Pipeline Technology—Expansion and Global Buckling

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1 INTRODUCTION

1.1 Expansion and restraint

Pipelines that operate at a temperature and pressure above the condition at which they were installed will tend to expand. If the pipeline is not free to expand, it will develop an axial compressive force. While the ends of the pipeline are usually free to expand, the axial resistance provided by the soil beneath and around the pipe will gradually increase with distance from the free end, until the force is sufficient to prevent movement; the condition of "full constraint." Any physical restraint, provided by attachments to the pipe such as end termination structures or connections, will add to this resistance and increase the restraining forces. The section of pipeline that reaches "full constraint" will experience no expansion or contraction under operating conditions. Many pipelines never reach a condition of full constraint, either because they are too short or because they buckle. Nevertheless, the "fully constrained" condition is an important concept in defining pipeline expansion and buckling behavior.

1.2 Pipeline buckling

It is most unlikely that a submarine pipeline can be installed perfectly straight, and any out-of-straightness will create a condition of potential instability that can lead to Euler (column) buckling. Buckling occurs at locations where the axial force and out-of-straightness are sufficient to overcome the vertical and lateral resistance provided by the soil, combined with the resistance provided by the weight and bending stiffness of the pipe.

Global buckling of a pipeline can occur either vertically (upheaval buckling) or horizontally (lateral buckling). A pipeline will tend to form a lateral buckle if it is laid on the seabed. Lateral buckling may often be tolerated in a lowly loaded pipeline, whereas it may be deliberately encouraged in a highly loaded pipeline, to relieve the axial compressive load.

If the pipeline is installed in a trench, then the lateral restraint provided by trenching or backfill will tend to cause upheaval buckling. Upheaval buckling is usually considered a precursor to pipe failure because the pipe is exposed and highly restrained by the backfill or burial.

However, a trench is not essential for upheaval buckling, which may also be triggered by any vertical out-of-straightness feature, such as an uneven seabed, or preinstalled feature beneath the pipe (Figure 1). In such cases, the initial upheaval will usually translate into a lateral buckle as pipe expansion feeds and grows the buckle. In all

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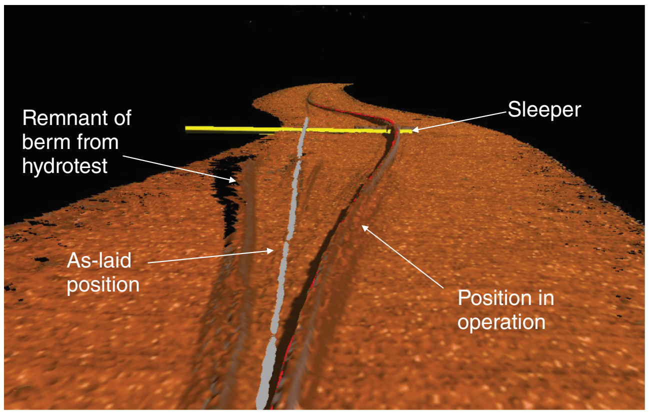

Figure 1. Survey of a lateral buckle on a sleeper of using high resolution digital terrain mapping.

cases, considerable displacements may occur as the global buckle forms.

This leads to two distinctly different design strategies:

1. *Upheaval Buckling* is considered in the design of trenched and buried pipelines; the design aim is to prevent buckling.
2. *Lateral Buckling* is considered in the design of pipelines laid on the seabed; the design aim is to encourage and control buckling at regular intervals along the pipe.

1.3 Pipeline walking

Pipeline walking is a phenomenon in which the pipe displacement can ratchet in the axial direction due to periodic variations in the operating conditions. It is usually associated with pipelines laid on the seabed or in an open trench and is caused by differential expansion and contraction of a pipeline along its length, which can lead to high cumulative end expansion leading to jumper or riser failure.

Design solutions must address the potential need to control walking, as well the interaction that occurs between pipeline walking and buckling. Controlling walking requires the pipeline to be restrained by adding weight (e.g., rock dump) or installing pipeline anchors.

1.4 Integrity monitoring surveys

Buckle formation is strongly influenced by pipe–soil interaction (PSI) and out-of-straightness and to a lesser extent, residual lay tension, which all carry significant uncertainty in design and remain unknown until after a pipeline has been installed. Therefore, a careful review of high resolution positional surveys (Figure 1) and monitoring of ends displacements, from installation, postinstallation, and poststartup, significantly reduces the level of uncertainty associated with the assumptions made in design and forms an essential input to monitoring long-term integrity in operation (Watson *et al*., 2011).

