N. J. R. Nielsen
Mærsk Olie og Gas A/S,
Copenhagen, Denmark

P. T. Pedersen
Department of Ocean Engineering,
Technical University of Denmark,
Lyngby, Denmark

A. K. Grundy

B. S. Lyngberg
Mærsk Olie og Gas A/S,
Copenhagen, Denmark

Design Criteria for Upheaval Creep of Buried Sub-Sea Pipelines

A new criterion is presented for the design against upheaval creep of buried hot marine pipelines. Observations have substantiated that the gradual upheaval of an "imperfect" buried pipe can take place when subjected to variable temperature and pressure loading. The imperfection amplitudes can thus grow until at a certain stage the overburden is insufficient to prevent upheaval (snap) buckling of the pipe. This paper shows that the "classical" upheaval buckling analysis is not applicable when designing against upheaval creep failure of an "imperfect" pipe. A new design procedure is established which determines the uplift resistance required to keep the upward movement of the "imperfect" pipe below critical values, thus preventing a progressive upheaval failure. The various aspects to be considered during the design and installation of a pipeline are highlighted, resulting in requirements for acceptable out-of-straightness of the pipe.

Introduction

It is known that buried pipelines operating at elevated temperatures should be designed against upheaval buckling failure. However, survey measurements of a pipeline in the North Sea have substantiated that variations in temperature and pressure loading, e.g., during shutdown periods, can result in a gradual upward movement (upheaval creep) of "imperfect" pipe sections, thus decreasing the soil cover locally. As a consequence, upheaval buckling failure can take place at a temperature which is lower than the specified design temperature.

The classical upheaval buckling analysis for buried pipelines is identical to the vertical stability analysis of railroad tracks. However, the assumption of a constant uplift resistance in the case of railroad track buckling, does not have physical relevance for the upheaval deflections of a buried pipe due to the nonlinear pipe/soil interaction and decreasing soil cover during upheaval. Consequently, the classical upheaval buckling analysis does not reflect the correct upward displacement history, and thus is not applicable for design against upheaval creep.

In this paper a new design criterion is presented for design against upheaval creep of buried sub-sea pipelines subject to variations in temperature loading.

A theoretical model has been established showing that a pipeline section with an "imperfection" can move itself upward upon experiencing the operating temperature, lifting the overburden a small amount without necessarily being able to break out of the soil. During a subsequent shutdown, the line will cool and attempt to return to its original position. However, the migration of sand particles will have tended to fill the cavity below the pipeline created by the upward movement, thereby preventing a complete return to its original position. Hence, sections of the pipeline with an initial "imperfection" above a certain limit can work their way upward upon changes in the operating temperature, progressively increasing the amplitude of the imperfection. The consequence of this growth in imperfection amplitude is that the local soil cover will decrease until at a certain stage the overburden is insufficient to prevent upheaval buckling, and hence, snap buckling will take place. Therefore, in order to prevent a progressive upheaval failure, the upward movement of "imperfect" pipe sections must not exceed critical values, e.g., by keeping the movements within the linear elastic deformation characteristics of the soil.

The upheaval creep phenomenon is a highly nonlinear problem due to the "imperfection" geometry, the pipe/soil interaction, and the elastic-plastic behavior of the pipe material. Consequently, a "correct" mathematical analysis of upheaval creep is rather complex. However, it is not the intention of this paper to give a detailed description of the established mathematical model, but to present the various aspects which should be considered during the design, installation and inspection of a buried sub-sea pipeline operating at high temperatures. The proposed design criteria will be substantiated by results obtained by use of the mathematical model.

Case Story of the Experienced Upheaval Buckling

During the annual pipeline inspection survey in July 1986, along a buried interfield pipeline in the Danish sector of the North Sea, a pipeline section was discovered to have protruded the seabottom as a result of upheaval buckling. The 17 km long pipeline is an o.d. 8.625 in. × w.t. 14.3 mm carbon steel line, which is insulated and concrete coated. A detailed description of the pipeline is given by Pallesen et al

Contributed by the OMAE Division for publication in the JOURNAL OF OFFSHORE MECHANICS AND ARCTIC ENGINEERING. Manuscript received by the OMAE Division, August 14, 1989; revised manuscript received November 20, 1989.

(1985). The pipeline was taken into service in January 1986 for transport of unstabilized hydrocarbons with a temperature of 180°F (82°C) from the Rolf satellite field to the central process facility at Gorm. The upheaval buckling had taken place about 300 m from the Rolf platform, just outside the anchor point for pipeline expansion.

Detailed diver measurements of the upheaval buckle showed that the apex of the buckle measured to bottom of pipe was 1.1 m above seabed level, leaving the pipe free spanning over a 10 m section. As the burial depth to bottom of pipe of the "undisturbed" pipeline sections to either side of the upheaval was approximately 1.5 m, the total buckling amplitude became of the order of 2.6 m. The buckling wavelength was localized to 24 m, corresponding to two pipe joints. The plastically deformed pipeline was repaired by cutting out a section of the line, before a repair spool was installed using hyperbaric welding. Figure 1 shows the buckled pipe section after having been retrieved from the seabottom and transported to shore.

