

UPHEAVAL BUCKLING OF PIPELINES

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DESIGN AND ENGINEERING PRACTICE



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1. INTRODUCTION

1.1 SCOPE

This DEP specifies requirements and gives recommendations for assessing the risk of upheaval buckling of offshore pipelines and provides alternatives for corrective action prior to or after pipeline construction to prevent upheaval buckling occurring.

The design equations in this DEP apply to single-pipe pipeline concepts. From these equations, design equations for other concepts such as pipe-in-pipe may be derived.

Generally applicable definitions and requirements for pipeline engineering can be found in DEP 31.40.00.10-Gen.

The principles described in this DEP may also be used to assist with the design of on-land pipelines against upheaval buckling.

This DEP is a revision of the DEP of the same number dated December 1998; see (1.6) regarding the changes.

1.2 DISTRIBUTION, INTENDED USE AND REGULATORY CONSIDERATIONS

Unless otherwise authorised by Shell GSI, the distribution of this DEP is confined to Shell companies and, where necessary, to Contractors and Manufacturers/Suppliers nominated by them.

This DEP is intended for use in oil refineries, chemical plants, gas plants, exploration and production facilities and, where applicable, supply/marketing installations.

When DEPs are applied, a Management of Change (MOC) process should be implemented; this is of particular importance when existing facilities are to be modified.

If national and/or local regulations exist in which some of the requirements may be more stringent than in this DEP the Contractor shall determine by careful scrutiny which of the requirements are the more stringent and which combination of requirements will be acceptable as regards safety, environmental, economic and legal aspects. In all cases the Contractor shall inform the Principal of any deviation from the requirements of this DEP which is considered to be necessary in order to comply with national and/or local regulations. The Principal may then negotiate with the Authorities concerned with the object of obtaining agreement to follow this DEP as closely as possible.

1.3 DEFINITIONS

1.3.1 General definitions

The **Contractor** is the party which carries out all or part of the design, engineering, procurement, construction, commissioning or management of a project, or operation or maintenance of a facility. The Principal may undertake all or part of the duties of the Contractor.

The **Principal** is the party which initiates the project and ultimately pays for its design and construction. The Principal will generally specify the technical requirements. The Principal may also include an agent or consultant, authorised to act for, and on behalf of, the Principal.

The word **shall** indicates a requirement.

The word **should** indicates a recommendation.

1.4 SYMBOLS

b	breadth of the geotextile (measured transverse to the pipeline)
D	outside diameter
D'	outside diameter + mattress thickness
E	elastic modulus (Young's modulus)
f	uplift resistance coefficient
f'	limiting longitudinal frictional resistance per unit length
h	height of isolated hill in profile
H	$1/2$ peak-to-trough height of seabed profile (Figure 2.4); cover height (2.4) (Figure 2.8)
L	$1/2$ wavelength of seabed profile
L _i	horizontal distance between i th and i+1 th inflection point
m	mass flow rate
M	bending moment
p	operating pressure
N _e	axial force (longitudinal compressive force)
q	downward force per unit length required to hold pipeline in position
r	uplift resistance per unit length
r'	additional uplift resistance per unit length from geotextile
R	mean radius, $1/2$ (outside pipe diameter minus wall thickness)
S	shear force
s _L	longitudinal stress
t	wall thickness
T _R	residual tension
U	flow velocity (mean across pipe cross-section)
w	weight per unit length of pipeline (2.3.3.3); weight per unit area of mattress (3.4)
x	horizontal distance along pipeline
y	height of pipeline from datum
z	height of seabed from datum (2.3.3.1); distance over which movement extends (2.2.2)
α	linear thermal expansion coefficient
γ	submerged unit weight of cover
Δ	height of prop imperfection
μ	coefficient of friction between rock and geotextile
μ'	coefficient of friction between geotextile and seabed
ν	Poisson's ratio
ΔT	difference between operating temperature and installation temperature (positive if operating temperature is higher than installation temperature)

1.5 CROSS-REFERENCES

Where cross-references to other parts of this DEP are made, the referenced section number is shown in brackets. Other documents referenced in this DEP are listed in (7) and (8).

1.6 SUMMARY OF MAIN CHANGES SINCE PREVIOUS EDITION

The previous edition of this DEP was dated December 1998. This revision has been editorial, with no significant technical changes.