2 DESIGN FOR BUCKLING

2.1 Pipeline expansion

For a pipeline in which the ends are free to expand, the effective axial force is zero at the ends[1] and gradually increases due to axial interface friction with the seabed, as illustrated in Figure 2. For the high axial friction case, the pipeline develops a fully constrained section in the middle bounded by virtual anchor points. In this figure, the fully constrained force is shown to reduce slightly along the pipeline length, indicating that the operating temperature reduces along the pipeline. Between these virtual anchor points, the frictional restraint is sufficient to suppress any expansion and the axial strain in the pipe is zero. Expansion only takes place between each virtual anchor and the pipeline end.

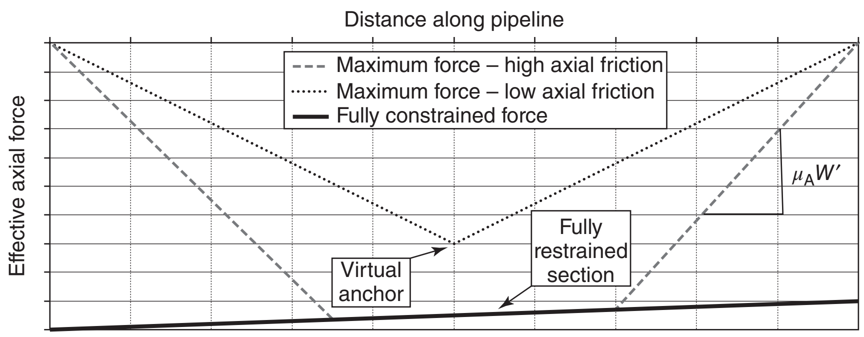

Figure 2. Effective axial force and expansion in a straight pipeline (example).

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The gradual increase in effective axial force, from zero at the free ends to full constraint, is due entirely to the cumulative axial restraint provided by the seabed. The slope of the force profile in this expansion zone is equal to the axial resistance (force) per unit length, which is typically modeled as being "frictional," being linked to the (submerged) pipeline weight per unit length (W_P), by an axial friction coefficient (μ_a). This maximum axial force profile is used to assess the susceptibility to buckling.

If the pipeline is short, or the axial resistance is low, the overall length may be insufficient to reach a condition of full restraint, as illustrated in Figure 2 for the low axial friction case. Instead, the pipeline forms a virtual anchor close to the center and expands outward from this point. In this case, the maximum axial force is significantly below the fully constrained force and the displacement at the virtual anchor is zero, but the axial strain is not.

This defines two groups of pipelines:

- Pipelines that develop the fully constrained axial force, typically long pipelines;
- Pipelines that never develop the fully constrained axial force, typically short pipelines.

In all cases, the profile of effective force along the pipeline defines the susceptibility to buckling. In the event of buckling, the pipe will expand into the buckle and out toward the ends, with virtual anchor points forming at the point where the direction of pipe expansion changes. If buckles do occur, the relief of force into the buckles means that long pipelines may never reach full constraint (Figure 3).

This maximum axial force profile and the fully constrained force profile are fundamental to pipeline design because they define the axial load in the pipe when it is restrained and pipeline expansion over those sections that are not fully constrained. Expansion is derived directly from the difference between the fully constrained force profile and the maximum force profile, which is defined by axial friction and the location of buckles, virtual anchors, and free ends. The axial strain at any point along a pipeline is defined by:

$$\varepsilon_A = (S - S_0)/E \qquad (1)$$

which may be integrated over the pipe length to find the end expansion.

