. Fyrileiv [12] discusses trawl loads from clump weights and updated design approaches including pull-over load estimates are presented. The conclusion is that clump weights may govern the trawl design of pipelines, especially for trawl gear impact and pull-over. Igland and Soreide [13] perform non-linear dynamic finite element analysis for the interference between clump weight and pipeline on seabed using ANSYS software package. Output from the analysis is the pull-over force magnitude, as well as shape and duration of impact on pipeline from the clump weight. Small-scale tests have been used to verify the FE model. Teigen et al [14] developed FE simulation of the rather complex interaction between pipelines and trawl boards for the first time. Herlianto et al [15] presents global response of subsea pipeline as a result of trawl gear pull-over loads. The external interference from trawl gear pull-over loads can create substantial imperfection or out-of-straightness on the pipeline and may generate global lateral buckling. The pull-over loads can also induce excessive bending moments and strains in the buckle region. In this research, response of submarine pipeline (displacement, bending moment and stress-strain) under trawl pull-over load has been investigated under the influence of height and length of free span changes. As a case study, submarine pipeline in the 19th South Pars gas field is located in the Persian Gulf which is having 32” diameter is considered. For numerical modeling is used of OrcaFlex software. The results of modeling by OrcaFlex is verified with DNV-RP-F111 and results of modeling by SAGE Profile [16].

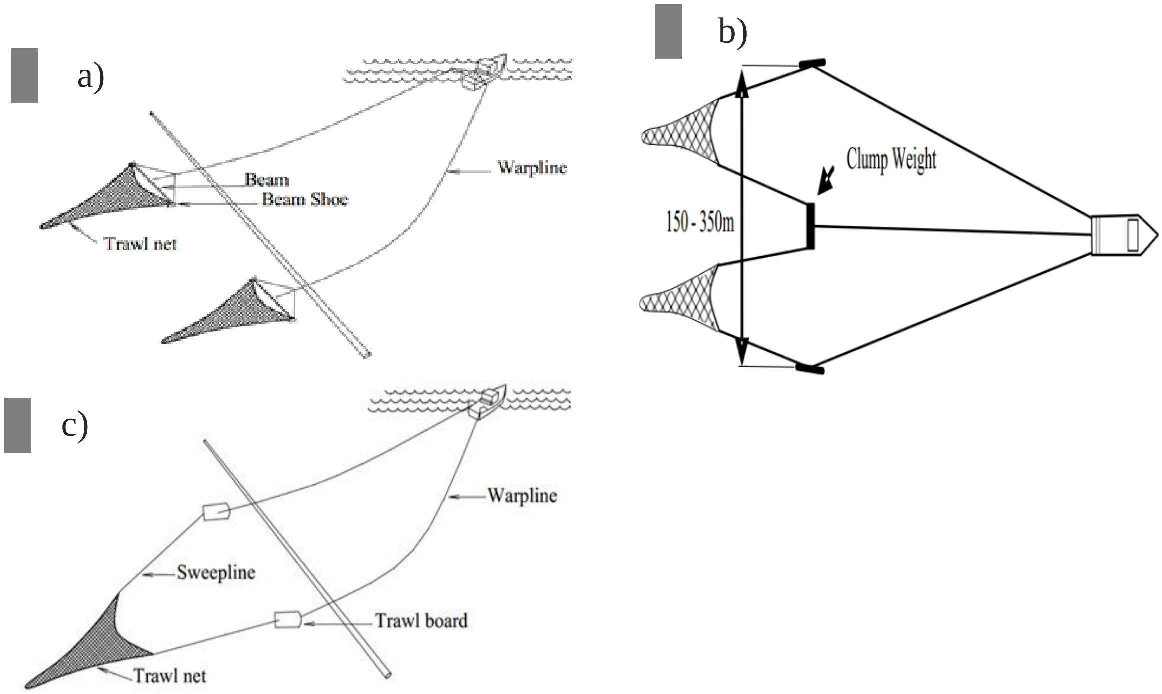


Figure1. Different types of trawl gear: a) Beam trawl, b) Twin trawl, and c) Otter trawl [5].

Pull-Over load

Pullover loads namely horizontal and vertical forces from trawl boards shall be applied as a single point load to the pipeline under consideration [17]. In this paper, trawling system is from type of Otter trawl by use of Polyvalent Board. The pull-over loads for trawl board are calculated by using the following empirical formulae given in DNV-RP-F111 [5].