Prior to the repair of the buckled line, it was decided to carry out a comprehensive out-of-straightness survey of the entire pipeline using sub-bottom profiling. By comparing this survey with the as-built survey, it became evident that certain out-of-straight pipe sections had moved upward in the soil, without having reached the surface of the seabed yet. This upheaval creep phenomenon had taken place during the half-year period the line had been in operation, which included approximately 25 shutdown situations. At a total of 26 locations, it was required to rock dump out-of-straight pipe sections to prevent further upheaval creep. At one location a severe out-of-straightness had resulted in an exposed pipe section, which required a hyperbaric repair.

Pre- and Postbuckling of a Heated Pipeline

Previous Work. The pre- and postbuckling of pipelines subject to high temperatures has been examined by several authors using numerical as well as analytical approaches. Without entering into a detailed discussion of the buckling theory, most of the work concerned with analytical models deal with a beam of uniform weight on a rigid foundation. Historically this model has been used by railroad engineers to analyze vertical track buckling. A frequently referenced paper is Kerr (1974), containing a review and discussion of various aspects of linear railroad track buckling. More recently, nonlinear upheaval buckling analysis has been discussed by various authors, including Ju and Kyriakides (1987).

In Fig. 2, results from a "classical" linear upheaval buckling analysis (i.e., beam of uniform weight on rigid foundation) are shown in a temperature versus deflection plot for an o.d. 12.75 in. bare pipe. It has been generally accepted to use the trough of the U-shaped curves as the design criterion, adding a certain safety margin. This has previously been considered to be a safe and conservative approach to prevent upheaval buckling. Further, as can be seen in Fig. 2, the trough appears to be insensitive to the out-of-straightness of the pipe, apparently "substantiating" the validity of the design criterion. However, the linear analysis assumes that the pipe material has linear elastic behavior even for relatively large strains and that the overburden is constant throughout the analysis irrespective that the uplift resistance varies nonlinearly with uplift of the pipe. Consequently, the linear analysis does not reflect the correct displacement history during uplift, and thus cannot be used in the analysis of the upheaval creep phenomenon.

Present Work. A nonlinear model has been developed capable of calculating the resistance required to limit the uplift movement of a geometrically imperfect pipeline subject to pressure and temperature loads. The model can account for varying soil cover due to the imperfection geometry, the nonlinear pipe/soil interaction and the nonlinear behavior of the pipe material, and is described by Pedersen and Michelsen (1988). Pedersen and Jensen (1988) present a consistent linearized approach, suitable for design of the required uplift resistance for a pipe in the prebuckling state.

Fig. 1 Pipeline section, which has suffered upheaval buckling

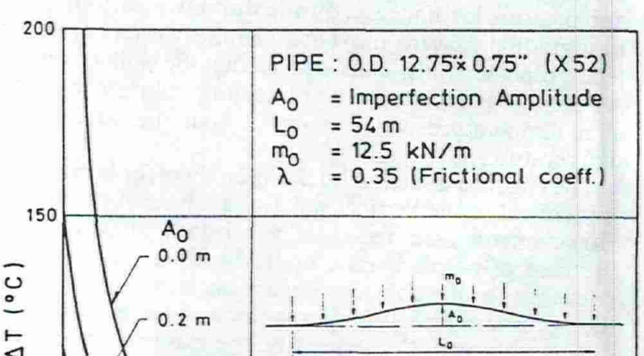

Fig. 2 "Classical" linear upheaval buckling analysis

For both models the imperfection is characterized by an imperfection amplitude and corresponding imperfection wavelength, assuming a symmetrical imperfection shape about the imperfection apex. This is illustrated in Fig. 3. In the unloaded condition (no temperature and pressure load) the pipe is fully supported by the foundation. Subjecting the pipe to temperature and pressure load generates an axial compression force in the pipe, causing the upper part of the pipe to "buckle" or bend into a new equilibrium shape characterized by a buckling wavelength L, and buckling amplitude W_{max}.

A comparison between the classical linear and the new nonlinear model is presented in Fig. 4, assuming linear behavior of the pipe material. In the classical model an equivalent constant overburden of 12.5 kN/m has been used, corresponding to the uplift resistance of the embedded pipe with 1.5 m sand cover assuming "vertical slip surface" model. For the nonlinear model the pipe/soil interaction is modeled using an analytical "upper-bound solution" for the uplift resistance (i.e., the actual uplift resistance is expected to be less than the calculated values). Since the soil uplift resistance is modeled differently in the two analyses, a direct comparison is not possible. However, it is noted that the difference between the two models is particularly pronounced for the postbuckling behavior of the pipe, indicating much lower equilibrium temperatures for the new nonlinear model compared to the classical linear model. Also, the difference in the prebuckling behavior for the two models becomes apparent with increasing imperfection amplitudes, making the "classical" upheaval buckling design procedure nonconservative for imperfections above a certain size. For a "perfect" pipe, the classical design approach will be conservative.

