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Upheaval buckling of pipelines

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UPHEAVAL BUCKLING OF OFFSHORE pipelines occurs as a result of axial compression induced along the pipelines due to large temperature differences and high internal pressures. This paper aims to research the causes of upheaval buckling, give an overview of the analytical methods, and develops an Excel spreadsheet for initial assessment.

Several models of upheaval buckling have been identified and discussed, such as those based on idealized or perfect pipelines, which are related to the railway track analysis and those based on imperfections. The buckle temperatures of the perfect pipelines are proportional to the buckle lengths and axial forces. With the consideration of imperfections, buckle temperatures become inversely proportional to the imperfection heights, therefore larger imperfections would require smaller temperatures to propagate upheaval buckling. Increasing the downward load on the pipelines aids the prevention of upheaval buckling.

Also, relevant methods to mitigate against the occurrence of upheaval buckling have been discussed. The use of finite-element analysis which considers the seabed profile and plastic deformation of pipe wall would be suitable for precise analysis.

THE OIL AND GAS INDUSTRY has maximized the use of both the onshore and offshore pipelines in transporting products from one location to another. During operation, due to high pressures and high temperatures of the fluid flow in pipelines, the pipelines expand which results to buckling. Buckling in offshore pipelines is caused by axial compression formed along the pipelines due to large temperature differences and high internal pressure [3]. Buckling may occur in pipelines downward in a free span, horizontally in lateral buckling on the seabed, or vertically in upheaval buckling of buried pipelines [6].

Buried or trenched pipelines are restrained from snaking horizontally or laterally, and are thereby not free to expand [8]. Thus, this pipeline develops an axial compressive force due to the restraint. When the force exerted by the pipeline exceeds the vertical restraint that resists the uplift movement (created by the pipe's size and submerged weight, the bending stiffness of the pipe, and the weight of the soil or rock cover), the pipe tends to move upward which results in a vertical displacement that can cause structural deformation or failure of the pipeline.

Several scholars have developed analytical models to mitigate against the occurrence of upheaval buckling and to sustain offshore pipeline integrity and reliability. Upheaval buckling according to Hobbs [9] and Boer *et al.* [2] are based on classical analysis relating pipeline stability to vertical stability of railway tracks (this is basically based on perfect pipelines). Richard [21] and Taylor *et al.* [23] established their models incorporating structural (initial) imperfections and deformation-dependent axial friction resistance (out-of-straightness of pipelines). Ju *et al.* [11] and Pederson *et al.* [20], developed models improving on analysing imperfectly heated pipelines, emphasizing the occurrence of upheaval in pipelines being caused by temperature fluctuations in combination with initial imperfections (upheaval creep of buried heated pipelines).

Software has been developed based on the established theoretical analysis of these models to define upheaval buckling of pipelines. This research paper concentrates on a review of these analytical models, and comparing the models using an assumed scenario.

This paper aims to identify the causes of upheaval buckling, review current and previous research on upheaval buckling, identify predictive models, and suggest approaches to mitigate against upheaval buckling in pipelines

Background study

Global buckling in pipelines connotes the buckling of pipeline as a bar in compression. It could occur downward in a free span, horizontally as in lateral buckling of a pipeline on the seabed, or vertically as in upheaval buckling of buried pipelines [6]. Buckling of pipelines occur as a result of thermal loading and internal pressure that produces axial compressive loads across the pipeline.

Lateral buckling occurs when the pipeline is laid on the surface of the seabed, and the buckle propagates as a lateral or snake-like deflection. Upheaval buckling occurs

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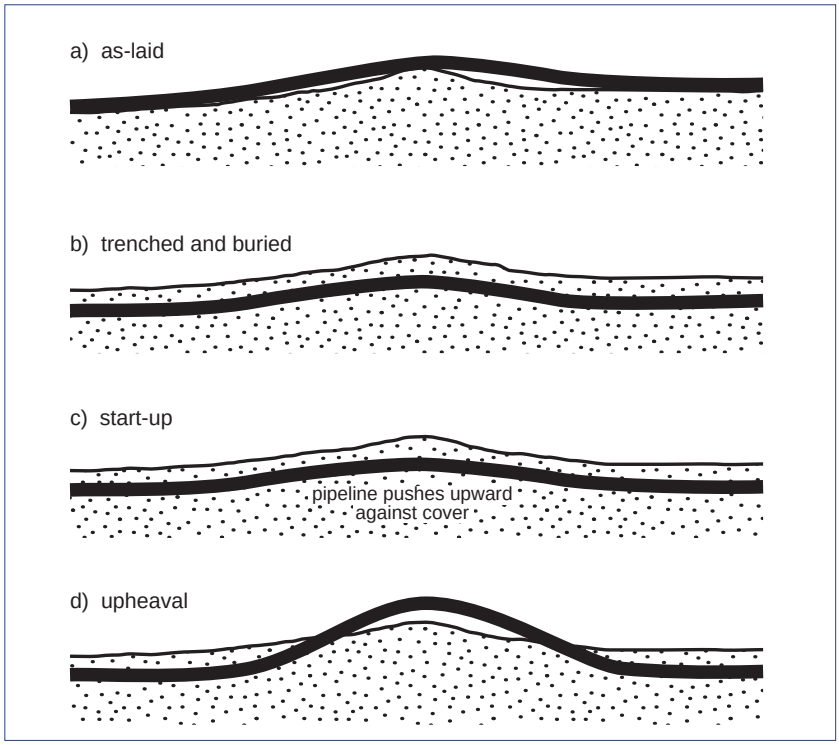


Fig. 1. Sequence of events illustrating buckling in buried pipeline [18].

when the pipeline is trenched or buried, and the buckle propagates in a vertical deflection.

When the temperature and pressure of an operating pipeline is higher than the ambient, the pipeline tends to expands. Due to the inadequate space to allow expansion of a trenched or buried pipeline, the pipeline develops an axial compressive force. If the force created by the pipeline is higher than the vertical force produced by the soil cover which prevents against the uplift movement created by the pipe, the pipe then tends to move upward causing a vertical displacement of the pipe. The excessive propagation of the vertical displacement of the pipeline can eventually result in failure of the pipeline [19].