Pull-over Loads for Trawl Board:

The maximum lateral pull-over load of a Trawl board F_p is given by Eq. (1) [5]**:**

$$F_p = C_F V \sqrt{m_t k_w} \tag{1}$$

Warp line stiffness from following equation is obtained Eq. (2):

$$k_w = \left(3.5\times10^7\right)/L_w \tag{2}$$

The coefficient C_F, for Polyvalent and rectangular boards is calculated as follows Eq. (3):

$$C_F = 8.(1-e^{-0.8\bar{H}}) \tag{3}$$

In addition, the dimensionless height $\bar{H}$ is given by Eq. (4):

$$\bar{H} = (H_{sp} + D_o / 2 + 0.2)/B \tag{4}$$

For Trawl boards the maximum vertical force acting in the downward direction can be estimated as Eq. (5):

$$F_z = F_p.(0.2 + 0.8e^{-2.5\bar{H}}) \tag{5}$$

Trawl Board Pull-over Duration:
The pull-over time T_p, is the total time where the trawl board is in contact with the pipe and it is given by the expression in bottom [5]:

$$T_p = 2C_F\sqrt{\frac{m_t}{k_w}} + \frac{\delta_p}{V} \tag{6}$$

According to DNV-RP-F111 assumed that:

$$\frac{\delta_p}{V} = \frac{2C_F\sqrt{\frac{m_t}{k_w}}}{10} \tag{7}$$

For a polyvalent board the time history in Figure 2 applies for both the vertical and the horizontal pull-over load.

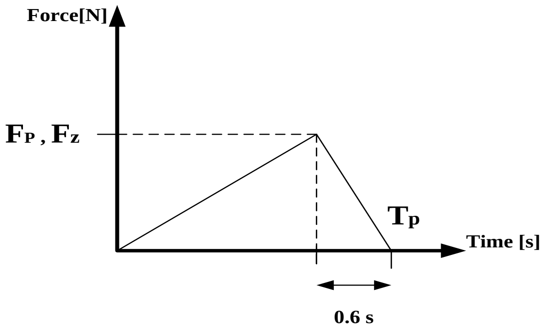


Figure 2. Polyvalent and rectangular pull-over force time history [5].

Finite Element Model
According to Yong Bia, the summary of Finite Element Analysis for pull-over load listed in Table 1 [4]. Pull-over load is estimated by modeling trawl gear interference as a dynamic load using non-linear finite element analysis. The FE modeling were performed using OrcaFlex that is includes modeling of seabed, pipeline parameter and Trawl gear parameters. The trawl gear configuration used in the OrcaFlex analysis is shown in Figures 3. In OrcaFlex both static and dynamic analysis can be performed. There are two objectives for static analysis [18]:

- To determine the equilibrium configuration of the system under weight, buoyancy, hydrodynamic drag, etc.
- To provide a starting configuration for dynamic simulation.

The dynamic analysis is a time simulation of the motions of the model over a specified period, starting from the position derived by the static analysis. The period of simulation is defined as a number of consecutive stages, whose durations are specified in the data [18]. In this paper, OrcaFlex is used in a dynamic analysis of a trawl gear and pipeline interference. Solution method for dynamic problem is implicit methods.

Table 1. Summary of trawl FE analysis

Characteristic	Pull-over
Time	Second
Load	Time history of horizontal &vertical loads
Solution	Time domain dynamic
Design parameter	Height of free span Length of free span
Design acceptance criteria	Allowable moment Allowable Stress/strain

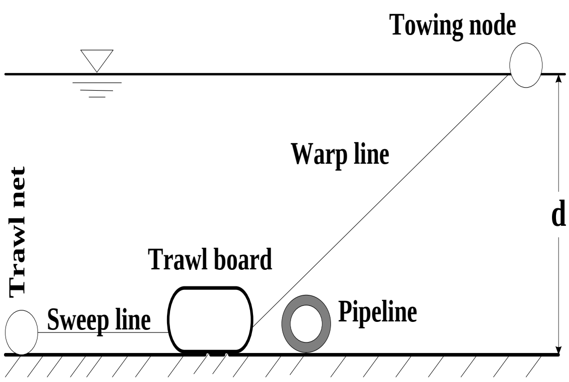


Figure 3. Trawl gear configuration, vertical plane.