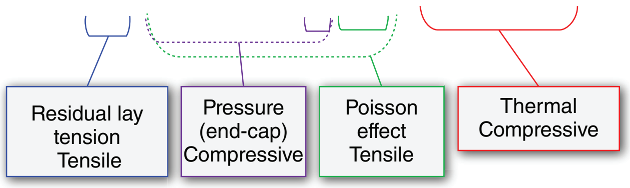
2.2 Pipeline effective force

The fully constrained force profile presented in Figures 2 and 3 is the effective axial force, which drives the structural response of the pipeline. The effective force is made up of the (true) force in the pipe wall and the pressure-induced axial force:

$$S = S_w + p_e \cdot A_e - p_i \cdot A_i \qquad (2)$$

For a straight pipeline with fixed ends, the axial strain is zero everywhere and the force developed in the system is known as the fully constrained effective force, which is usually defined (based on true thick-wall shell theory) as:

$$S_0 = S_L - ([p_i - p_{iL}] \cdot A_i) \cdot (1-2 \cdot \nu) - E \cdot A_s \cdot \alpha \cdot \Delta\theta$$



(3)

This equation shows that restrained effective force is independent of external hydrostatic pressure, which is already imposed in the pipe lay catenary before the pipeline reaches the seabed (Figure 4). However, external pressure influences the load distribution due to hoop stress, and the axial stress defined by the wall force (defined in Equation 2) can be

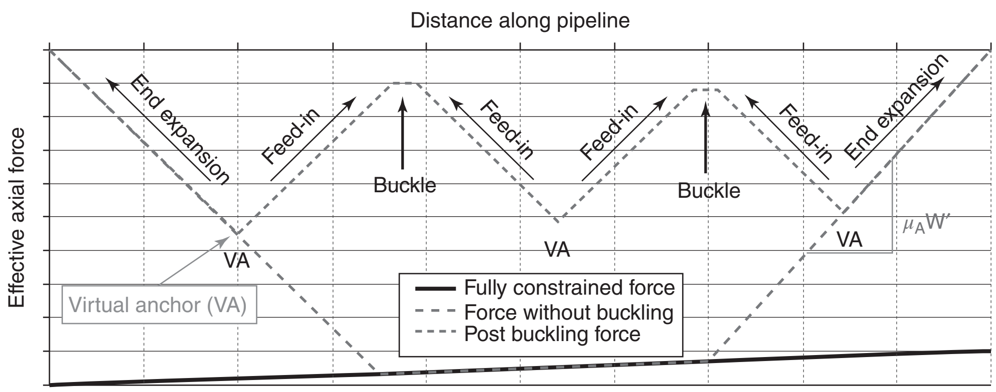


Figure 3. Effective axial force and postlateral buckling force (example).

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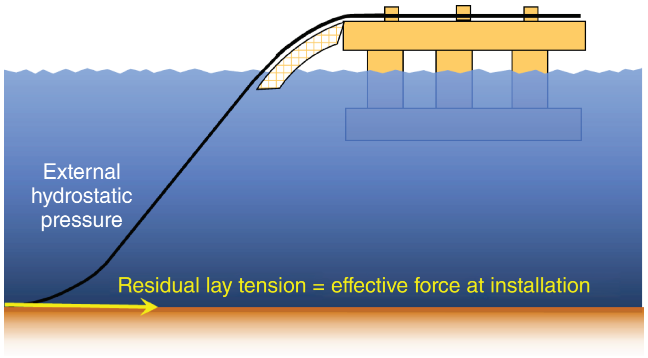

Figure 4. Residual lay tension from installation.

significantly modified by it. This is an important consideration in a buckle-sensitive pipeline. After installation, some residual effective lay tension remains in a pipeline. This force is usually small in comparison with the forces that develop in operation.

2.3 Pipeline expansion spools and end restraint

Pipeline ends usually expand freely by means of “expansion spools” or “jumpers” that connect the pipeline to a subsea facility (such as a manifold or well), or to a pipeline riser connected to a surface production facility.

The purpose of the expansion spool or jumper is threefold:

1. To allow the pipeline to be installed separately from the subsea facility or riser, which can then be precommissioned prior to connection by divers or by ROV (remote operated vehicle);
2. To provide an installation tolerance between the pipeline end and the subsea facility, so that the final dimensions of the spool can be fabricated to fit, based on subsea metrology;
3. To absorb expansion and contraction of the flowline in operation without overloading the spool or the mechanical connections at each end of the spool.

The loads due to expansion and contraction in operation are often critical in determining the size of the expansion spool. In general, the greater the expected end expansion is, the greater will be the length of the spool required. There is a clear incentive to minimize the total end expansion, to reduce the size of the connecting spool, installation vessel, and crane.

In some cases, expansion is prevented by being buried over a significant length, such as at a landfall, or because the pipeline end termination is fixed by a foundation or pile. In such cases, the fixed end may experience the fully constrained force exerted by the pipeline.