Figure 1 shows a diagram of events that initiates propagation of vertical displacement (upheaval buckling) in buried pipelines. Figure 1a illustrates the pipeline being laid on the seabed. The pipeline is then trenched or buried, as shown in Fig.1b. This process therefore modifies the foundation profile where the pipe rests. In operation, as depicted in Fig.1c, the increased temperature and pressure creates a compressive axial force which causes a lift of the pipeline. Continuous increase of the temperature and pressure while in operation causes the pipeline to push upward against the soil cover, creating an upheaval buckling of the pipeline as shown in Fig.1d.

In order to prevent impact on pipeline by other marine activities, such as fishing nets or ships' anchors, and for the safety of the pipeline and the environment, the pipelines are usually buried and trenched [7].

Considerable research has been made into this topic, and the first paper on pipeline buckling was published in 1974 [7]. Different incidences of upheaval buckling occurred in the 1980s: the first occurrence of upheaval buckling took place in 1986 in the Danish sector of the North Sea associated on Maersk Olie Og Gas A/S' Rolf pipeline [17]. Authors including Hobbs [10], Boer [2], Richards [21], Taylor *et al.* [23], Ju *et al.* [11], Pederson *et al.* [20], Palmer *et al.* [19], and Klever *et al.* [13] have addressed and contributed to upheaval buckling problem in pipelines.

Hobbs [9] emphasized in his research two methods of buckling propagation in pipelines: lateral and upheaval buckling. The classical analysis proposed in his research was identical to the one of the vertical stability of railway tracks [12], and his paper addressed responses produced by the compressive force generated on the pipeline, which is similar to the bending deformation that propagates in the elastic buckling of an axially loaded column. He also considered the pipeline to be perfectly elastic and assumed pipeline to be straight without considering imperfections or out-of-straightness [10].

Further research was directed to this topic, and the classical model proposed in Hobbs' paper was modified and refined to consider imperfections (out-of-straightness) and the elasto-plastic behaviour of pipelines undergoing buckling.

In his paper Boer [2] discusses buckling associated with operating a pipeline at high temperature (using the 15.3-km long, 12-in diameter, Alwyn pipeline in the N Sea as a case study). He established his research by focusing on previous studies developed by Delft Hydraulics Laboratory (DHL) and Lloyds Register of Shipping (LRS). The research showed in detail the effects of vertical constraint force and prop height on upheaval buckling propagation.

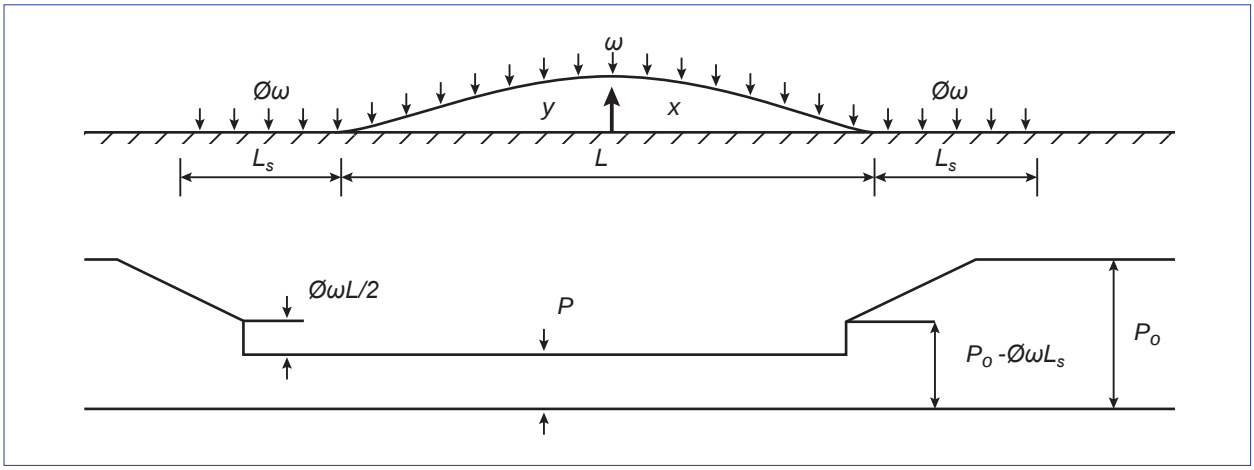


Fig.2. Force analysis of a pipeline section with vertical buckling [9]: (a – top) pipeline buckling mode with dimensions; (b – bottom) axial force distribution.

Taylor and Gan [23] put together an analysis incorporating structural imperfection and deformation-dependent axial-friction resistance; their study concentrated on both the vertical and the lateral modes of deformation.
Pendersen and Jenson [20] also described the vertical buckling of pipelines due to thermal expansion and internal pressure; they observed that the effect of temperature fluctuations in imperfect pipelines could produce upheaval buckling at a temperature lower than the design temperature. The paper presented a model which designs against propagation of upheaval buckling of buried pipelines subject to time-varying temperature loading.

Palmer *et al.* [19] developed a simplified analytical model focusing on pipeline stability which analysed whether the downward force (of the soil cover) would be capable or enough to hold the pipeline in its position and prevent propagation of upheaval buckling.

This paper focused on three basic models: the theoretical analysis for upheaval buckling of perfect straight pipelines, imperfect pipelines, and simplified Palmer's model.

Theoretical analysis for upheaval buckling of perfectly straight pipelines

As identified earlier, compressive axial forces are developed along a pipeline due to the increased internal temperature and pressure during operation. This compressive axial forces along a pipeline can result in upheaval buckling of the pipeline.

Similar occurrences of upheaval buckling have occurred in railway track, and a works were published analysing the problem. In 1936, Matrinet first developed a theory to analyse the vertical mode of buckling in railway track [9]. Granstrom's discussion on behaviour of continuous crane rails in 1972, and a research paper published by Marek and Daniels in 1971 which described the analysis of vertical buckling of crane rails, agrees with the theory first made by Matrinet. In 1974 Kerr [12] published an extensive literature analysis on upheaval buckling of railway tracks.

The analyses made by these authors are closely related to buckling problems in pipelines, and thus Hobbs [10] developed the basic models for buckling in pipeline relating his theory to the previous theory of buckling in railway track. In this model, the force created by full restraint of thermal expansion across the pipeline is:

$$P_0 = EA\alpha\Delta T \qquad (1)$$

where P_0 is the force, E is the Young's modulus, α is the coefficient of linear thermal expansion, and ΔT is the temperature change.