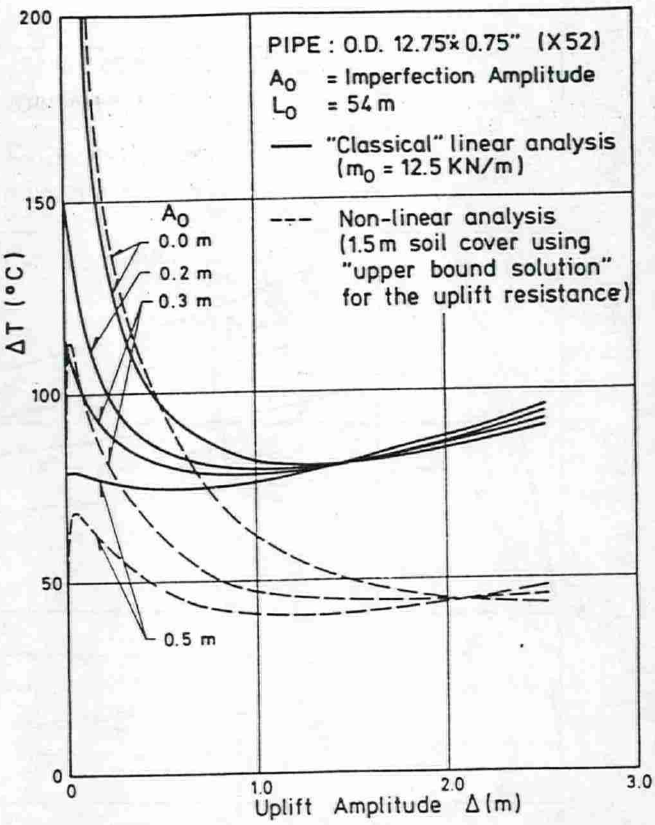

Fig. 4 Comparison between the "classical" linear and the new nonlinear upheaval buckling analysis

Critical Parameters of Upheaval Creep

Imperfections. The amount of uplift movement of imperfect pipelines is strongly dependent upon the imperfection characteristics, e.g., imperfection shape and residual stress components. In the following, two imperfection types in the vertical plane will be addressed corresponding to foundation imperfection and geometric pipe imperfection.

Foundation imperfections are characterized by the normally encountered variations in the vertical support conditions for a buried pipe, e.g., due to varying soil properties along the pipeline route or the presence of a stone or similar discrete obstacle.

The equilibrium shape obtained by the pipe due to normal vertical support undulations is governed by the bending stiffness and self-weight of the pipe. The adjustment of the pipe shape to the foundation undulations induces bending stresses in the pipe cross section, which would tend to straighten out the pipe again should the foundation imperfection be removed (assuming that no plastification has occurred in the pipe cross section).

Geometric pipe imperfections are defined by a permanent vertical out-of-straightness of the pipe centerline (i.e., the pipe wall has plastified). Hence, in the unloaded condition (i.e., no temperature and pressure load), an effective residual bending stress is not present in the pipe cross section to "straighten" the pipe. Thus, the pipe would tend to keep its "imperfect" shape even though the soil underneath the pipe was removed. Consequently, the geometric pipe imperfection results in larger uplift movements as compared to a pipe with a similar foundation imperfection, for the same applied temperature and pressure load.

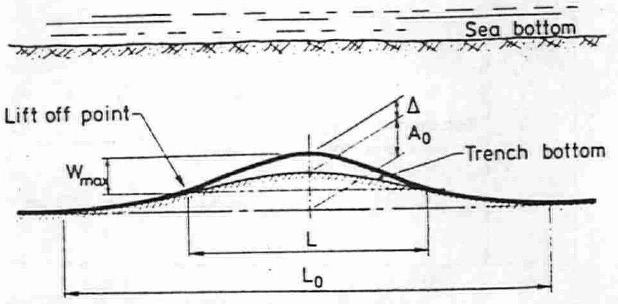

Fig. 3 Uplift behavior of a pipeline on foundation imperfection

To illustrate the difference in uplift movements between a "perfect" pipe on a foundation imperfection and a plastically deformed "stress-free" pipe on a foundation imperfection, the resulting uplift movement for increasing temperature load is shown in Fig. 5, for an o.d. 12.75 in. pipe with an initial out-of-straightness of 0.2 m and 0.3 m over a wavelength of 54 m, assuming linear behavior of the pipe material. It is seen that the same uplift movement is obtained at a lower temperature load for the plastically deformed pipe compared to the "perfect" pipe; note that the difference between the two imperfection types is particularly pronounced for small uplift movements.