Trawling equipment model:
In this paper according to Figure 4, polyvalent & rectangular trawl board was used in the FE analysis. This type of trawl board has been found to give the highest loads on pipelines [5]. The properties of polyvalent and rectangular trawl boards is shown in Table 2. The elastic stiffness of the warp line in OrcaFlex is obtained by Eq. (2). The mass of the warp line is not modelled.

Table 2. Polyvalent trawl gear data

Parameter	Value
Trawl board steel mass	4000 [*kg*]
Trawl size (length × height)	4.5*3.5 [*m*]
Trawl velocity	2.8 [*m/s*]
Warp line length	900[*m*]
Warp line diameter	38 [*mm*]
Load effect factor	1.1
Condition load effect factor	1.07

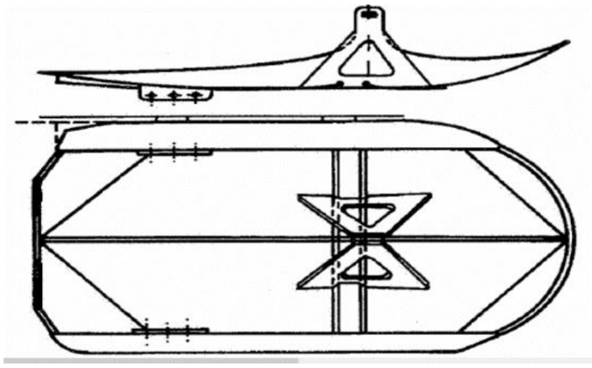


Figure 4. Polyvalent and rectangular trawl boards [4].

Pipeline model:
A 32in OD pipeline was modeled as a 112.17 km straight pipeline (SOUTH PARS PHASE 19A). The pipeline and trawl gear interference is assumed to occur at a location where the water depth is 65 m. The detail of pipeline parameter is shown in Table 3. OrcaFlex uses a finite element model for a line as shown in the Figure 5. The line is divided into a series of line segments, which are then modelled by straight massless model segments with a node at each end. The model segments only model the axial and torsional properties of the line. The other properties (mass, weight, buoyancy etc.) are all lumped to the nodes, as indicated by the arrows in the figure 5. Nodes and segments are numbered 1, 2, 3 and … sequentially from End A of the line to End B. Therefore, segment n joins nodes n and (n+1). The line type for pipeline is a homogeneous pipe type. Three standard materials is for a homogeneous pipe: Steel, Titanium and High Density Polyethylene. For these standard materials, OrcaFlex automatically sets Material Density, Young's Modulus and Poisson Ratio [18]. In this paper, the homogeneous steel pipe is considered.

Table 3. Submarine Pipeline South Pars Phase 19 data

Parameter	Value
Outer diameter	812.8 [*mm*]
Wall thickness	20.6 [*mm*]
Corrosion allowance	3 [*mm*]
Steel quality	SAWL450 I SF(X-65)
Specified minimum yield stress	450 [*N/mm²*]
Specified minimum tensile strength	535 [*N/mm²*]
Coating type	Concrete
Coating thickness	50 [*mm*]
Coating density	3040 [kg/*m³*]
Drag and Added mass coefficient	2.0
Content	Gas
Content specific weight	109.5 [kg/*m³*]
Design temperature	90 [*ºC*]
Design pressure	139 [bar]
Water depth	65 [m]
Ambient temperature	10 [*ºC*]
Safety class	Normal