2.4 Pipe–soil interaction

PSI influences the behavior of the pipe during and after installation (Bruton *et al*., 2006, 2008). The resistance to pipeline penetration in the catenary touchdown zone during installation defines the initial pipeline embedment, which usually exceeds the static self-weight embedment, for two reasons:

1. Additional static vertical load concentration in the touchdown zone;
2. Dynamics of the lay process arising from vertical and lateral catenary oscillations that load the soil in the touchdown zone, displacing and weakening the soil.

The installed embedment then influences subsequent lateral and axial soil resistance. In clay soils, the remolded soil around the pipe following installation reconsolidates under the weight of the pipe, influencing the subsequent additional penetration that can occur upon flooding and modifying the initial axial resistance associated with pipeline start-up.

When a pipeline is trenched and buried in clay to prevent upheaval buckling, the backfill soil is also remolded during the trenching and backfilling process, leaving a weakened soil that needs time to reconsolidate and regain strength. Rock is often added on top of the backfill to increase the download required to prevent upheaval buckling. Upheaval buckling design requires good characterization of the soil and backfill to define the uplift resistance with vertical displacement.

When a pipeline is designed to laterally buckle, the pipe must first break out from the as-laid position overcoming the lateral breakout resistance, and move across the seabed, typically by several diameters, overcoming the lateral residual resistance. The pipe may then cycle back and forth across the seabed as operating conditions change, mobilizing berms of soil that increasingly restrain the pipe and prevent relaxation of buckle curvature. This soil behavior, from initial breakout through to the large displacement response, is well outside the bounds of conventional geotechnics or extensive earlier pipe–soil research on hydrodynamic stability (Bruton *et al*., 2008).

It is clear that a good understanding of PSI is critical to structural modeling of upheaval and lateral buckling, since the pipe–soil response is the largest uncertainty in the design. Generic guidance is available to guide the design process, but project-specific physical model testing is often necessary (Bruton et al 2009). The properties of the soil are usually

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established by an offshore geotechnical site investigation carried out along the route of the pipeline (*see* **Geotechnical Site Investigation and in Situ Testing**). It is essential to have good geotechnical data, to depths of about 2 m, to derive reliable PSI responses. Effective coordination between suitably experienced geotechnical and pipeline engineers is essential. Uncertainty in soil properties or an absence of data can lead to high levels of conservatism in design or an unmanageable design process.

For more information on PSI, *see* **Pipeline-Seabed Interaction**.

2.5 Pipeline buckling design limit states

Global pipeline buckling may not lead to failure unless bending of the pipe is severe enough to reach a failure limit state. "Global" buckling is distinguished from "local" buckling of the pipe cross section, which is normally associated with failure.

High stresses and strains can develop in a buckle, so that conventional stress-based design is generally unsuitable. The conventional stress (or moment) limit is therefore relaxed and replaced by a strain limit. However, in doing so the design must address issues associated with strain localization. This leads to the following failure modes or limit design states, associated with global buckling:

1. *Local Buckling*—deformation of the pipe cross section including wrinkling or bifurcation buckling, where the load is defined by the imposed mechanical strain due to bending and axial effective force; local buckling is also influenced by internal or external overpressure and the stress–strain response of the pipe material.
2. *Fatigue and Fracture*—crack growth under low frequency cyclic loading, caused by operational shutdown–restart cycles. Fatigue and fracture must take account of stress concentrations, corrosive environments, and loading frequency. The low frequency loading in a buckle, combined with internal and external corrosive environments can reduce the fatigue life by a significant margin (Baxter and Tubby, 2011). For more information, *see* **Pipeline Fatigue and Fracture Design**.
3. *Plasticity*—the imposed strain should not exceed the uniform strain capacity of the pipe material under high levels of effective force. In some sour corrosive environments, plasticity may not be permitted.
4. Supplemental limit states that can influence the buckling design solution include the potential for external interference, such as snagging, or vibration of spans due to slugging, or vortex-induced vibration.