The axial strain ε across the wall of the pipeline due to the pressure difference is given by:

$$\varepsilon = \frac{1}{E}\left(\frac{\mathrm{Pr}}{2t} - \nu\frac{\mathrm{Pr}}{t}\right) \qquad (2)$$

where ν is Poisson's ratio, P is the internal pressure, t is the wall thickness, and r is the radius.

If the axial strain is restrained, the axial compressive force P_0 to propagate buckling will be:

$$P_0 = EA\varepsilon = \frac{\mathrm{A\,Pr}}{t}(0.5-\nu) \qquad (3)$$

The pipeline is analysed as a beam under uniform lateral load, as illustrated in Fig.2. The linear differential equation of the deflected shape of the buckled area of the pipeline, assuming the moment of the lift-off point is zero, is given as [10]:

$$Y'' + n^2 Y + \frac{m}{8}\left(4x^2 - L^2\right) = 0 \qquad (4)$$

in which $m = \omega/EI$ and $n^2 = P/EI$, and ω is the submerged weight of pipeline per unit length

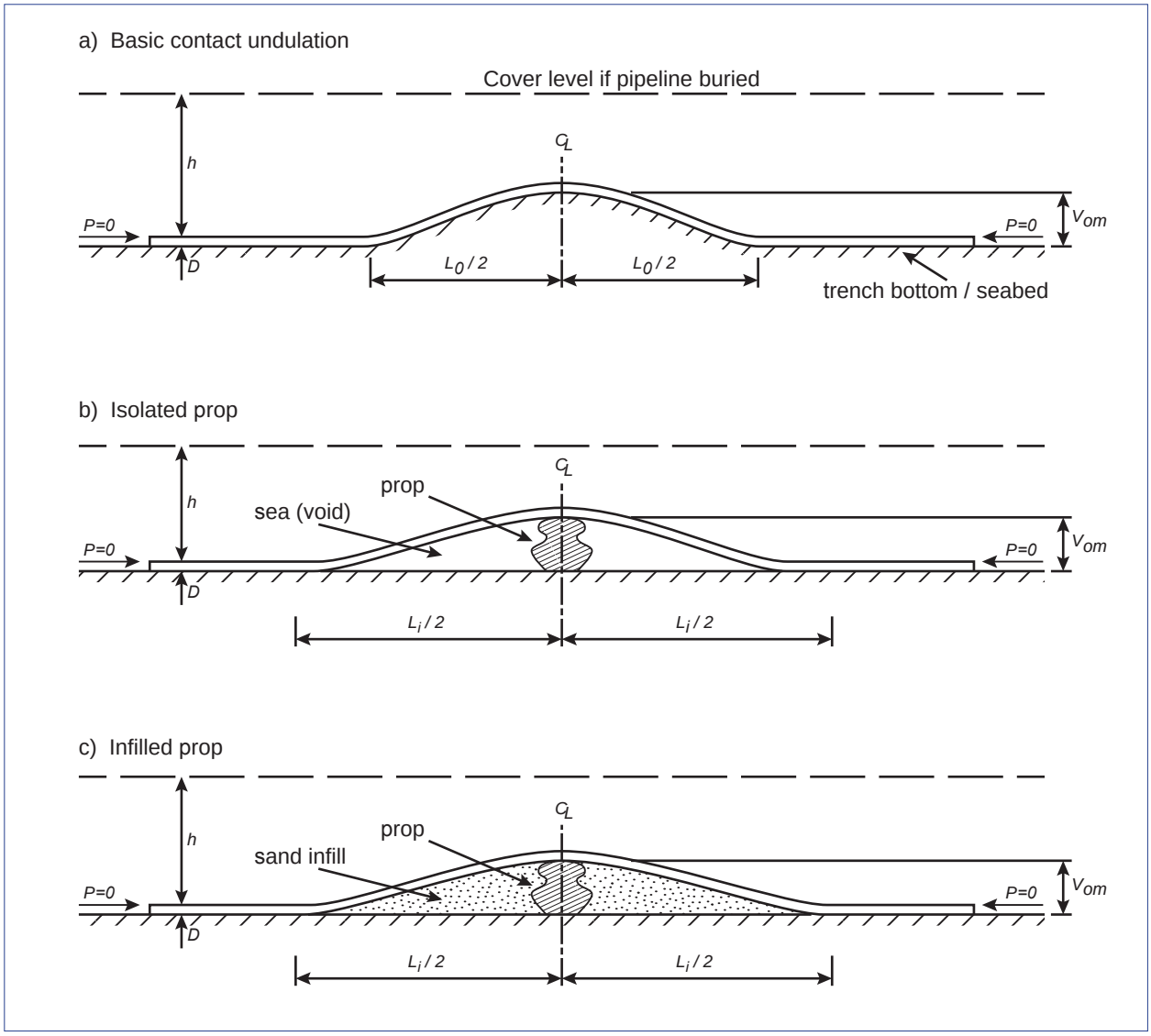


Fig.3.Typical imperfection configuration [24].

Figure 2b compares the axial load P in the buckling area with the axial load P_0 away from the buckle area. The axial load P in the buckle area is less than the axial load away from the buckle area because of the extra length around buckle area L_s compared to the length of the buckle area L.

Equation 4 is can be solved and gives the following result for the axial loads:

$$P = 80.76\frac{EI}{L^2} \tag{5}$$

and

$$P_0 = P + \frac{\omega L}{EI}\left[\left(1.59\times10^{-5}EA\phi\omega L^5\right) - 0.25\left(\phi EI\right)^2\right]^{\frac{1}{2}} \tag{6}$$

P represent the axial load in buckled region, P_0 is the axial load away from the buckled area, and is the coefficient of friction between the pipe and the subgrade.