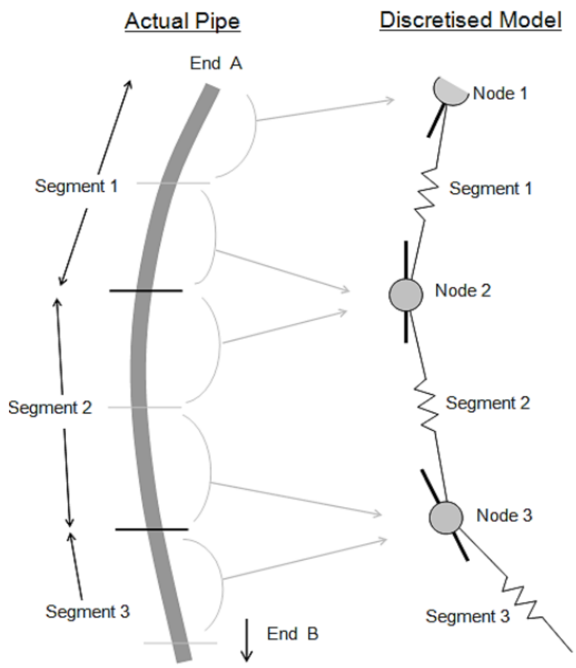


Figure 5. OrcaFlex Line Model [18].

Seabed model:
In the event of trawling, sea bed friction resulting from soil-pipe interaction can have a major influence on pull-over loads when it is in full contact with the seabed as it is develops a lateral restraint. However, this soil friction effects on

free spanning pipelines are negligible and hence the soil friction for free span pipelines is not a significant parameter to consider [17]. OrcaFlex applies Coulomb friction between the line and the seabed. The friction force applied never exceeds μR where R is the seabed reaction force and μ is the friction coefficient. Lines lying on the seabed often move axially more readily than they move laterally. To enable this effect to be modelled, you can specify different friction coefficients μ for motion normal (i.e. lateral) and axial to the line. For intermediate directions of motion, OrcaFlex interpolates between these two values to obtain the friction coefficient μ to use [18]. The soil condition for case study in this paper as shown in table 4. Soil stiffness is applicable only to pipelines resting on seabed. No soil stiffness is assumed for pipeline free spans. A flat seabed is a simple plane, which it is modeled for pipeline with span heights of 0 m. A Profiled seabed is one where the shape is specified by a 2D profile in a particular direction. Normal to that profile direction the seabed is horizontal. A profiled seabed is designed for pipeline with free span.

Table 4. Soil condition

Parameter	Value
Sand , friction angle, ϕ	35[*deg*]
Axial friction coefficient	0.4
Lateral friction coefficient	0.6

OrcaFlex model

Submarine pipeline is modeled with different height of free span (0, 1 m) and different length of free span (20 and 100 m), which is pulled in the direction of 90 degrees by trawl gear. For example, interaction between pipeline and trawl board for height of free span 1m and length of free span 100m before, during and after collisions shown in Figure 6.