Generation of Imperfections. In practice imperfections of some type will be introduced during the installation of buried sub-sea pipelines. In particular, a potential problem area is the lowering of a pipe, as the achievable pipe straightness depends strongly upon the soil conditions along the pipe, the lowering depth, the lowering technique applied (e.g., jetting, digging, ploughing) and the extent to which the lowering can be controlled (e.g., upon intermediate stop and start of trenching).

For buried pressurized pipelines operating at high temperatures, the combined equivalent stresses (i.e., von Mises reference stress) in the pipe cross section can be high. For example, the temperature and pressure-induced von Mises stress in a restrained, straight, o.d. 12.75 in. pipe with 0.75 in. wall thickness and API steel grade X52, subject to the design conditions of 180°F and 3000 psi equals 75 percent

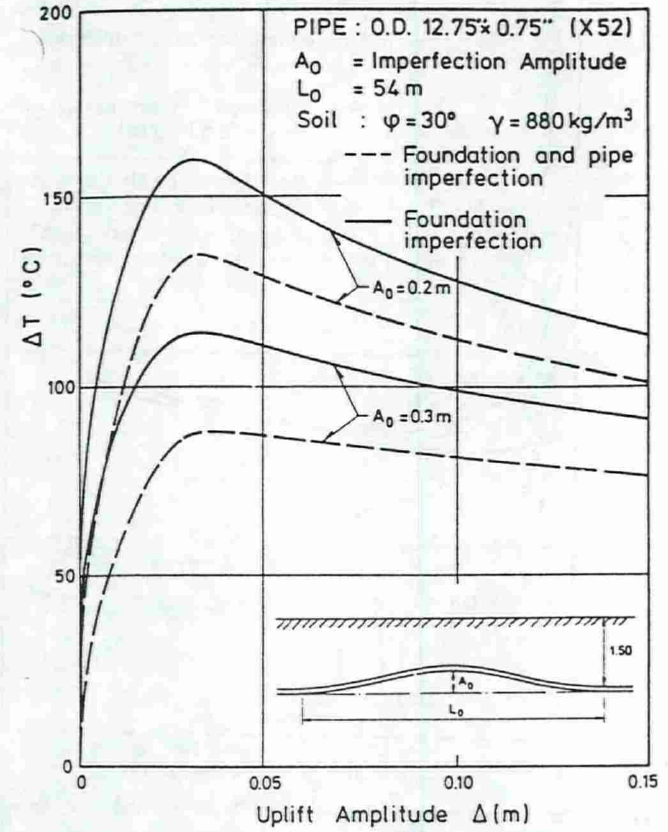

Fig. 5 Equilibrium temperatures for a "perfect" pipe on foundation imperfection and a plastically deformed "stress-free" pipe on a foundation imperfection

SMYS. Taking into account the additional bending-induced stresses due to natural undulations local yielding of the pipe can take place for foundation imperfections above a certain critical size. Thus, a pipeline which originally was installed with only foundation imperfections can, upon start of production, undergo local plastification in the pipe cross section resulting in a geometrically imperfect pipe. Therefore, when designing against upheaval failure, a combination of foundation and pipe imperfection must be considered for pipe undulations exceeding a certain critical size; for most pipes this corresponds to an out-of-straightness of 1/150 – 1/250.

As an illustration, the order of magnitude of the foundation undulations which can cause initial yielding, and thus generate some geometric pipe imperfection, for the above pipeline subject to design conditions, is relatively small at 0.2 m over an imperfection wavelength of 54 m. Therefore, if yielding is to be prevented, the installation of the pipe must be controlled with a precision, which with present technology is impractical.

Pipe joint misalignment and welding repairs on the lay barge can further introduce some permanent pipe out-of-straightness.

Pipe-Soil Interaction. To obtain a realistic model of the uplift behavior of buried pipelines, it is essential to establish physically relevant pipe-soil interaction characteristics for the uplift resistance.

Previously, most of the soil-mechanics research concerning uplift resistance of embedded bodies in sand or clay has been dedicated to the determination of pull-out forces of circular and rectangular anchor plates. However, recently two papers have been published containing experimental data on the uplift resistance of buried pipelines. In one paper, Trautmann et al. (1985) presented model test results of an o.d. 102 mm and 1 m long pipe section embedded in sand, and gave the force-displacement relationship of the pipe for different embedment depths and sand friction angles. In another paper, Boer et al. (1986) described the results of full-scale pull-out tests for a 2 m long test section of an o.d. 12.75 in. concrete-coated pipe covered with gravel.

