

Reliability Analysis of Subsea Pipeline against Upheaval Buckling

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ARTICLE INFO

Article History:

Received: 6 Sep. 2018

Accepted: 6 Mar. 2019

Keywords:

Upheaval Buckling

Reliability

Subsea Pipeline

ABSTRACT

The importance of oil transportation in the maritime industry has increased in recent years due to increased oil and gas production. According to technical and financial aspects, on hydrocarbon transfer methods, the pipelines are the best option for the transfer of oil and gas in the maritime industry. High temperature and high pressure in the pipeline can lead to the buckling. Buckling can either be in the direction of vertical (upheaval) and horizontally (lateral). The uncertainty in the buckling parameters of the pipeline increases error in the uplift and the effective axial compressive force calculation. The existence of these errors in the pipeline design is costly for the project. So reducing the errors can be very important. This paper presents the reliability analyses for studying and quantifying the variation of the reliability index (β) with the main parameters involved during the upheaval buckling of submarine buried pipes caused by high temperature and pressure conditions (HTHP). In this paper, uncertainty is considered in the geometric parameters of the pipeline. PDF and reliability index (β) can be determined by FORM and other. FORM, FOSM and sampling methods are three main methods which are used to account the PDF and reliability index (β). This research shows that among these three methods, for a fixed state, the sampling method has the lowest beta and the highest probability of buckle, which has a higher accuracy than the other methods. For soil cover with a thickness of more than 1000, it is worth noting that by increasing the thickness of the soil cover, more force is required for the upheaval buckling in the pipeline.

1. Introduction

Offshore pipelines are used for some targets in the development of submarine hydrocarbon resources. Submarine Pipelines as one of the most effective tools for transporting hydrocarbon productions from the well to the terminals/the platform located on the shore are considered [1,2]. Nowadays, pipelines go deeper and cover a wide range of miles. As offshore industries go for deeper resources, so pipelines should be checked to resistance against new loads in subsea condition [3]. Due to the high uncertainty in the new environment and also in the operating conditions of the pipelines, need to use of methods based on reliability greatly increases.

To measure the reliability of a system, the system first breaks down into components, and the reliability of the system is expressed in terms of the reliability of its components. To calculate the reliability of each component based on available statistical data, a model for the failure rate is selected and its parameters are estimated based on available data. Reliability

evaluation methods, considering the uncertainty in the geometric parameters of the structure as well as the environmental conditions, show the probability of failure of the structure under special loading conditions. Uncertainties affecting the health of marine structures, such as drought structures, exist both in loading and in the strength of structural components and fittings. Resistance of marine structures should provide health and safety of the structure in different loading conditions.

Buckling as one of the ultimate limit state failure modes, affect son the maintenance costs. Normally, buckling can be occurred in two modes: Global and Local. Local buckling occurs due to the out-of-roundness and global buckling happens due to high temperature/ high pressure gradient along subsea pipelines. Based on the buckle plane, global buckling can be occurred in horizontal and vertical direction which are called lateral and upheaval buckling, respectively [4, 5]. Furthermore, lateral and upheaval

buckling occur for on-bottom and buried pipelines, respectively.

If a pipeline is not free to expand in the operation, restrained axial deformation results in an axial compressive force in the pipeline. The pipeline usually is not perfectly straight with some out of straightness (OOS), and the imperfections are typically due to the pipeline being laid over irregularities in the seabed profile. When the lateral restraint of a trenched pipeline exceeds the vertical restraint force against vertical displacements created by the pipeline submerged weight, the pipeline bending stiffness, and the covered soil resistance, the pipeline tends to move upward, and considerable uplift movement may occur. This phenomenon is called upheaval buckling [6, 7, 8], which is a failure mode that has to be taken into account in the design of buried and trenched pipelines. The pipeline moves upward due to upheaval buckling, leading to possibly unacceptable local plastic deformations or collapse or vulnerability to fishing gear and other third-party activities. The upheaval buckling of a pipeline has been known for a long time as a problem of land pipelines, and it has become one of the primary concerns in submarine pipeline design [9].