The maximum amplitude of the buckle is given as:

$$V_m = 2.408\times10^{-3}\frac{\omega L^4}{EI} \tag{7}$$

The maximum bending moment at $x = 0$ is:

$$M' = 0.06938\omega L^2 \tag{8}$$

The slipping length L_s, adjacent to the buckle is given as:

$$L_s = \frac{P - P_0}{\phi\omega} - 0.5L \tag{9}$$

For a very large coefficient of friction when $L_s = 0$:

$$P_0 = 80.76\frac{EI}{L^2} + 1.597x10^{-5}\frac{\omega^2 AEL^6}{\left(EI\right)^2} \tag{10}$$

Equation 10 is a minimum when:

$$L' = \left(\frac{1.6856\times10^6\left(EI\right)^3}{\omega^2 AE}\right)^{0.125} \tag{11}$$

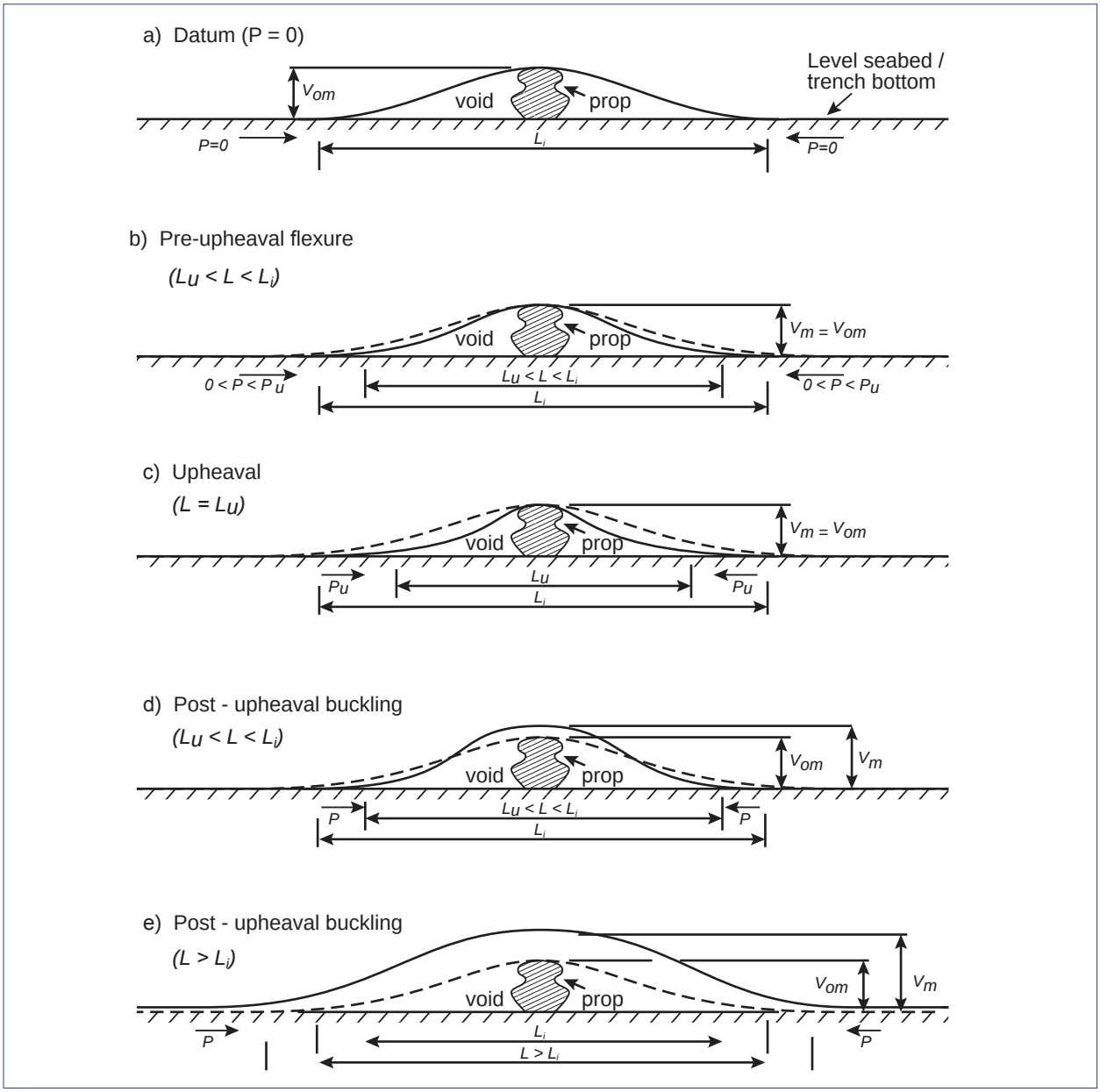


Fig.4. Isolated prop topologies [24].

Upheaval buckling of imperfect pipelines

Recent research has expanded the classical view of upheaval buckling thereby making void the engineering practice that the shape of a buried pipeline is straight. This is due to the presence of initial imperfections during the pipe laying.

Initial imperfection in pipelines can be due to irregularities of the seabed profile, or laying the pipeline over a boulder or prop. The presence of the initial imperfection causes a deformation on the pipeline during the laying process and during operation as the temperature-increased propagation of upheaval buckling takes place.

Many researchers have contributed to the study of upheaval buckling of imperfect pipelines. A number of authors including Taylor and Gan [23], Boer *et al.* [2], Ju and Kyriakides [11], Perdersen and Jensen [20], Ballet and Hobbs [1], Maltby and Calladine [15], Taylor and Tran [24], and Croll [5], have published papers analysing the upheaval buckling of imperfect pipelines.

Initial imperfections in pipelines could occur in three different forms as shown in Fig.3. These are illustrated with different parameters such as V_{om} which represents the amplitude of the initial imperfection, and L_0 which represents the length.

Taylor and Tran [24] developed models describing each case of the initial imperfections. The first case, in Fig.3a, illustrates the pipeline lying in contact with the vertical undulation of the seabed in a straight line. Figure 3b shows the isolated-prop scenario where the pipeline is laid on a sharp vertical irregularity or prop. The third scenario,

in Fig.3c, is an extension of the scenario in Fig.3b which occurs when the prop becomes in-filled with sand.

The isolated-prop case involves the pipe been laid on a sharp vertical irregularity ('prop') in such a way that a void exists at either side, as shown in Fig.4. The prop could be a rock on the seabed or a pipe crossing. The voids at either sides of the prop allow pre-buckling flexible movement of the pipe due to temperature and pressure cycling. As the temperature during operation rises, the span length of the pipeline reduces as the pipeline tightens up under the force *P*, and the length reduces to a point where the pipeline lifts from the top of the prop.