A typical uplift resistance curve of a buried pipeline is shown in Fig. 6. The force-displacement relationship is characterized by 3 discrete points. Point 1 corresponds to the uplift resistance due to the submerged weight of the pipe and the weight of the soil column directly above the pipe. The displacement at point 1 can for all practical purposes be assumed to be zero. From point 1 to 2, the gradual upward movement of the "imperfect" pipe section mobilizes an uplift resistance due to the activation of shear stresses in the soil. Based upon the model test results presented by Trautmann et al. (1985), it has been assumed that the displacement required to reach the peak uplift resistance, point 2, can be estimated by

$$d_2 = (0.02 + 0.008H/D)D \leq 0.1D \qquad (1)$$

where D is the outer pipe diameter, and H is the depth of burial measured to the centerline of the pipe. As an example, for an o.d. 12.75 in. pipe with 1 m soil cover to top the pipe ($H = 1.16$ m), the displacement d_2, using equation (1), equals 16 mm. If the upward movement of the pipe exceeds the displacement corresponding to peak uplift resistance, general shear failure in the soil occurs resulting in decreasing uplift resistance until point 3, where the pipe centerline has reached the surface of the sea-bottom. The only resistance against further upward displacement of the pipe is thus the submerged weight of the pipe.

Design Parameters

The uplift behavior and corresponding required uplift resistance of buried pipelines operating at high temperatures should be predicted as accurately as possible when designing against upheaval creep "failure." However, as the uplift behavior of such pipelines is complex, the establishment of a realistic and safe design criterion requires a careful review of *all* parameters (e.g., pipe cross section geometry, pipe material, imperfection configuration, soil characteristics and operational conditions). In the following, the establishment of realistic design parameters for imperfection configurations and maximum allowable uplift movements will be commented upon.

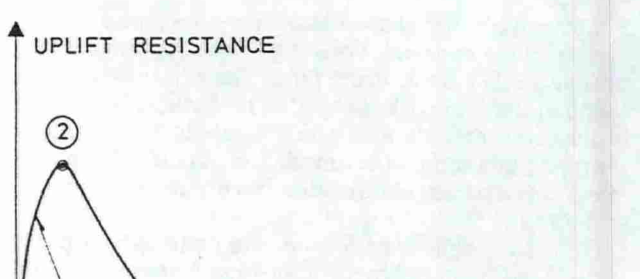

Fig. 6 Typical uplift resistance/displacement curve for a buried pipe

Establishment of Imperfection Configuration. Typical imperfection configurations which could be generated during the installation should be established already at the design stage, e.g., to assess the feasibility of using a particular installation technique and to identify critical imperfections in the lowered pipeline. The equilibrium shape of a propped pipe due to self-weight is considered to be a conservative and realistic imperfection configuration suitable for modeling installation-initiated imperfections. The mathematical expression for this equilibrium shape is given by (origin of x being the touchdown point)

$$w(x) = \frac{m_o}{72EI} x^3(2L_o - 3x) \qquad 0 \le x \le 0.5L_o \text{(symm.)}$$

$$w(x) = 0 \qquad x < 0 \qquad (2)$$

where m_o is the submerged weight and EI the bending stiffness of the pipe. Assuming the equilibrium shape given by equation (2), the relationship between the imperfection wavelength L_o and the corresponding imperfection amplitude A_o is uniquely defined by

$$L_o = (1152EIA_o/m_o)^{1/4} \qquad (3)$$

For a pipe in a trench, it is assumed that the cavity below the propped pipe will be filled with soil upon the subsequent backfilling process (either natural backfill or mechanically induced backfill), thus leaving the pipe on a foundation imperfection of the same shape as the "propped" pipe. Depending upon the imperfection size and the imposed temperature and pressure load, yielding can take place in the cross section of the out-of-straight pipe, thus resulting in a geometrical pipe imperfection in combination with foundation imperfection. In Pedersen and Jensen (1988) is indicated how the response of the pipeline depends on the amplitude and wavelength of the imperfection.

Finite Uplift Movement. Due to the nonlinear behavior of the soil, the ability of the uplifted pipe to recover to the original position depends upon the actual uplift movement. Therefore, in order to control the upward creep of an "imperfect" pipe, the uplift movement in each temperature cycle should be limited to the "elastic" deformation characteristics of the soil, i.e., between point 1 and 2 in Fig. 6. Otherwise, an upward racheting effect of the pipe movement is possible. This racheting may be caused partly by the inability to return to the original position and due to the buildup of a small residual axial compression in the pipeline at the side of the buckle. For pipes buried in a trench with natural backfill, an upward movement of 10–20 mm can be considered acceptable in most cases.

Design Examples

In the following, a rational design procedure will be presented by the use of examples.

Critical Imperfections. Consider an o.d. 12.75 in. pipe of 0.75 in. w.t. with a FBE coating. The submerged weight and moment of inertia of the pipe are 124.8 kg/m (water-filled) and 2.127×10^{-4} m^4, respectively.

Relevant imperfection parameters can be established using the relationship between imperfection amplitude and corresponding imperfection wavelength given by equation (3) (see Table 1). Due to extra weight from, e.g., installed anodes and the risk of soil load on top of the pipe during lowering, a somewhat increased submerged pipe weight could be considered, resulting in a reduced and thus more critical imperfection wavelength.

The maximum allowable uplift movement of the imperfect pipe depends upon the pipe-soil interaction characteristics (i.e., Fig. 6). As a guide, design values can be obtained by the use of equation (1), resulting in the maximum allowable uplift movements listed in Table 2. The uplift movement, which should be used in each case, depends upon the linearity of the pipe/soil interaction and the required safety margin.