The DNV-OS-F101 [10] gives criteria and recommendations on concept development, design, construction, operation, and abandonment of submarine pipeline systems and The DNV-RP-F110 [11] is the common industry recommended practice for designing submarine pipeline against global buckling. The DNV uses the mean values of soil uplift resistance and driving force (i.e., on effective axial load) in the design process as a deterministic method. The variability in soil resistance and force is reduced by applying the load factor (γ_{UF}) on driving force. The appropriate values for partial safety factors (γ_{UR} , γ_{UF}) should be used in the design phase to increase the safety and the factors depend on the accuracy of field measurements and the targeted safety class. This conventional deterministic method is simple and straightforward but does not take into account the variability in appropriate manner. Thus the methodology does not explicitly consider the effect of variability in backfill stiffness or operational conditions in the safety assessment against upheaval buckling. These aspects can be examined by probabilistic approach consideration the variability in the inputs and assessing their effects on the overall upheaval buckling behavior.

On the other hand, in a probabilistic approach, the input parameters and loading are treated as continuous random variables and the performance of the structure resulting from different failure criteria is expressed in probabilistic framework as probability of failure (P_f) and/or reliability index (β) [12].

Al-Sharif et al. [14] in a paper with topic “Structural Reliability Assessment of the Oman India Pipeline”

investigated the effect of variability in soil backfill stiffness and operation conditions on the performance of the pipeline upheaval behavior. And its result was useful to better understand the performance of offshore pipeline and probabilistic upheaval buckling assessment.

In this paper, the effect of variability in pipe properties that contains thickness, diameter and elastic modulus of the pipeline are investigated.

2. Case Study

The considered steel pipeline has a diameter (D) of 0.816m (32.12 in.), thickness of 0.0242 m and a length of 40 m. The buckling length could be influenced by the imperfection height; thus, it was decided to consider the length of 40 m. Poisson's ratio (ν) of the pipe was considered equal to 0.3 and the coefficient of thermal expansion (α_t) was equal to $11.5 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$. The distribution of undrained shear strengths was determined to be lognormal using the field data. Residual tension during installation was not considered in this study. The reasons for neglecting the residual tension are that those axial forces are generally associated with a high degree of uncertainty and their influence is very case-specific [13]. Pipeline Submerged Weight in Operation Condition is equal to $4273 (N/m)$. Table 1 presents the general parameters of pipelines.

Table 1. The properties of the pipeline [13]

Characteristic	Value
Pipeline outside diameter	0.816 [m]
Steel pipeline wall thickness	0.0242 [m]
Steel pipeline density	7850 [kg/m ³]
Modulus of elasticity	210 [GPa]
Poisson's ratio	0.3
Thermal expansion coefficient	$11.5 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$
Pipeline submerged weight in operation condition	4293 [N/m]
Maximum water depth	85 [m]
Seawater density	1023 [kg/m ³]
Difference Between Operating and Installation Temperature	75 [c]
Local Incidental Pressure During Operations	10.8493 [MPa]

Table 2. Uncertainties of parameters with their relevant mean and C.O.V [13]

Row	Parameter	Distribution Type	Mean	C.O.V
1	Young's modulus	Log-normal	210×10^9	0.05
2	Pipeline wall thickness	Normal	0.024	0.05
3	Pipeline diameter	Normal	0.6156	0.05

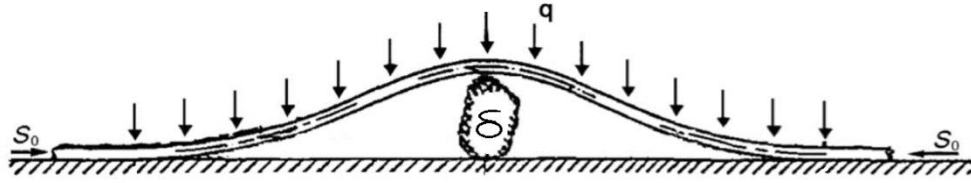


Figure 1. Schematic diagram of buried offshore pipeline profile [9]

3. Analytical Solution of Upheaval Buckling

Upheaval buckling is caused by an increase in effective compressive axial force in buried pipelines lying on an uneven seabed, due to pressure and temperature in the operating condition. The upheaval buckling phenomena is related to the following factors [9]:

- The geometry, weight, and material properties of the pipeline.
- Operational pressure and temperature.
- Seabed profile and environmental characteristics.
- Cover and soil properties.