2.6 Buckling mitigation of effective force

Buckling can be mitigated by reducing the effective force in the system, for example, by installing in-line expansion spools or by the use of cooling spools to reduce the fluid temperature. However, such mitigation measures can have significant cost implications. Alternatively, the pipeline might be installed at above ambient temperature, which is common for highly insulated systems because the pipe does not have sufficient time to cool down from surface deployment temperatures during its transition through the lay catenary (Anderson *et al*., 2007). However, this effect may not be relied upon as a mitigation method, since pipeline installation could be interrupted by unforeseen events that allow the pipeline to cool down prematurely. Nevertheless, partial cooling of the pipe in the lay catenary is known to alleviate buckling loads and inhibit buckle formation.

3 UPHEAVAL BUCKLING

3.1 Introduction to upheaval buckling

Upheaval buckling design methodologies aim to prevent buckling. Upheaval buckling was first encountered on landlines and since then has been experienced on many trenched or buried submarine pipelines. Pipelines are frequently trenched and sometimes buried for hydrodynamic stability or for protection from external interference, such as fishing or anchors. Since large diameter pipelines (usually over 16-inch diameter) are often sufficiently robust to resist external interference, upheaval buckling is more commonly associated with pipelines of diameters less than 16-inch. However, larger pipelines are often trenched and buried in shallow water and are susceptible to upheaval buckling.

When a pipeline is laid over an uneven seabed and then trenched or buried, the pipeline is unlikely to be perfectly straight. The out-of-straightness of the pipeline, combined with the high axial compressive force caused by elevated temperature and pressure, could cause the pipeline to buckle upward out of the trench. Design of pipelines against upheaval buckling requires a good understanding of the three ingredients necessary for a buckle to occur: (i) the effective force in the pipe; (ii) the OOS (out-of-straightness); and (iii) the resistance to buckling, mainly provided by download from backfill in the trench or supplemental rock dump (Figure 5).

Upheaval buckling is generally considered a failure condition due to the following:

1. High levels of bending strain and plastic yielding, caused by high download over the buckle. Although there

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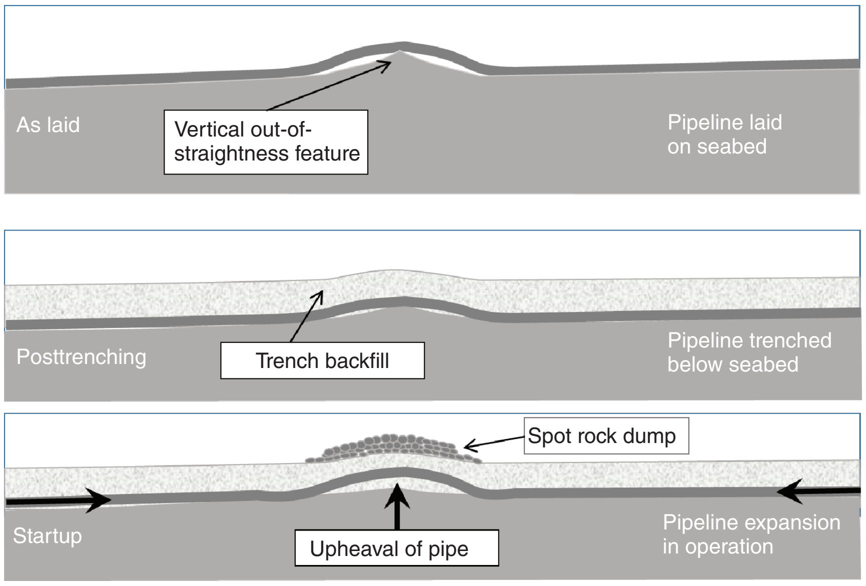

Figure 5. Sequence of laying, trenching, backfilling, and upheaval.

may be no immediate loss of containment, operational cycling can subsequently cause cracking and rupture;

2. Excessive vertical displacement and the loss of protection from the trench, leading to external damage by fishing or anchor interaction.

3.2 Effective force

The effective force required for buckling was discussed earlier in Section 2.1. The high axial resistance provided by an overburden of soil and rock, means that buried pipelines usually become fully constrained over much of their length (Figure 6). If buckling does occur, then it is likely to be highly localized.

3.3 Uplift resistance

The resistance to uplift is provided by the bending stiffness of the pipe, the submerged weight of the pipe, and the uplift resistance provided by the overburden of soil or rock placed on top of the pipe. Soil is placed on top of the pipe using a backfill plow, or by jetting and fluidization of the soil, allowing the pipe to sink down through the fluidized soil. These methods ensure that as much soil as possible is retained in the trench on top of the pipe, although this soil is disturbed and may require time to reconsolidate and regain strength. If the soil backfill is not deep or strong enough to provide sufficient uplift resistance, then rock can also be lowered into the trench.