1.7 COMMENTS ON THIS DEP

Comments on this DEP may be sent to the DEP Administrator at standards@shell.com. Shell staff may also post comments on this DEP on the Surface Global Network (SGN) under the Standards folder. The DEP Administrator and DEP Author monitor these folders on a regular basis.

2. ASSESSMENT OF RISK OF UPHEAVAL

2.1 INTRODUCTION

Upheaval buckling occurs in buried pipelines that operate at high temperatures and pressures. Figure 1.1(a) shows a dramatic example in a land pipeline bowing upward in a long raised loop, and Figure 1.1(b) a buckled marine pipeline (8.1). The line can be deformed to an unacceptable extent, and/or the buckle may move it into a position in which it is exposed to other kinds of damage. For instance, an underwater line bowed above the seabed becomes exposed to damage by fishing trawls and by current/wave action.

Upheaval buckling has been known for a very long time as a problem of land pipelines, but at first was generally believed not to affect underwater pipelines. Since the late 1980s it has been recognised as a serious problem. The earliest and best-documented example was the 8-inch Rolf to Gorm pipeline in the Danish sector of the North Sea (8.1), but there have been many other instances in the British, Norwegian and Danish sectors. None of them has yet led to a loss-of-containment incident, but the problem has been recognised as potentially serious. Industry sensitivity to the problem has been increased by a continuing trend towards higher operating pressures. Operating temperatures above 100 °C are nowadays commonplace, and temperatures well above 150 °C are being considered. At such temperatures almost every trenched or buried pipeline has an upheaval problem.

Figure 1.2 provides a systematic approach to upheaval buckling, and cross-references the relevant sections in this DEP.

This Section describes how to assess whether or not there is a risk of upheaval. The assessment proceeds in four steps.

The first step is the calculation of driving force, and is covered in (2.2). Three aspects are covered: (2.2.1) covers fully-constrained lines, (2.2.2) covers partially constrained lines, and (2.2.3) discusses residual tension.

The second step is the determination of the total downward force required for the pipeline to stay in position without upheaval: this step is covered in (2.3).

The third step is the calculation of the available uplift resistance from pipeline weight, and weight and shear resistance of the pipeline cover if the line is buried: this step is covered in (2.4).

The fourth step is the comparison between the required downward force and the available downward force, described in (2.5).

2.2 DRIVING FORCE

2.2.1 Driving force: fully-constrained pipelines

The driving force that creates the upheaval buckling is the longitudinal compressive force in the restrained pipeline and its contents.

One component of this force is due to temperature increase. A second component of the driving force is due to pressure, which generates a compressive force resultant over the whole cross-section, taking the fluid contents and the pipe wall together. The third component is the residual tension left by laying, and is subtracted from the other two.

The longitudinal compressive force N_e in the wall and contents together induced by the operating temperature and pressure and the residual tension is

$$N_e = (1-2\nu)\pi R^2 p + 2\pi R t E \alpha \Delta T - T_R \quad (\text{equation 2.2.1})$$

If the operating pressure p and temperature increase ΔT are each positive or zero, as is usually the case, N_e is positive.

The notation is listed below:

pipeline dimensions;

- t wall thickness
- R mean radius, $\frac{1}{2} (D - t)$

material properties;

- E Young's modulus (elastic modulus)
- ν Poisson's ratio
- α linear thermal expansion coefficient

operating conditions;

- p operating pressure
- ΔT difference between operating temperature and installation temperature (taken as positive if the operating temperature is higher than the installation temperature)

construction parameters;

- T_R residual tension, see (2.2.3).

It is important to avoid over-conservative choices of operating parameters. The calculation of the driving force at a particular point on the pipeline should take account of the predicted temperature and pressure profiles **along** the line, and not use the maximum values at pipeline inlet. Production profiles and reservoir analysis might indicate that the maximum operating temperature might not occur at the same time as the maximum operating pressure: the design longitudinal force should then be based on the worst combination that can occur, rather than on the two individual maxima.