As the temperature increases, as illustrated in Fig.4, the length L_i reduces to length L_u where upheaval propagates. Post-upheaval buckling occurs when $L_u < L < L_i$ with $L > L_i$.

Adopting the approach of Richards *et al.* [21] and Ballet and Hobbs [1] as summarized by Mohammed [16], the rise due to temperature is given in Equn 12 below, where *E* is the Young's modulus, *A* is the cross-sectional area of the pipeline, α is the coefficient of thermal expansion, *I* is the second-moment area of the pipeline, μ is the coefficient of friction, ω is the vertical load per unit length, *H* is the height of the prop, *L* is the length of buckle, and *P* is the axial fore in the buckle region.

Where there is zero slippage in the region adjacent to the buckle, Equn 12 can be rearranged [16] as:

$$T_{\min} = \left(\frac{\omega}{E\alpha^2}\right)^{1/2}\left\{2.9885\left(\frac{1}{A^3}\right)^{1/4} - \left(\frac{8H^3}{1225I}\right)^{1/2}\right\} \quad (13)$$

where T_{min} is the minimum temperature to propagate buckle, and other parameters are as stated above. The buckle amplitude associated with the minimum temperature from Equn 13 is given by:

$$V_{T\min} = 3.1249\left(\frac{I}{A}\right)^{1/2} \quad (14)$$

This can also be re written as:

$$V_{T\min} = 0.7812\left(D^2 + d^2\right)^{1/2} \quad (15)$$

where *D* is the external diameter and *d* is the internal diameter of the pipe.

In addition, the equations required to determine the buckle length *L* and the axial force *P* associated to the T_{min} are:

$$L_{T\min} = \left(\frac{1.6856\times10^6\left(EI\right)^3}{\omega^2 EA}\right)^{1/8} \quad (16)$$

$$P_{T\min} = \left(5.0273E\omega\left(IA\right)^{1/2}\right)^{1/2} \quad (17)$$

Croll [4] proposed that the initial wavelength of the suspended part of the pipeline when laid on the seabed imperfection to be given by:

$$L_0 = 5.826\left(\frac{EIH}{\omega}\right)^{1/4} \quad (18)$$

where L_O is the initial wavelength, *E* is Young's modulus, *I* represent the moment of inertia, *H* is the imperfection height, and ω is the submerged weight.

The load and wavelength for the initial lift-off during operation can be calculated with the following equations:

$$P_{L0} = 3.007\left(\frac{EI\omega}{H}\right)^{1/2} \quad (19)$$

and

$$L_L = 4.427\left(\frac{EIH}{\omega}\right)^{1/4} \quad (20)$$

The maximum load for buckle propagation is then given by:

$$P_{bo} = 9.478\left(\frac{EIW}{H}\right)^{1/2} \quad (21)$$

Palmer *et al.*'s method

Palmer *et al.* [19] gave a detailed explanation of upheaval buckling with imperfection, and developed a simplified analytical model to support the explanation. The model proposed by Palmer and his team has been confirmed to produce good results when checked in a full-scale laboratory test and with more-refined computational tools [13, 22].

The stability of the pipeline was assumed to depend on the local profile of the pipe in contact with the seabed, and on the ability of the downward force being able to hold the pipeline in its position [19]. The authors proposed, using the elementary beam-column theory, that the downward force per unit length ω(*x*) that is needed to maintain the equilibrium position of the pipeline is given by:

$$\omega\left(x\right) = -EI\frac{d^4y}{dx^4} - p\frac{d^2y}{dx^2} \quad (22)$$

where *EI* is the flexural rigidity and is the axial compressive force.

$$\Delta T = \frac{1}{EA\alpha}\left\{P + \left[\left(EZ\mu\omega\int_0^{1/2} Y^2 x dx\right) - \left(\frac{8\omega H^3L^2}{1225EI}\right)^{1/2} - \left(\frac{\mu\omega L}{2}\right)^2\right]^{1/2}\right\} \quad (12)$$

The pipeline, after laying on the seabed, is deformed due to the height of the imperfection, the weight of the pipeline, and the flexural stiffness of the pipeline. Therefore, Palmer *et al.* proposed a simple sinusoidal profile of the pipeline after installation considering the height of imperfection and length of imperfection, given by:

$$Y = H\cos^2\left(\frac{\pi x}{L}\right) \qquad (23)$$

where H is the imperfection height, and L is the length of imperfection and ranging from $-0.5L < x < 0.5L$.

To maintain the position of the pipeline profile, the downward force required is proposed as:

$$\omega(x) = \left(-8HEI\left(\frac{\pi}{L}\right)^4 + 2HP\left(\frac{\pi}{L}\right)^2\right)\cos\frac{2\pi X}{L} \qquad (24)$$

At the tip of the imperfection when $x = 0$, the download force is maximum and is given by:

$$\omega = 2H\left(\frac{\pi}{L}\right)^2 - 8HEI\left(\frac{\pi}{L}\right)^4 \qquad (25)$$

where ω is the downward force per unit length to stabilize the pipeline at the tip of the pipeline imperfection.

In the paper [19], it was proposed that Equn 25 can be re-written as a relationship between dimensionless downward parameters:

$$\phi_w = A\phi_l^{-4} - B\phi_l^{-4} \qquad (26)$$

with $\phi_w = \omega EI/HP^2$ and $\phi_l = L\left(P/EI\right)^{1/2}$.

Constants A and *B* can be determined numerically by plotting $\varphi_w\varphi_l^2$ against φ_l^2 using finite-element software (UPBUCK) [19]. The authors confirmed the general profile of pipeline supported by the axial force in the post-buckling mode to be given by:

$$\phi_w = \frac{9.6}{\phi_l^2} - \frac{343}{\phi_l^4} \qquad (27)$$

In the situation where the maximum height of the imperfection is known and the length is unknown, an estimated imperfection length is assumed for pipeline that takes a form dependent on the flexural stiffness and the weight of installed pipe before operation [19].

Palmer *et al.* further derived the formula for preliminary design to determine the required download stability during operation, which is given by:

$$\omega = \left(1.16 - 4.76\frac{\left(\frac{EI\omega_0}{H}\right)^{1/2}}{P}\right)P\left(\frac{H\omega_0}{EI}\right)^{1/2} \qquad (28)$$

where EI is the flexural rigidity of the pipeline, ω_o is the submerged weight of the pipeline, H is the imperfection height, and P is axial force in operation.