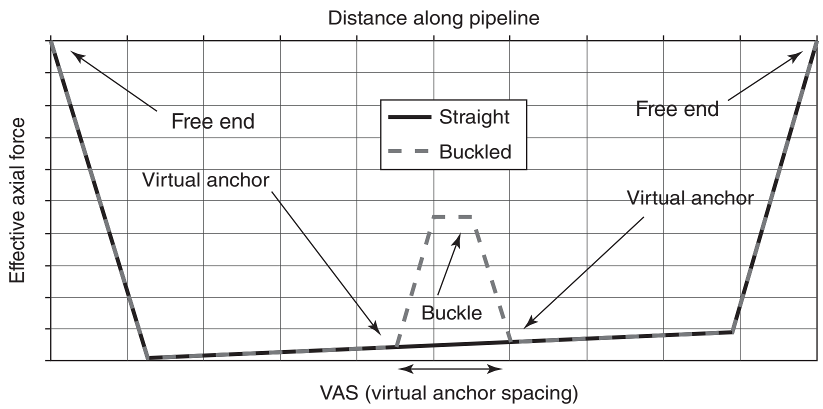

Figure 6. Effective force and postupheaval buckling force profile (example).

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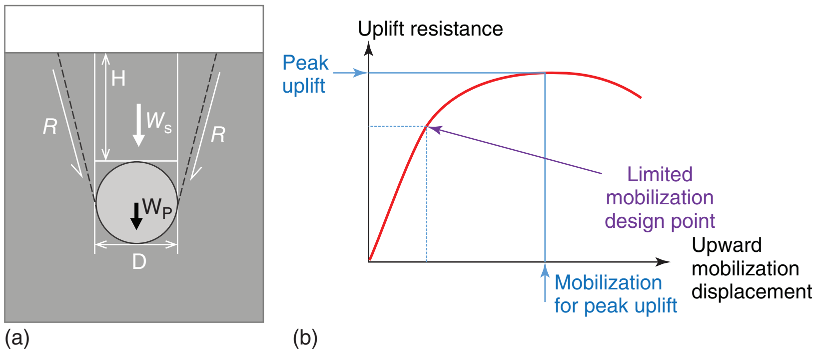

Figure 7. Uplift resistance (a) and mobilization displacement (b).

The design approach requires the depth of backfill and rock to provide sufficient uplift resistance (Figure 7a). The required uplift resistance is defined by the submerged weight of the pipe (W_P) of the soil above the pipe (W_S) and the shear resistance that must be overcome to raise the soil upward (R), usually defined by an uplift factor. The uplift factor varies for different types of soil (clay, sand, or rock) and the condition of the backfill in the trench, which may be highly remolded or contain voids. Any suction force due to excess pore pressure in clay soils above and below the pipe is usually ignored because it will dissipate and reduce with time under operational loading.

Some initial upward displacement of the pipe is required to mobilize the uplift resistance. The peak uplift resistance provided by the backfill is therefore associated with a mobilization displacement (Figure 7b). In effect, this means that any OOS feature must increase in amplitude to mobilize the peak uplift resistance. In addition, the ratio of soil height above the pipe (H) and the diameter of the pipe (D) influence the mobilization displacement required to reach the peak uplift resistance (Thusyanthan *et al*., 2011). Therefore, uplift resistance and mobilization displacement are both critical design parameters for upheaval buckling.

3.3.1 *OOS (out-of-straightness) survey*

In most cases, an OOS survey is carried out after the pipeline has been installed. OOS is measured along the pipeline by a suitably equipped ROV, or by internal inspection using a geometric survey pig. OOS features are identified along the length of the pipeline from the survey and used to assess the level of backfill required to prevent upheaval buckling. Design approaches incorporate an assessment of the uncertainties associated with each design input parameter, to arrive at an appropriate factor of safety for design.

If the cover is insufficient, then additional download will be required. Additional download is commonly applied using rock, lowered over the pipe using a fall pipe from a rock-dumping vessel. The most efficient and cost-effective method is to spot rock dump on critical overbends identified from the OOS survey. The rock dump contractor will usually add a level of additional rock (possibly up to 0.5 m) to ensure that minimum depth prescribed by design is met.