The vertical imperfections in pipelines are defined as as-trenched out of straightness, which are associated with upheaval buckling from the following sources:

- Imperfections of foundation (seabed), such as boulder, seabed profile, pipeline crossing locations, and the like. Depending on the shape of the foundation, the pipeline may follow the shape of the foundation.
- Pipeline imperfections introduced during the installation process by, for example, the reeling process or poor lineup during the welding process. The pipeline imperfection can be described in terms of its height and length, which may be determined by survey in the construction phase.
- Pipeline imperfections in the trench after the laying and trenching operation, such as variations in trencher performance or stop and start of the plough.

The driving force for triggering the pipeline upheaval buckling is the compressive axial force in the restrained pipeline due to the increase of temperature, the increase of internal pressure, and the residual tension left by laying pipe. The effective axial compressive force of fully constrained pipelines can be expressed as:

$$S_0 = F_{residual} - (1 - 2\nu)(\Delta P_i)A_i - EA_S \alpha(\Delta T_i) \quad (1)$$

Where in Eq.(1) S_0 stands for effective axial compressive force, (compressive, -; tension, +), ΔP_i stands for difference of internal pressure relative to laying condition Since the internal pressure during installation normally is zero, this is identical to the operating internal pressure, ΔT_i stands for difference between operating temperature and installation

temperature, A_i stands for Internal bore area of the pipe, A_S stand for cross-sectional area of the pipe, $F_{residual}$ stands for residual lay tension, ν stands for Poisson's ratio, E stands for Young's modulus and α stands for thermal expansion coefficient.

Figure 1 illustrates the profile of pipeline with a vertical imperfection under axial and vertical loads. This is a typical configuration for pipeline crossing. The horizontal distance is denoted by x , measured from the left pipeline touchdown point. The height of the pipeline is denoted by w , measured upward from seabed. The height of the vertical imperfection is denoted by δ , the total pipeline span length is $2L$. Only half of the system is considered, due to symmetry.

The pipeline is idealized as an elastic beam that carries an effective axial force S_0 and has flexural rigidity EI . It follows from elementary beam-column theory that the downward load $q(x)$ per unit length required to maintain the pipeline in equilibrium condition is [9]:

$$EI \frac{d^4 w}{dx^4} - S_0 \frac{d^2 w}{dx^2} = -q \quad (2)$$

For the deflection shape of an elastic pipeline with no internal axial tension but with a bending stiffness of EI placed over an object with height of δ_f and loaded with a pipeline submerged weight per unit length, wS , Eq.(3) gives the span length as [9]:

$$L_0 = \left[\frac{72 \times EI \times \delta_f}{wS} \right]^{1/4} \quad (3)$$

The analytical solution also gives the pipeline profile by following equation [9]:

$$w(x) = \delta_f \times \left(\frac{x}{L_0} \right)^3 \times \left(4 - \frac{3x}{L_0} \right) \quad (4)$$

3. Reliability Assessment

A reliability assessment accounts for the inevitable variability in pipe properties (geometry and material strength) which is the result of the normal perturbations in manufacturing processes used to produce the pipe. Variability in pipe properties produces uncertainty in respect of collapse resistance, which can be addressed and managed through the reliability assessment.

The collapse pressure limit state depend on the pipe dimensions (diameter, ovality and wall thickness), and material strength properties (stress-strain curve in the

hoop and axial directions). Therefore, it is necessary to develop appropriate probability density functions (PDFs) which characterize the expected statistical variations in these geometric and material properties, for use in a reliability analysis.