The preliminary design formula compares the required download force determined from Equn 28 with the actual load (which is the sum of the submerged weight and the uplift resistance of the cover).

Schaminee *et al.* [22] did further research on calculating the uplift resistance of a pipeline buried in rock or in cohesionless soil. The equations to calculate the uplift cohesion are:

for cohesionless sand, silt and rock:

$$q = \gamma RD\left(1 + f\frac{R}{D}\right) \qquad (29)$$

for cohesionless clay and silt:

$$q = \gamma cD_{\min}\left(3\frac{R}{D}\right) \qquad (30)$$

where q is the uplift resistance, R is the depth of the cover, γ is the submerged unit weight of the cover material, D is the diameter of pipe, c is the shear strength, and f is the uplift coefficient (0.5 for dense materials and 0.1 for loose materials) [19].

Methodology

In order to be able to evaluate the use of the proposed upheaval models, an Excel spread sheet was developed for each upheaval-buckling method described above. A typical sample pipeline with parameters given in Table 1 was used for each of the models.

Theoretical analysis of perfect straight pipeline

According to the theoretical analysis of upheaval buckling of perfect straight pipelines [10], the following would be used to determine the force or temperature change corresponding to the buckle length:

- considering high coefficient of friction:
  - the value of Ĺ can be computed using Equn 11;
  - for a range of values of length L from the computed Ĺ, determine P_o using Equn 10;
  - determine the value of T using Equn 1, and the buckle amplitude V_m using Equn 7.
- considering real coefficient of friction:
  - for a range of coefficient of friction and values of L from the computed Ĺ, compute P_o using Equn 6;

Parameter	notation			Metric unit
outside diameter	D	25.6 in	0.65024	m
wall thickness	t	0.59 in	0.014986	m
Cross-sectional area	A	46.38 sq in	0.029923	sq m
second moment of area	I	3625 in^4	1.51 E-03	m^4
submerged weight	w	260 lb/ft	3823.399	N/m
coefficient of linear thermal expansion	α	0.000011 ^oC	1.10E-05	C
Young's modulus	E	2.07E + 11		
coefficient of friction	ϕ	$0.3 \leq \phi \geq 0.7$		

Table 1. Parameters of the sample pipeline.

- the change in temperature can be computed using Equn 1, and the buckle amplitude V_m from Equn 7.

Analysis of imperfect pipelines

Due to the complexity of the study of the upheaval buckling of pipelines containing imperfections or out-of-straightness, the simplified model summarized by Raoof [16] was used, where the minimum temperature for propagation of upheaval buckling can be determine using Equn 13. The buckle amplitude at the minimum temperature T_{min} can be calculated using Equns 14 or 15; the buckle length can be determined using Equn 16, and the axial force that would propagate upheaval buckling can be determined from Equn 17.

Further analysis can be done using Equn 18 to determine the initial wavelength suspended by the imperfection. The lift-off load, wavelength, and the maximum load for buckle propagation can be calculated with Equns 19, 20, and 21, respectively.

Analysis of Palmer et al.'s model

The method summarizes how to evaluate the possibility of the occurrence of upheaval buckling on an operating pipeline. The steps involved are:

- determine the axial force;
- calculate the total downward force needed to keep the pipeline in its position without occurrence of upheaval buckling using Equn 28;
- determine the sum of the pipeline submerged weight and the uplift resistance (the available load on the pipe);
- compare between the total downward force that keeps the pipeline in its position with the available load on the pipe. For stability to occur $\omega > \omega_0 + q$.

Results and discussion

A typical pipeline is considered with parameters shown in Table 1.

For the theoretical analysis of a perfectly straight pipeline using a spread sheet (which is fully shown in the Appendix*) the steps discussed above were followed. The result, in Figs 5 and 6, shows the temperature rise required to produce an axial force that will propagate upheaval buckling. Figure 5 shows the relationship between the temperature and the buckle length, while Fig.6 depicts the relationship between the temperature increase and the buckle amplitude.

Considering a very large coefficient of friction (the worst-case scenario for design), Fig.5 shows that the largest safe temperature change required to avoid upheaval buckling in the sample pipeline is 101^0C (i.e. the minimum temperature to propagate upheaval buckling). Hobbs explained the mode pattern A to B in Fig.5 to be unstable due to the assumption of fully mobilized friction for a small displacement. The path B to C then explains the relationship between temperature and buckle length for the sample pipeline with a small imperfection [7.

It was observed that the effect of the coefficient of friction φ was noticed and relevant in the post-buckling region B to C, as shown in Fig.7. An approximated value of the coefficient of friction between the seabed and the pipeline was used in the model.

The model examined only perfect systems with no account of the initial out-of-straightness or the magnitude and nature of the initial imperfections of the seabed.

Considering the case of initial imperfections where the pipe is laid on a prop with a varying imperfection height *H*,

*Editor's note: space unfortunately precludes the inclusion of the authors' Appendix which is made up of a considerable amount of tabular data. A copy can be sent to readers for whom it would be helpful: to obtain this, please contact the editor, who's details are given on p.142.

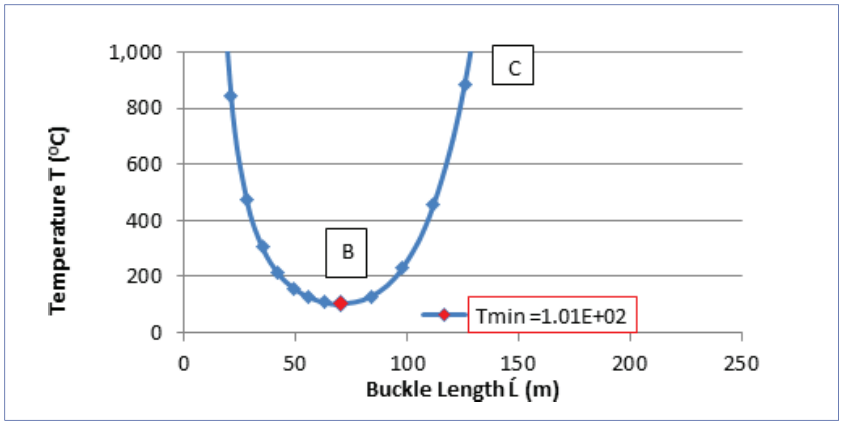


Fig.5. Relationship between temperature and buckle length.