Results from the nonlinear computer model described in Pedersen and Michelsen (1988) are presented in Fig. 7 showing pre and postbuckling equilibrium curves for different imperfection sizes at a burial depth of 1.5 m. In the analysis, it is assumed that the pipe has an initial geometric imperfection amplitude of 0.1–0.2 m over the imperfection wavelength.

It is noticed that the resulting uplift movement at peak temperature decreases with decreasing imperfection ampli-

Table 1 Imperfection parameters

Imperfection amplitude (m)	Imperfection wavelength (m)
0.2	53.8
0.3	59.6
0.4	64.0
0.5	67.7

Table 2 Design values for maximum allowable uplift movements for an o.d. 12.75 in. pipe and corresponding peak values for uplift resistance (analytical upper-bound solution)

Soil cover (m)	Design values for maximum allowable uplift movement 50 percent d_2 (m)	100 percent d_2 (m)	Peak uplift resistance (kN/m)
1.0	0.008	0.016	10.4
1.5	0.010	0.020	18.8
2.0	0.012	0.024	30.0

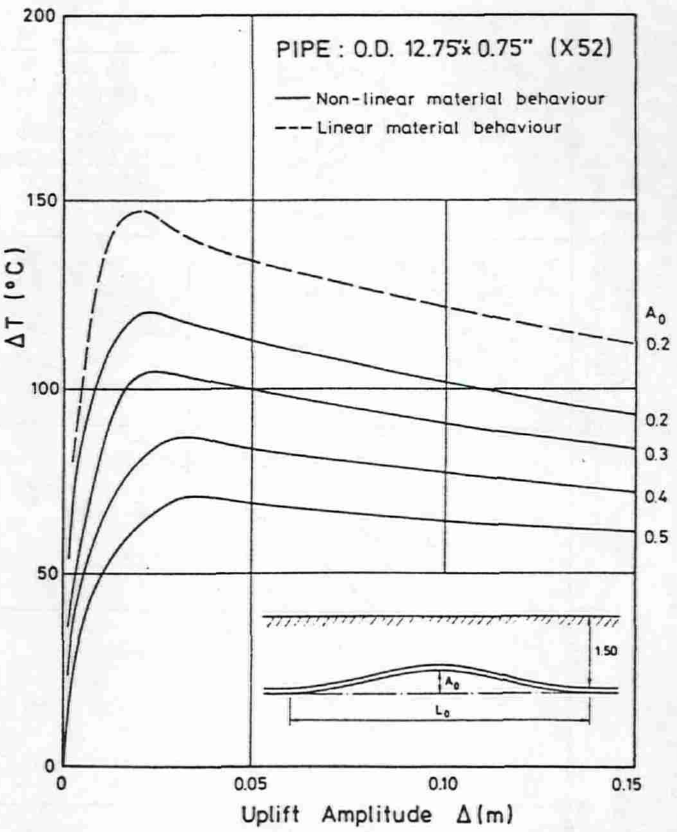

Fig. 7 Pre- and postbuckling equilibrium curves for different imperfection sizes

tude, while at the same time the "peaky" shape of the equilibrium curves becomes more distinct. Thus, when limiting the ift to 10–20 mm (Table 2) in order to prevent upheaval creep of the pipe, it is seen that the susceptibility to snap buckling increases when going from a 0.5 m imperfection to a 0.2 m imperfection. Therefore, in order to ensure that a small disturbance of the pipe will not result in a snap buckling failure, a "snap-through" design criterion must be considered in addition to the "upheaval creep" design criterion.

The width between the stable prebuckling and unstable postbuckling equilibrium curves is a natural measure of the safety margin against snap buckling. As a guidance, a width of minimum 0.1 m is considered to be acceptable in most cases.

A summary of further nonlinear computer analyses is presented in Fig. 8, showing critical temperatures as a function of soil cover for different imperfection sizes. The curves are produced under the constraint that the maximum uplift movement of the pipe is limited to the displacements given in Table 2 together with the "snap-through" buckling criterion. As can be seen from Fig. 8, the determination of a "critical" imperfection for a specified design temperature depends upon the amount of soil cover (the soil cover being measured relative to the "undisturbed" pipe sections to either side of the imperfection). The effect of taking the nonlinear behavior of the material into account becomes apparent for increasing soil cover and temperature.

To illustrate the use of the curves in Fig. 8, assume a specified design temperature difference $\Delta T = 80°C$ and that a soil cover of 1.5 m can be achieved by the lowering equipment. The critical imperfection amplitude is found to be of the order of 0.35 m (62 m wavelength), which is a strict lowering requirement indeed.

It is recognized that for certain pipeline configurations and design conditions, the resulting lowering requirement in terms of depth and out-of-straightness may be impractical for the construction equipment, procedures to be used and the local seabed conditions. In such cases, alternative installation methods, e.g., rock dumping, will have to be examined, although these are outside the scope of the present paper.