3.3.2 *Ratcheting*

Pipelines experience shutdown and restart cycles in operation. As OOS features in the pipeline move upward to mobilize the uplift resistance, it is possible for soil to migrate around the pipe into the void left beneath the pipe, preventing the pipe from returning to its original elevation on cool down. Over a number of operational cycles, the pipe can experience incremental upward movement, leading to an increase in OOS that may ultimately lead to upheaval buckling failure. This type of cyclic vertical ratcheting must be considered when designing for upheaval buckling and may require that a maximum mobilization displacement limit be set Figure 7b. It is thought that mobilization displacements more than 3–9% of pipe diameter could lead to ratcheting (Thusyanthan *et al*., 2011).

4 LATERAL BUCKLING

4.1 Introduction to lateral buckling

Lateral buckling design methodologies aim to encourage and control buckling. The attraction of lateral buckling as a design solution is that it provides a cost-effective way to avoid trenching and burial by reducing the compressive axial force in the pipeline. Lateral buckling is observed in many low temperature pipeline systems laid on the seabed. In many cases, these buckles were unplanned and are frequently benign. However, the advantage of lateral buckling is that the load in each buckle can be controlled

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by sharing that load between adjacent buckles. Buckling is therefore deliberately triggered at regular intervals along the pipeline. While the severity of the load increases with increasing pressure and temperature, this approach is an elegant design solution for deepwater and HPHT (high pressure, high temperature) pipelines and may be the only economic solution in extreme cases.

Buckling displacement results in significant bending moment at the crown of the buckle. This moment can be very high and stresses in excess of yield are normal (although these are relatively limited in axial extent and usually occur only on first load). Thus, under the lateral buckling philosophy, although the axial force is reduced, the bending stresses are significantly increased.

Reducing the load in each buckle can be achieved by placing the buckles closer together. However, placing the buckles close together also reduces the reliability of buckling, since as soon as each buckle forms, the force in the pipeline reduces sharply in the vicinity of the buckle (as pipe feeds into the buckle), which inhibits the formation of further buckles close by. The spacing between buckles must therefore be large enough for buckles to form reliably and small enough to limit the loads in each buckle. It is also clear that the expected variability and uncertainty in pipe–soil response and OOS increase the uncertainty in defining buckle spacing. This leads to the concept of VAS (virtual anchor spacing) as a critical parameter in design.

4.2 Virtual anchor spacing and buckle prediction

As the flowline is encouraged to form a number of discrete lateral buckles along its length to share the load between them, the force in the pipe reduces at each lateral buckle. Approximately halfway between the buckles, the pipe forms a virtual anchor point. Virtual anchors are nominally stationary[2] points that form between buckles (as shown in Section 2.1); the distance between them, the VAS (virtual anchor spacing) is an important design parameter that defines the distance between adjacent buckles and the overall length of pipe feeding into each buckle. The level of feed-in (flowline axial expansion) defines the extent of growth and load in the lateral buckles.

The VAS concept can be used to quantify the load severity of a lateral buckle, the shorter the VAS, the less pipe is feeding into the buckle. However, the shorter the VAS, the less likely buckles will form. In other words, there is a limit to how closely the buckles can be placed and guaranteed to form; this practical limit must be incorporated in the overall design.

Buckle formation is an imperfection-sensitive process that is intimately linked to the initial condition of the pipeline—the OOS. The buckling response of a pipeline will always be inherently uncertain because project-specific OOS information is not known prior to pipe lay. The designer must understand this uncertainty and reduce it to levels whereby the project can proceed with confidence. It is essential to have a rational and robust method for assessing the reliability of buckle formation.

This is done using a probabilistic approach to predict the “characteristic VAS,” which defines the maximum VAS expected at any point along a pipeline. This approach leads to an iterative design approach to define the design spacing at which design limit states are not exceeded (Cosham *et al*., 2009).

The first step is to confirm that the pipeline is susceptible to lateral buckling and if so, select a mitigation method. The simplest mitigation method is to do nothing. If it can be shown that uncontrolled buckling is acceptable, then a buckle initiation strategy is not required.

If the likelihood of unacceptable buckles is too high, then an initiation strategy is required to increase the likelihood of acceptable buckles (and reduce the likelihood of unacceptable buckles).