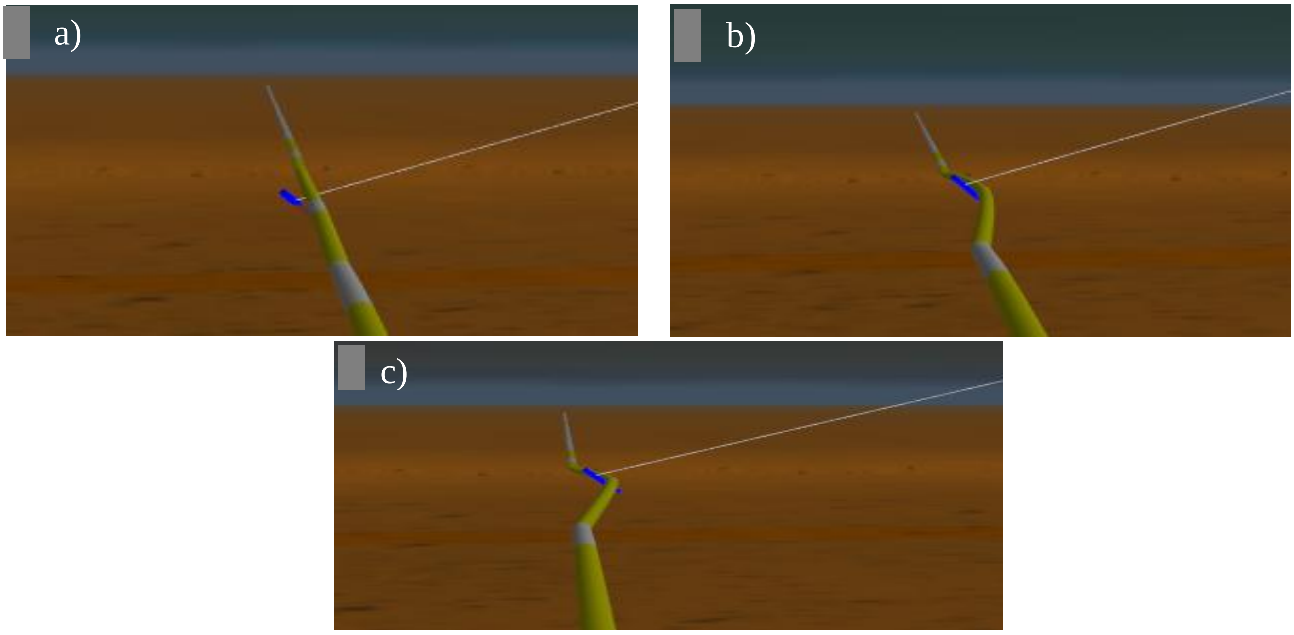


Figure 6. Trawl board and pipeline simulation a) before, b) during and c) after collisions.

Verification of modeling

For this purpose, the example provided in Appendix B of the DNV Recommend Practice on Trawl Gear Interference. The simulated displacement for four subsequent trawl pull-over load for free span with height 0m and length 20m. The displacements response of pipeline using OrcaFlex are compared to the DNV-RP-F111 and results of modeling by SAGE Profile software [16], which is shown in Figure 7. As can be seen OrcaFlex predicts a similar trend: the lateral displacement increase for each pull-over. As an error analysis results, difference of 9% is observed.

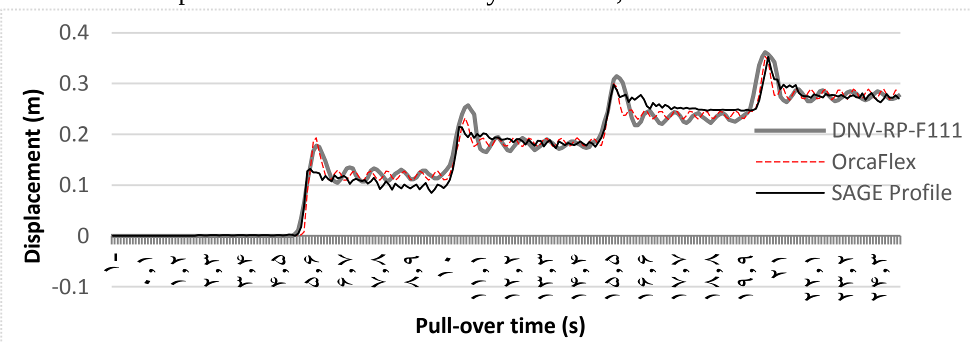


Figure 7. Pipeline response to subsequent trawl gear pull-over load.

Results and discussion

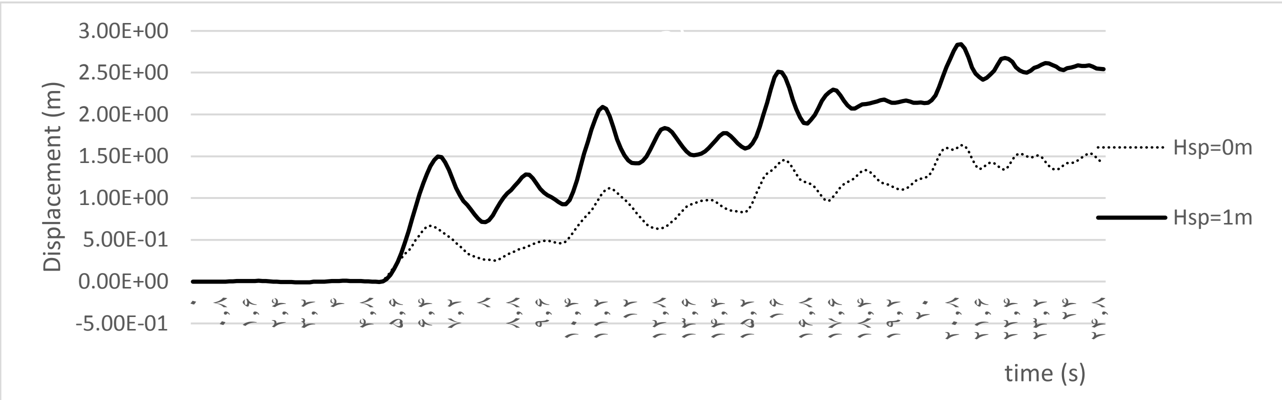
According to Eqs. (1-5), respectively pull-over load and time duration, depend on height of free span. Therefore, for any height of free span will be pull-over load and time duration that is shown in Table 5. The results are present for four subsequent trawl pull-over loads.