The magnitudes involved can be seen by a sample calculation, for the following parameters:

Outside Diameter	273.05	mm (nominal 10-inch)
t	11.3	Mm
E	210000	N/mm ²
ν	0.3	
α	1.17×10^{-5}	/°C
p	30	N/mm ² (300 bar)
ΔT	100	°C
T_R	500	KN

and then

$(1-2\nu)\pi R^2 p$	0.65	MN
$2\pi R t E \alpha \Delta T$	2.28	MN
T_R	0.50	MN
N_e	2.43	MN

Equation 2.2.1 and this sample calculation both assume that the pipeline remains elastic. If in fact the pipeline is no longer elastic but has reached yield under the design operating

conditions, as it might do if strain-based design has been adopted, then the calculation of longitudinal force shall take account of yield.

2.2.2 Quantification of driving force: partial longitudinal constraint

Pipelines are not always fully constrained. At an elbow connecting a pipeline to a platform riser, for instance, the pipeline is free to expand towards the platform, because the riser is flexible by comparison with the pipeline. Similarly, an expansion loop is incorporated in order to allow a pipeline to expand, and this expansion reduces the axial force N_e .

Figure 2.1 illustrates one simple case, a vertical riser connected through an elbow to a seabed pipeline. At the elbow, the total longitudinal force is the shear force S in the vertical arm between the elbow and the lowest clamp. As far as the pipeline is concerned, S is usually negligible in comparison with the axial force defined in equation 2.2.1.

The expansion movement of the pipeline towards the platform is resisted by seabed friction. If the frictional force between the pipeline and the seabed is f' per unit length, the axial force at a distance x from the platform is $S+f'x$, up to the point at which the axial force becomes equal to the force in a fully-constrained line.

If the operating pressure and temperature are uniform along the length of the line, and the residual tension T_R is negligible, the distance z at which the axial force reaches the fully-constrained value is

$$z = \frac{1}{f'}(1 - 2\nu)\pi R^2 p + 2\pi R t E \alpha \Delta T - S) \quad (\text{equation 2.2.2})$$

Accordingly, if $x < z$

$$N_e = f' x + S \quad (\text{equation 2.2.3})$$

but if $x > z$, N_e is given by equation 2.2.1 as before.

This theory can be generalised (8.2) to the case where the temperature is not uniform but decreases exponentially with distance from the platform, and to the case where the longitudinal resistance f' is not uniform with distance along the pipeline. It can readily be generalised further to the case where the pressure is non-uniform, but this is in practice a small effect.

If a lateral or upheaval buckle occurs, the pipeline generally comes to rest with the longitudinal force in the buckle less compressive than the force before the buckle occurred. The pipeline moves longitudinally towards the buckle, but these movements too are resisted by frictional resistance from the seabed. The effect on the longitudinal force in the pipeline is illustrated in Figure 2.2. As far as the force in the rest of the pipeline is concerned, the buckle behaves rather like an expansion loop, and reduces the longitudinal force on either side. For this reason, buckles rarely occur close together.

The longitudinal frictional force per unit length f' must be chosen thoughtfully. It is usually calculated by multiplying the submerged weight per unit length by a friction coefficient μ , but the appropriate value is often uncertain. Soil mechanics indicates that μ is to be expected to be about 0.5 on frictional soils such as sand, but lower on stiff clay. Calculations from expansion movements measured in the field suggest higher values, about 0.9, probably because of the effect of small lateral movements.

It is not always conservative to assign a low value to μ . If μ is assumed smaller than the correct value, f' is smaller and z is larger than the correct value, so that a low value of μ will indicate that the partial restraint reduces the longitudinal force below the fully-constrained value over a longer distance. Calculations should therefore be made for a high value and a low value, and the worst case used in design.

2.2.3 Residual tension

The residual effective tension T_R on the seabed can be calculated with a laystress calculation programme.

If the line is installed by pull or tow, the residual tension is the pull force or the tow force.

Relaxation of the installation tensions should be evaluated.

External pressure should not be incorporated in the longitudinal force as the pipeline is not restrained when external pressure is applied during installation (8.3).

2.3 STABILISATION AGAINST UPHEAVAL

2.3.1 Upheaval

A longitudinally compressed pipeline tends to lift upwards on overbends ('hills') in the profile, and to move downwards on sagbends ('valleys'). There is almost always a high degree of resistance to downward movement, which is of little concern. There is much less resistance to upward movement, which may lead to upheaval.