In the present context, Reliability is defined as the probability that an individual length of pipe will not collapse due to a combination of external pressure and bending loads during construction or operation. Reliability is equal to the probability of failure subtracted from unity [14].

4. Analysis Methodology

For the problem under consideration, the probability of failure is equal to the probability that the load effect, exceeds the collapse resistance, R (or probability that $R-L \leq 0$). This is described mathematically by $P(g \leq 0)$, where g is the limit state function of a set of random parameters X that influence L and R , and we are therefore interested in evaluating the probability $P(g \leq 0)$ where:

$$g = g(x) \quad (5)$$

This probability is equal to the probability of occurrence of all combinations of the parameters X that lead to $g \leq 0$. These combinations can be visualized as the domain in the n -dimensional space of X variables (where n is the number of variables in the set X) on one side of the function $g \leq 0$. Thus the failure probability is expressed by:

$$P_f = P(g \leq 0) = \int_{g(x) \leq 0} \{f_x(X) dx\} \quad (6)$$

Where $f(X)$ is the multivariate density function for the random vector X .

The limit state function $g(X)$, is so defined so that:

$$g(x) = \begin{cases} > 0 & \text{safe state} \\ = 0 & \text{limit state} \\ < 0 & \text{failure state} \end{cases}$$

Since the basic random variables are modeled by continuous probability functions and the failure probabilities are small, it is preferable to apply the analytical first and second order reliability methods (FORM and SORM). These methods are very efficient and accurate for small failure probability problems,

FORM is of particular interest when the limit state function is relatively simple (i.e. expressed analytically).

In general, numerical solution is necessary by one of two classes of methods: (i) Monte Carlo simulation and (ii) Reliability Methods.

The Monte Carlo simulation method is conceptually simple. It is based on numerical sampling where a set of x values are simulated from the corresponding probability distributions. These values are substituted in the function $g(x)$ and the value of g is compared to zero. The process is repeated a large number of times and count is kept of the ratio between the number of trials that lead to $g \leq 0$ and the total number of trials. The ratio is used as an estimate of the desired probability value.

Reliability methods, which is developed in connection with structural reliability, provides approximate solutions for general probability integrals of the type in Eq.(6) over domains with smooth boundaries. The approximations involve a transformation of all parameter distributions into independent normal variables and the replacement of the function $g(X)$ by an approximate one. This allows the use of a special case for which an analytical solution for Eq.(6) exists. Of the two basic methods available, SORM provides a more accurate approximation than FORM because the function $g(X)$ is approximated by a second order Taylor series expansion as opposed to a first order expansion used in FORM. It is also possible to increase the accuracy of SORM results by using a simulation procedure which by virtue of the SORM analysis can be done very efficiently.

Each of the above approaches has advantages and disadvantages. The Monte Carlo method is conceptually simple and can easily deal with parameter dependencies, distribution truncations and discrete random parameters. The main disadvantage is that in most practical cases a very large number of simulations (tens to hundreds of thousands, or even more for small probabilities) are needed and this tends to pose restrictions on the number of analyses that can be carried out. However, it must be noted here that there are some recent developments in this method which may result in enhancement in efficiency.