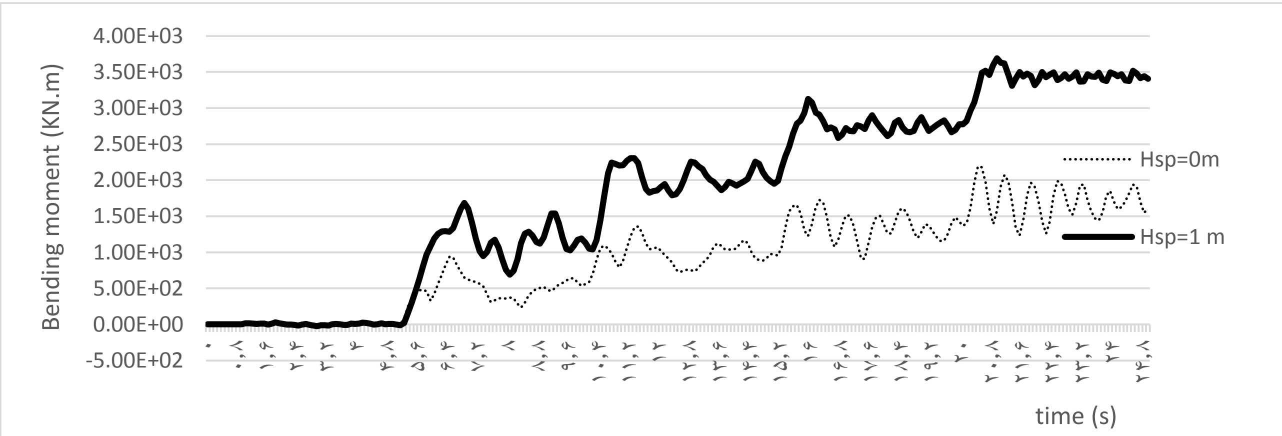
Table 5. Pullover forces according to DNV-RP-F111 for span height 0, 1m

Hsp [m]	Fp [kN]	Tp [s]
0	179.48	0.64
1	312.22	1.36

Response of submarine pipeline under pull-over load for constant length of free span:

In here as sample, response of pipeline for Lsp=100 m is shown Figure 8. By increasing the free span height, because of friction soil decreasing, the effect of F_z would not be clearly Hsp=0 m. by considering Hsp as a none zero value, remarkable increment in results is observed which is increasing in time. As the time passes with dynamic analysis, the response difference between free span height changes becomes grater. In other word, the diagram diverges. The system response always increases by increasing the free span height.





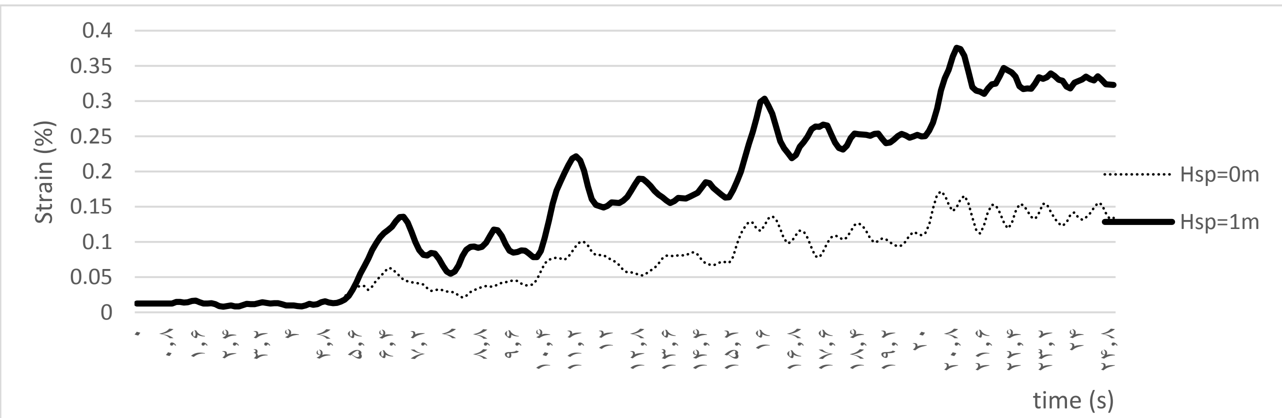


Figure 8. Submarine pipeline response under trawl gear pull-over load for Lsp=100m.