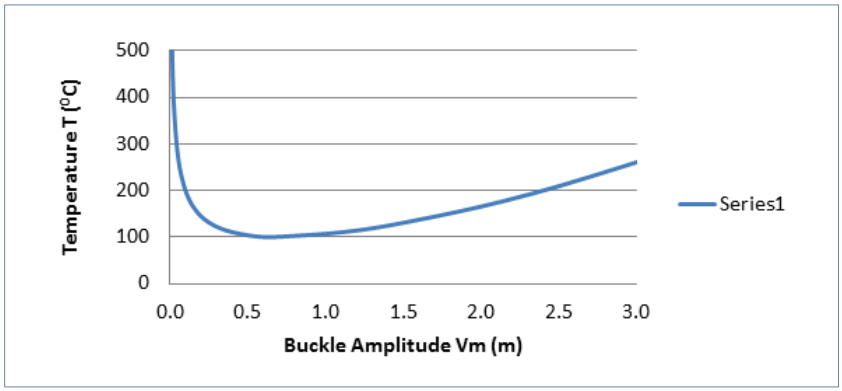


Fig.6. Relationship between temperature and buckle amplitude.

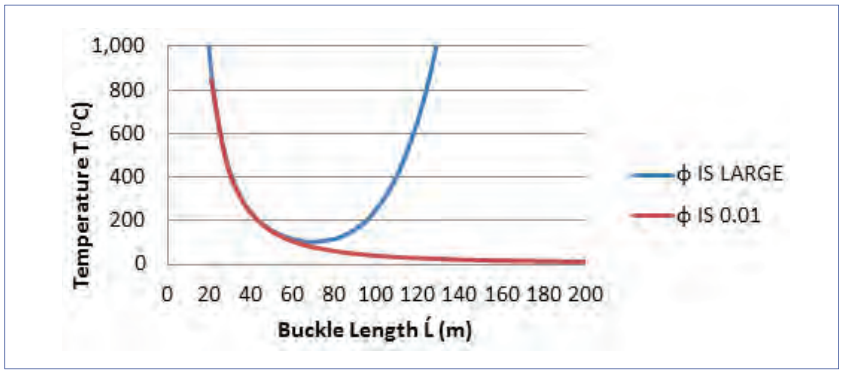


Fig.7. Relationship between temperature and buckle length with different coefficients of friction.

the natural length of the suspended portion is given as L_i as shown in Fig.4a above, assuming the out-of-straightness of the pipeline is free of an axial load i.e. $P = 0$.

During operation with increasing axial load P, it was observed that the values of the wavelength (the lift of wavelength L_L) begins to reduce when compared to the initial wavelength L_o as shown in Fig.4b and Table 2.

Following the approach described above, and using the sample pipeline in Table 1, Table 2 depicts the relationship between the safe temperature (T_{min}), initial wavelength (L_o), the uplift wavelength (L_L), the uplift load (P_L), and the maximum buckling load (P_b) for various imperfection heights.

As the initial imperfection height increased the minimum safe temperature T_{min} to propagate vertical buckling decreased and the maximum axial load for buckle propagation reduced. This is illustrated in Figs 8 and 9. The maximum buckling load is reached with a very small imperfection height, and the safe temperature obtained in the imperfect model is smaller than the one calculated using the perfect model.

The model proposed by Palmer *et al.* established a preliminary design to determine the stability of buried pipelines following the procedure of the analysis described in above. A full calculation can be seen in the Appendix*.

Using the sample pipeline with an axial force of 15 MN and an imperfection height of 0.2 m, when the depth cover used was 0.8 m the factor of safety was less than 1; when a cover depth of 1.4 m was used, the factor of safety increased slightly (1.04), and with a cover depth of 1.7 m, the factor of safety increased to 1.17. This shows that a cover depth of 1.7 m would be required to keep the pipeline stable, and could be used for upheaval design.

*Editor's note: space unfortunately precludes the inclusion of the authors' Appendix which is made up of a considerable amount of tabular data. A copy can be sent to readers for whom it would be helpful: to obtain this, please contact the editor, who's details are given on p.142.

H (m)	T_{min} (°C)	L_0(m)	L_i(m)	P_{lo} (N)	P_{bo} (N)
0.05	101	46.57511	32.20925	14695347	16997146
0.1	100	55.38745	38.30347	10391180	12018797
0.2	98.9	65.86715	45.55076	7347674	8498573
0.3	96.9	72.89399	50.41021	5999350	6939056
0.4	94.6	78.32969	54.16929	5195590	6009399
0.5	92.1	82.82356	57.27705	4647077	5374970
0.6	89.2	86.68605	59.94818	4242181	4906653
0.7	86.1	90.09193	62.30353	3927497	4542678
0.8	82.8	93.15022	64.41851	3673837	4249287
0.9	79.2	95.93388	66.34356	3463727	4006266
1	75.4	98.49437	68.11428	3285980	3800677

Table 2. Values of safe temperature, initial wavelength, uplift wavelength, uplift load, and maximum buckling load for various imperfection heights.

Imperfection height H (m)	Required download W (N/m)	Total download W0 (N/m)	stability
0.05	-7992.225716	8787.611116	TRUE
0.1	-1594.783839	8787.611116	TRUE
0.2	7452.565228	8787.611116	TRUE
0.3	14394.84034	8787.611116	FALSE
0.4	20247.44898	8787.611116	FALSE
0.5	25403.70071	8787.611116	FALSE
0.6	30065.3086	8787.611116	FALSE
0.7	34352.09946	8787.611116	FALSE
0.8	38342.14712	8787.611116	FALSE
0.9	42089.6818	8787.611116	FALSE
1	45634.18824	8787.611116	FALSE

Table 3. Values of required download and pipeline stability level at different imperfection heights.

It was observed that as the imperfection height increased the required download and the necessary cover depth that would be required to keep the pipeline stable to avoid upheaval buckling of the buried pipeline, as shown in the Fig.10 and Table 3. If the pipeline is stable, further action could be ignored; however if, from the analysis, the pipeline is shown to be unstable, further investigation using finite-element analysis would be required.