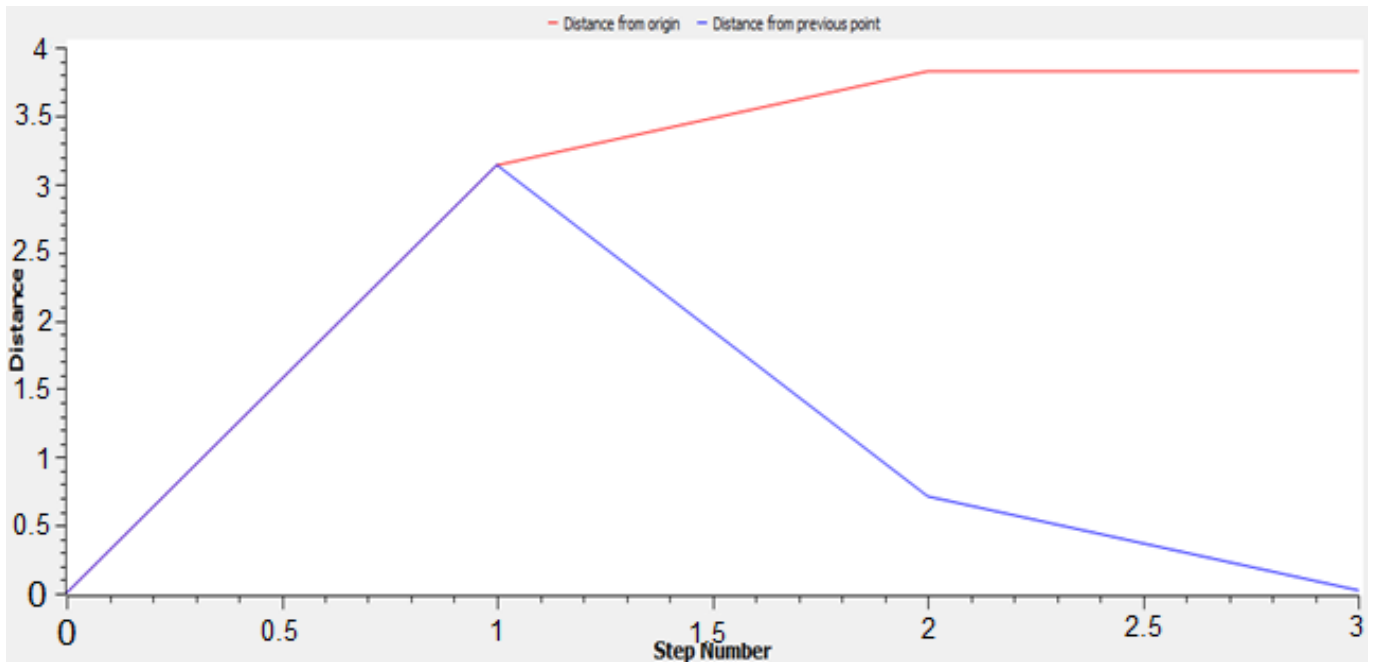


Figure 2. PDF method

FORM and SORM have the advantage of being very efficient. Results can usually be obtained in a fraction of the time required for a Monte Carlo simulation. In addition the analysis provides, as a by-product a measure of the sensitivity, within the overall probability of failure to the different input variable parameters and their distributions. These methods have also been shown to provide sufficiently accurate solutions for small probabilities in a wide range of practical problems. Their disadvantage is that they use iterative numerical procedures which are not guaranteed to converge and occasionally cases may be encountered for which solutions cannot be found [14]. The reliability analyses have been computed by linking the buckling model to the reliability analysis software RT. The reliabilities have been calculated by use of FORM, SORM and the Monte Carlo method.

5. Results and Discussion

This paper presents the reliability analyses for studying and quantifying the variation of the reliability index (β) with the main parameters involved during the upheaval buckling of submarine buried pipes caused by high pressure and temperature conditions (HPHT).

In order to assess the effect of geometric specification's pipeline on upheaval buckling of subsea pipelines using DNV recommended model (Eq.(2)), the downward load $q(x)$ per unit length required to maintain the pipeline in equilibrium condition is calculated for uncertainties of parameters that shown in Table 2.

Snap buckling generally occurs with a jump of vertical movement of pipeline because the driving force is sufficient to overcome all resistive forces when the pipeline is first put into operation. Upheaval

creep is a phenomenon in which a buried pipeline progressively moves upward through backfill material due to driving forces by cyclic thermal loads of heat-up and cool down.

The distributions of the uplift motion are obtained by using Eq.(4)(vertical slip model), which involves lognormal distributed random parameters.

The results of the reliability evaluations for uncertainties of parameters assumed in the analysis are presented in Table 2. Uncertainties which are considered for reliability assessment are described in Table 2. The ratio of distance to step number for pipeline with introduced uncertainties in FORM method for soil cover equal to 1000(mm) is shown in Figure 2.