Influence of Pipe Cross Section on Critical Temperature. The relative influence on the critical temperature due to different pipe cross section parameters will be demonstrated by comparing the response from a bare pipe, a pipe with 1.5 in. concrete coating and a pipe with 2 in. of polyurethane insulation foam and 1.5 in. concrete coating. In all cases, the steel pipe is of 6.625 in. diameter and 0.432 in. wall thickness. The resulting submerged weight for each of the water-filled pipes reads 37 kg/m (bare pipe), 87 kg/m (concrete-coated) and 89 kg/m (insulated and concrete-coated). As a conservative assumption, only the steel pipe is considered to contribute to the bending stiffness.

The results are presented in a temperature versus imperfection amplitude coordinate system, Fig. 9, for a soil cover of 1.0 m. It is apparent that the pipe with concrete coating can sustain a lower equilibrium temperature than the bare pipe, whereas both of these exhibit lower equilibrium temperatures than the insulated pipe. Therefore, even though the increased diameter of the concrete-coated pipe mobilizes more uplift resistance compared to the bare pipe, the concrete also increases the submerged weight of the pipe resulting in a more critical imperfection configuration (i.e., smaller wavelength). However, by insulating the pipe the enlarged outer pipe diameter results in a substantial increase in uplift resistance which more than accounts for the critical imperfection configuration produced by the increased self-weight.

Post-Installation Inspection

Following installation of a buried pipeline which has been designed for high temperature service, it is important to verify that specified depth of lowering, level of backfill (either natural or installed), and out-of-straightness tolerance has been

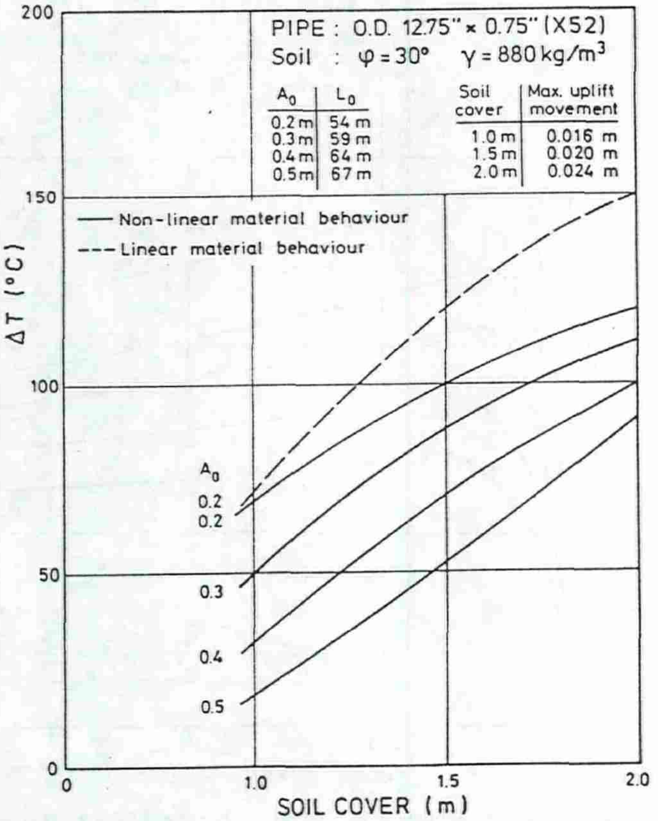

Fig. 8 Critical temperatures to prevent upheaval creep of a buried "out-of-straight" pipeline

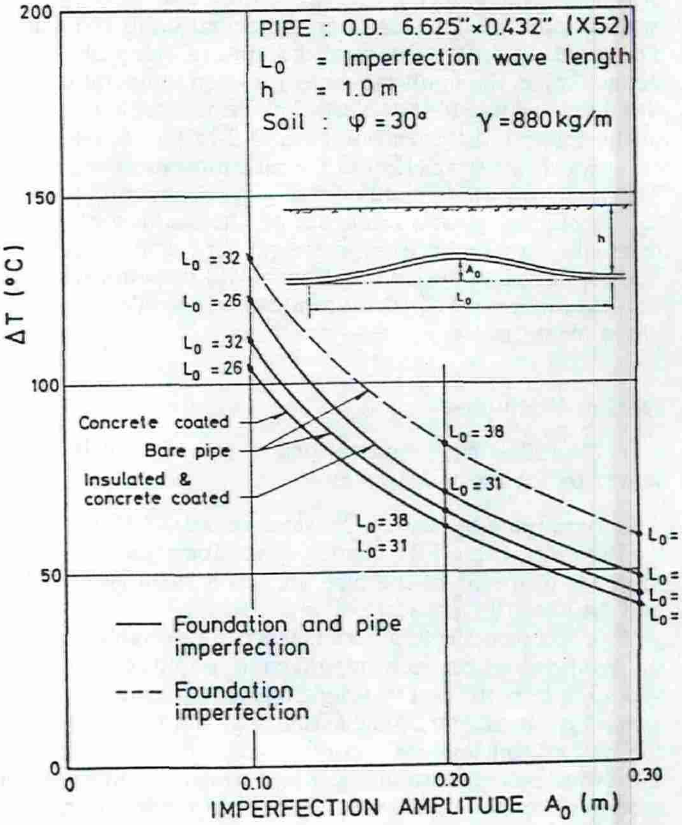

Fig. 9 Influence of pipe cross section on critical temperature

achieved. This will enable remedial action (e.g., rock dumping) to be taken in any areas which have not met the criteria.