Response of submarine pipeline under pull-over load for constant height of free span:

In here as sample, response of pipeline for Hsp=1m is shown Figure 9. By increasing the free span length, Oscillation period and amplitude is increased. By increasing in free span length, considerable increment is occurred in the displacement response. By increasing the free span length, only side relocation increases considerably. But strain and bending moment do not change so much.

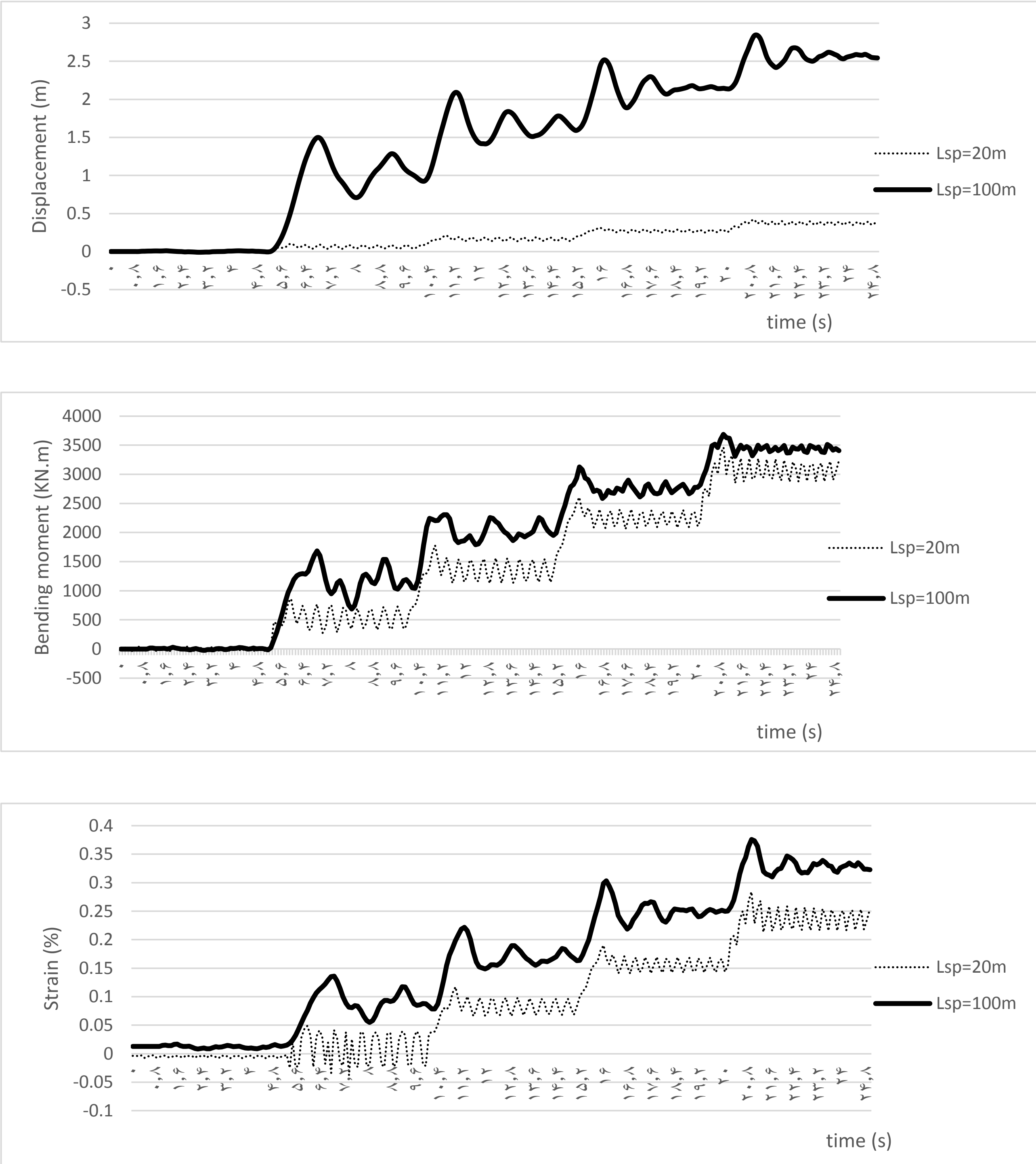


Figure 9. Submarine pipeline response under trawl gear pull-over load for Hsp=1m

The maximum response range increase(%) is shown following Table 6.