CDF and PDF diagram represents the uncertainty characteristics of the considered parameters. These graphs are constant for all methods of calculating the probability of failure.

Reliability methods as a mathematical tool, are used for determining probability of failure (POF) in some special conditions by considering uncertainties in both load and resistance parameters [15]. The uncertainties can be divided to epistemic and aleatoric [16].

P_f and reliability index (β) can be calculate by FORM and other methods [17]. In this research used 3 methods. FORM, FOSM, sampling are 3 main method for P_f and reliability index (β) determination. Table 3 shows the β in different methods.

Figure 3 indicated 3 curves of PDF, CDF and COV in sampling method that shown in one graph.

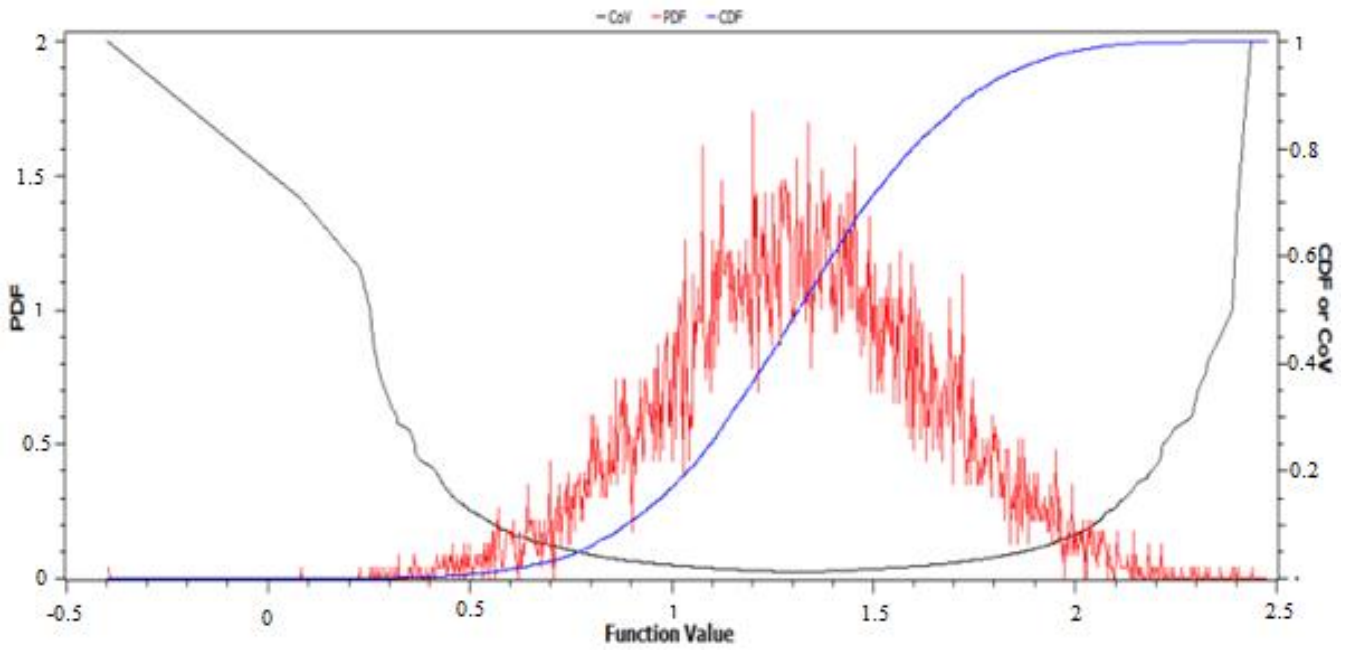


Figure 3. PDF, CDF and COV in sampling method

Table 3. β in FORM, FOSM, Sampling methods

Row	Methods	Soil Cover(mm)	β
1	FORM	800	-1.62
2	FORM	1000	3.826
3	FORM	1200	1.099
4	FORM	1400	1.583
5	FOSM	800	-1.64
6	FOSM	1000	3.915
7	FOSM	1200	1.107
8	FOSM	1400	1.59
9	Sampling	800	-0.92
10	Sampling	1000	3.54
11	Sampling	1200	0.93
12	Sampling	1400	1.348