The vertical out-of-straightness and depth of burial of a buried pipe can be determined utilizing a sub-bottom profiler survey, provided that the survey crossings are carried out with sufficient frequency to resolve the pipe undulations. As a governing rule, the pipe should be crossed at intervals less than half the critical buckling length (i.e., uplifted pipe length) in order to reveal pipe sections susceptible to upheaval creep. However, it should be noted that the survey accuracy is limited, typically to 0.10–0.15 m for a soil cover of 1.0–1.5 m. Consequently, the emphasis should be on ensuring that the installation method chosen can achieve the specified level of accuracy with confidence, and then using the survey to confirm that the specifications have been met.

Conclusion

A new design criterion has been established for design against upheaval creep of buried sub-sea pipelines subject to variations in temperature loading.

The classical upheaval buckling approach of using the trough of the U-shaped postbuckling equilibrium curves in the temperature versus buckling wavelength plane (or temperature versus uplift movement plane) as design criterion is not applicable when designing against upheaval creep of buried imperfect pipelines. The new design procedure determines the uplift resistance required to keep the upward movement of imperfect pipe sections below critical values, thus preventing a progressive upheaval failure. For pipes buried in a trench with a natural backfill, an uplift movement of 10–20 mm can be considered acceptable in most cases.

Distinction is made between foundation imperfections and geometric pipe imperfections, and the paper shows that a pipeline which was originally installed with foundation imperfections only, can undergo local plastification in the pipe cross section when subjected to the operational conditions. Consequently, a combination of foundation imperfection and some geometric pipe imperfection must be considered for pipe undulations exceeding a certain critical size.

For design purposes, an installation initiated imperfection configuration is proposed corresponding to the equilibrium shape of a propped pipe due to self-weight. The cavity below the propped pipe is assumed filled with soil upon the subsequent backfilling process, thus leaving the pipe on a foundation imperfection of the same shape as the "propped" pipe.

The design examples demonstrate that extremely tight installation tolerances for the pipe out-of-straightness are required in certain cases if yielding is not allowed in the pipe cross section of a buried pipe operating at elevated temperatures (e.g., out-of-straightness less than about $1/150 - 1/250$). Therefore, it is contended that stress relaxation of such pipelines must be expected in practice. Also, the design examples show that, in order to prevent upheaval creep of a buried pipeline, the lowering of the pipe must be controlled such that the pipe out-of-straightness does not exceed critical values. For certain high-temperature pipelines this may require alternative design and installation methods (e.g., rock dumping) to be employed.

References

Pallesen, T. R., Braestrup, M. W., Jørgensen, O., and Andersen, J. B., 1985, "Insulated Pipeline Design for the Danish North Sea," *6th International Conference on the Internal and External Protection of Pipes*, Nice, France, November 5–7, pp. 189–202; also, *Oil and Gas Journal*, Vol. 84, No. 17, April 21, 1986, pp. 50–56.

Kerr, A. D., 1974, "On the Stability of the Railroad Track in the Vertical Plane," *Rail International*, Vol. 5, pp. 131–142.

Ju, G. T., and Kyriakides, S., 1987, "Thermal Buckling of Offshore Pipelines," EMRL Rep. No. 87/1, Department of Aerospace Engineering and Engineering Mechanics, University of Texas Austin, Jan.

Pedersen, P. T., and Michelsen, J., 1988, "Large Deflection Upheaval Buckling of Marine Pipelines," *Proceedings of Behaviour of Offshore Structures (BOSS)*, Trondheim, Norway, June.

Pedersen, P. T., and Jensen, J. J., 1988, "Upheaval Creep of Buried Heated Pipelines with Initial Imperfection," *Journal of Marine Structures, Design, Construction and Safety*, Vol. 1, Elsevier Applied Science.

Trautmann, C. H., O'Rourke, T. D., and Kulhawy, F. H., 1985, "Uplift Force-Displacement Response of Buried Pipe," *Journal of Geotechnical Engineering*, Vol. III, No. 9, Sept.

Boer, S., Hulsbergen, C. H., Richards, D. M., Klok, A., and Biaggi, J. P., 1986, "Buckling Considerations in the Design of the Gravel Cover for a High Temperature Oil Line," Offshore Technology Conference, OTC Paper No. 5294.