Table 6. maximum response range.

Response	Hsp=0m (Lsp=20 to 100m)	Hsp=1m _(Lsp=20 to 100m)	Lsp=20m (Hsp=0 to 1m)	Lsp=100m (Hsp=0 to1m)

Displacement (%)	700	700	100	75
Bending moment (%)	29	3	112.5	68
Strain (%)	65	32	180	130

Checking design acceptance criteria for trawling pull-over load:
According to Table 1, allowable Moment and allowable Stress/strain are design acceptance criteria for trawling pull-over load. The amount of allowable Moment is obtained from load controlled combined buckling check in accordance with DNV-OS-F101, which is shown in Eq. (8). The amount of allowable Stress/strain is obtained from displacement controlled combined buckling check in accordance with DNV-OS-F101, which is shown in Eq. (9). For case study of this work, allowable Moment and allowable Strain are 4033 [kN/m] and 0.426 [%] respectively. As we know changing free span length does not influence strain and bending moment responses. So, we determine the maximum endurance time for meeting design criteria for model with the free span length of 100 m. Results for different free span height has been illustrated in Table 7. As one can see by increasing the height, endurance time is decreased.

$$M_{allowable} = \left[\frac{\alpha_c}{\gamma_m \cdot \gamma_{sc}} \cdot \sqrt{1 - \left(\alpha_p \cdot \frac{p_i - p_e}{\alpha_c \cdot p_b} \right)^2} - \frac{\gamma_m \cdot \gamma_{sc} . s_{dn}^{\ 2}}{\alpha_c} \right] . M_p \cdot \frac{1}{\gamma_f \cdot \gamma_c} \quad (8)$$

$$\varepsilon_{sd} = \frac{0.78}{\gamma_\varepsilon . \gamma_{sc}} \left(\frac{t}{D} - 0.01 \right) . \left(1 + 5.75 . \frac{p_{min-} p_e}{p_b} \right) . \alpha_h^{-1.5} . \alpha_{gw} \quad (9)$$

Hsp [m]	Bending moment Endurance time[s]	Strain Endurance time[s]
0	60	60
1	30	30

Table 7. Endurance time According to free span height

Conclusion

Results indicate that because of trawl gear, there is probability of failure and buckling in submarine pipeline. By considering Hsp as a none zero value, remarkable increment in results is observed which is increasing in time. By increasing the free span length, only side relocation increases considerably. But strain and bending moment do not change so much. By increasing the height of free span, endurance time is decreased.

List of Symbols (Optional)

F_p	maximum lateral pull-over load [kN]
k_w	Warp line Stiffness [kN]
V	Trawling velocity [m/s]
m_t	Trawl board steel mass [kg]
L_w	Length of the warp line [m]
H_{sp}	Span height [m]
D_o	Pipe outer diameter [m]
B	Half-height of the trawl board [m]
C_F	Coefficient
$\bar{H}$	Dimensionless height
F_z	Maximum vertical force [kN]

T_p	Pull-over time [s]
δ_p	Displacement of the pipe at the point of interaction
Lsp	Length of free span [m]
$M_{allowable}$	Allowable moment
M_p	Plastic moment capacities
p_i	Internal pressure
p_e	External pressure
$p_{\min}$	Minimum internal pressure
p_b	Burst pressure
s_{dn}	Normalized effective force
α_c	Flow stress parameter
α_p	Pressure factor
ε_{sd}	Characteristic bending strain resistance
γ_{sc}	Safety class resistance factor
γ_m	Material resistance factor
γ_f	Load effect factor for functional load
γ_ε	Resistance factor
α_h	Yield strength / tensile strength ratio
α_{gw}	Girth weld factor (strain resistance)

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