In this paper, in order to evaluate the effect of soil cover as one of the ways of preventing buckling, the probability of failure of the South Pars Gas Field pipeline is investigated. Figure 4 demonstrates the probability of failure and the reliability index (β). As shown in the figure, the reliability index (β) movement of the sinus passes through and does not follow the linear relationship.

The submarine pipeline has an upheaval buckling if the vertical load on the pipeline is less than the force exerted inside the pipeline due to high pressure and high load. In Figure 5, the amount of load required to defeat the pipeline is certain.

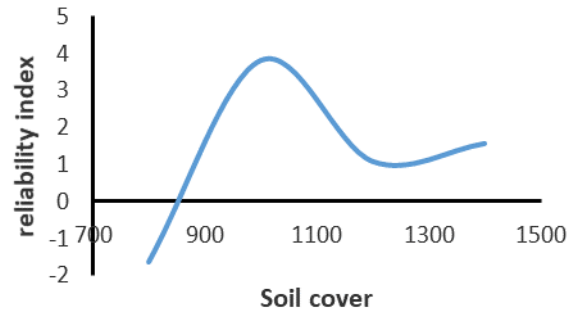


Figure 4. The effect of soil cover on reliability index (β) parameter

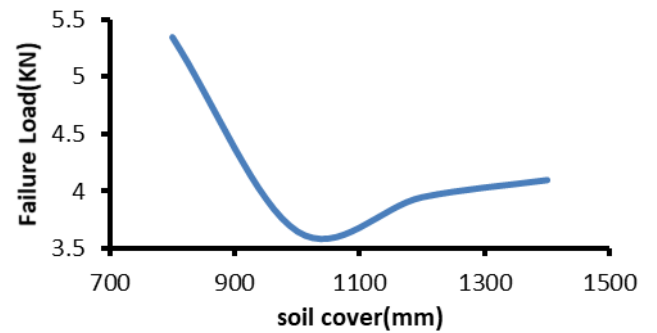


Figure 5. Load required to defeat the pipeline

According to Figure 5, it is concluded that before reaching the soil cover to 1000(mm) for the direct upheaval buckling of the pipeline, the trajectory of the pipeline is descending, and after passing through this amount, the Uptrend is, or in other words, for soil cover with a thickness of more than 1000, it is worth noting that by increasing the thickness of the soil cover, more force is required for the upheaval buckling in the pipeline.

6. Conclusions

The reliability index (β) movement of the sinus passes through and does not follow the linear relationship.

For soil cover with a thickness of more than 1000, it is worth noting that by increasing the thickness of the soil cover, more force is required for the upheaval buckling in the pipeline.

Sampling method due to several samplings has more accurate values offers and in the Sampling method, we have less β than another.

In order to calculate the failure of the pipeline due to upheaval buckling, three methods were used. Among these three methods, for a fixed condition, the sampling method was the lowest beta and the highest probability, which has a higher accuracy than the other available methods. And the least precision is also related to the FOSM method. It is also worth noting that the results are very close together and provide approximate estimates with respect to the approximation.

7. List of Symbols

E	Modulus of elasticity [GPa]
S_0	Effective axial compressive force, (compressive, -; tension, +)
Δp_i	Difference of internal pressure relative to laying condition.
ΔT_i	Difference between operating temperature and installation temperature
A_i	Internal bore area of the pipe
A_s	Cross-sectional area of the pipe
ν	Poisson's ratio
α	Thermal expansion coefficient
$F_{residual}$	Residual lay tension
x	Horizontal distance
w_s	Pipeline submerged weight per unit length
δ	Height of the vertical imperfection
q	Downward load per unit length
L_0	Span length
P_f	Probability of failure
F_x	multivariate density function

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