Mitigation against upheaval buckling

There are several methods to mitigate against the occurrence of upheaval buckling in pipelines. As briefly discussed in Palmer *et al.* [19], mentioned below are few of the approaches available to reduce the propagation of upheaval buckling in offshore pipelines.

The simplest method is to stabilize pipeline against upheaval buckling by burying the pipeline; due to the difficulties and high cost involved in this method, other options have been introduced. One of these is to reduce the design temperature and pressure and to increase the submerged weight of the pipeline, although this method is impractical because too much weight would be needed to accomplish this, and reducing the temperature might necessitate adding a heat exchanger to the system.

Occurrence of upheaval buckling in pipeline can also be minimized by reducing the driving force (the axial compressive force) of the pipeline and also by reducing the wall thickness of the pipeline. Since the effect of temperature on the axial force is proportional to the wall thickness, the reduction of the wall thickness therefore reduces the effect of the temperature which causes upheaval buckling. In addition, pre-heating the pipeline,

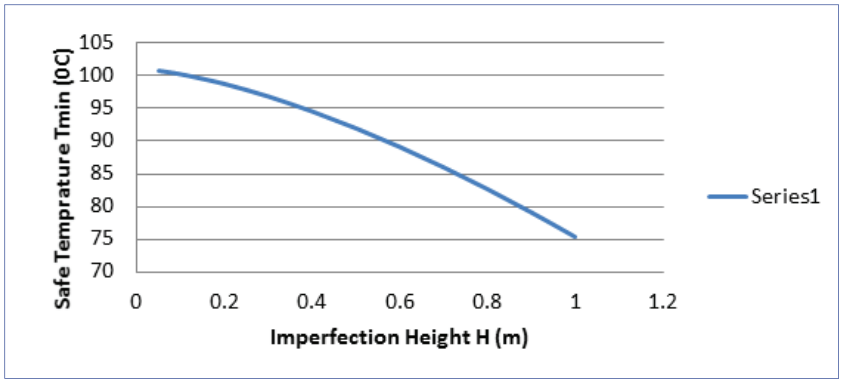


Fig.8. Relationship between safe temperature and imperfection height.

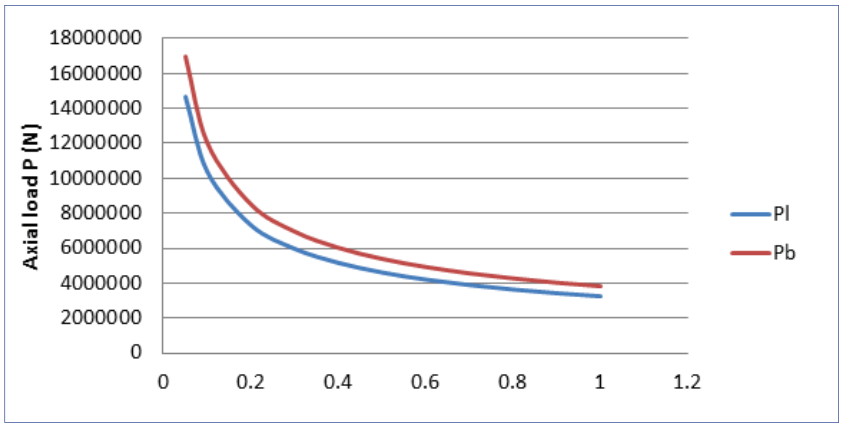


Fig.9. Relationship between axial load and imperfection height.

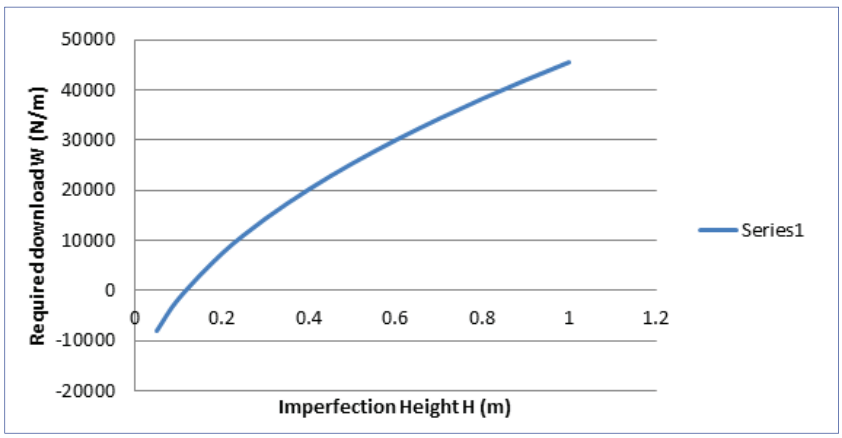


Fig.10. Relationship between required download and the imperfection height.

and increasing the residual tension of the pipeline in order to balance the axial compressive force during operation, are other important approaches to mitigate against the occurrence of upheaval buckling.

Another option is to change the structure of the pipeline by replacing some of the pipelines with closed bundles, or introducing a pipe-in-pipe system [19]. The steel pipe system could be replaced with flexible pipes which would allow expansion movement to occur in the pipeline so as to restrain the occurrence of upheaval buckling.

The risk of upheaval buckling can also be avoided by keeping the pipeline in its position by holding the pipeline down, and this can be achieved by placing concrete mattresses or rocks on critical over-bends where buckling tends to occur, or at intermittent intervals along the pipeline [14].

Conclusions

Three models have been discussed. The model considering imperfection was able to eliminate the limitation existing in the perfect-pipeline model (which does not include the initial imperfection and out-of-straightness of the pipeline). Similarly the Palmer *et al.*'s model was able to establish a preliminary design calculation method to confirm the stability of a buried (or covered) pipeline system. With the inclusion of the imperfections, buckle temperatures become inversely proportional to imperfection heights. Thus a larger imperfection would require a smaller temperature to propagate upheaval buckling, and a larger cover depth would be required to keep the pipeline in its position.

The increased development in offshore oil and gas fields that requires exploration in deeper waters will

encourage the use of longer pipelines operating at higher temperatures and pressures. There might not be a need for burying or trenching of pipelines (which is a known practice associated to shallow waters) due to the high cost and techniques that would be involved. Therefore laying the pipeline on the seabed would be a good option. This option exposes the pipeline to horizontal snaking which is associated to with lateral buckling. Further research into lateral buckling would therefore be of necessity for the future of offshore pipelines.

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