Once the pipeline begins to move upward, the external force required to hold it in position almost always increases, whereas the external resistance to movement almost always decreases. Generally, the pipeline becomes unstable soon after it starts to move, and then 'jumps' into a new position with very much larger deflections. This is the kind of upheaval it is important to avoid.

The strategy adopted in this DEP is to find the external force required to hold the pipeline against upheaval, and to check whether that force can be supplied by weight or by forces exerted by the surroundings.

2.3.2 Is the pipeline profile fixed or can it change ?

Two cases have to be distinguished when assessing the profile of a pipeline.

In the first case the pipeline profile is fixed, because the pipe is continuously (or almost continuously) in contact with a foundation, such as a trench or the seabed, to hold the pipeline in that position. This case is examined in (2.3.3).

In the second case the pipeline is not continuously supported everywhere and its profile may change during start-up. Also, stabilisation measures such as rock dumping may themselves change the pipeline profile. This case is examined in (2.3.4).

2.3.3 Stabilisation in a fixed profile

2.3.3.1 General profile

The external force required to keep a pipeline in equilibrium depends on the pipe profile. Figure 2.3 shows a pipeline profile and a seabed profile. Horizontal distance is denoted by x , measured from an arbitrary datum. The height of the pipeline is denoted y , measured upwards from an arbitrary datum. The height of the seabed (or, for a trenched pipeline, the trench bottom) is denoted z , measured upwards from the same datum. y and z may not be the same, because the pipeline can lose conformity with the seabed by lifting off it.

From applied mechanics theories, the external force per unit length required to hold the pipe in position is:

$$q = N_e \frac{d^2 y}{dx^2} - \frac{d^2 M}{dx^2} \quad (\text{equation 2.3.1})$$

If the curvature $d^2 y/dx^2$ is less than the yield curvature, the bending moment M is proportional to the curvature $d^2 y/dx^2$. The constant of proportionality is the flexural rigidity EI , so that:

$$M = EI \frac{d^2 y}{dx^2} \quad (\text{equation 2.3.2})$$

where I is the second moment of area of the cross-section and can be taken as $\pi R^3 t$, which neglects ovalisation.

Substituting into equation 2.3.1,

$$q = -N_e \frac{d^2 y}{dx^2} - EI \frac{d^4 y}{dx^4} \quad (\text{equation 2.3.3})$$

Equation 2.3.1 is always applicable. Equation 2.3.3 is applicable if the pipe is known not to have bent so far that it has yielded.

These equations can be used to find the force required to keep the pipeline in position. If the pipe profile is known or can be calculated, the profile can be differentiated to determine the curvature $d^2 y/dx^2$ and its second derivative $d^4 y/dx^4$, and then the equations determine the external force needed to hold the pipeline in position. If the profile does not change when the longitudinal force is increased, and if there is enough external force available to keep the pipe in position, the pipeline does not move and upheaval does not occur.

2.3.3.2 Sinusoidal profile

A continuous supported sinusoidal profile is shown in Figure 2.4. It is composed of regular 'waves' of height $2H$ and wavelength $2L$, described by the equation:

$$y = H(1 - \cos \pi x / L)$$

so that:

$$\frac{d^2 y}{dx^2} = H \left(\frac{\pi}{L} \right)^2 \cos \pi x / L \quad (\text{equation 2.3.4})$$

$$\frac{d^4 y}{dx^4} = H \left(\frac{\pi}{L} \right)^4 \cos \pi x / L \quad (\text{equation 2.3.4})$$

From equation 2.3.3:

$$q = \left(N_e H \left(\frac{\pi}{L} \right)^2 - EI \left(\frac{\pi}{L} \right)^4 \right) \cos \pi x / L \quad (\text{equation 2.3.5})$$

The largest required downward force $q_{\max}$ occurs on the summit of the hills when $x = L$, and is

$$q_{\max} = N_e H \left(\frac{\pi}{L} \right)^2 - EI \left(\frac{\pi}{L} \right)^4 \quad \text{if } L > 4.44 \sqrt{\frac{EI}{N_e}} \quad (\text{equation 2.3.6})$$

$$q_{\max} = \frac{1}{4} \frac{N_e^2 H}{EI} \quad \text{if } L \leq 4.44 \sqrt{\frac{EI}{N_e}} \quad (\text{equation 2.3.6})$$