If the mitigation method does not provide a successful outcome, then there are two ways to improve the initiation strategy:

1. Reduce the force required to initiate a buckle (reduce the critical buckling force)
2. Reduce the bending load in each buckle, allowing buckles to be spaced further apart.

Answering these two challenges has led to a number of innovative methods to control buckle formation using engineered buckle initiators (triggers), placed at intervals along the pipeline, to trigger regular lateral buckles that share the load between them and increase the reliability of buckle formation (Sinclair *et al*., 2009).

4.3 Lateral buckle initiation

Various methods to trigger lateral buckles reliably have been developed, with a high level of success (Sinclair *et al*., 2009). All of these techniques seek to improve the reliability of buckle formation by lowering the buckle initiation force. The buckle initiation force is governed by (i) OOS features and (ii) lateral breakout resistance. The following initiation techniques work by modifying one or both of these parameters:

- Snake lay;
- Vertical upset;
- Local weight reduction;
- Zero radius bends;
- Local residual curvature.

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There is a further advantage in the use of engineered buckle triggers, since the postbuckle shape is generally more benign. Consequently, the lateral resistance to large displacements may also be reduced and the integrity of the pipe within the buckle is improved. This has the knock-on benefit of allowing an increase in the spacing between buckles, normally defined by the VAS, which further helps promote reliable buckle initiation.

Careful consideration is required to assess the reliability of buckling at each trigger and the potential for unplanned "rogue" buckles. A rogue buckle may compromise the design solution by occurring in preference to a planned buckle. This is a particular concern where the conditions are less favorable; for example, weight coating at a rogue buckle would concentrate buckling strain at the field joint.

4.3.1 Snake lay

Snake lay requires the pipeline to be laid in a series of gentle curves (Figure 8). The propensity for buckling is controlled by the bend radius of the snake, which is designed to act as the buckle initiator, with the aim of developing a lateral buckle at some point on the curve.

4.3.2 Vertical upset

The vertical upset technique deliberately introduces significant vertical OOS at a number of points along the pipeline. Two techniques have been employed:-

- Sleepers (Harrison *et al*., 2003; Jayson *et al*., 2008)
- Gravel dump berms (Nystrom *et al*., 2001)

The concepts are similar, although the more gradual rise in slope toward a gravel berm can modify the formation

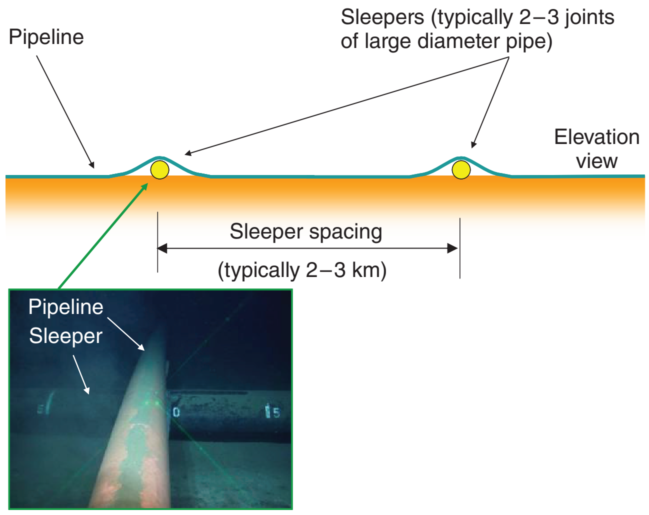

Figure 9. Buckle initiation using sleepers. (Reproduced with permission from Bruton *et al*. (2008) © Society of Petroleum Engineers, 2008.)

response. The sleepers are installed prior to (or during) pipe lay at the appropriate spacing (Figure 9). The height of the sleeper upset defines the buckle initiation force. This method also reduces interaction with the soil by lifting the apex of the buckle out of the soil, although the touchdown points continue to interact with the soil.

The vertical upset can result in pipeline spans, which may limit the maximum allowable height of the upset, since these spans could be susceptible to vortex-induced vibrations (VIVs) or flow-induced vibration caused by two-phase flow slugging. Dual, parallel sleepers have been used to reduce span length and reduce touchdown restraint (Bai *et al*., 2009). Spans may also be susceptible to snagging (fishing) interaction; in these cases, it is possible to use a reduced length

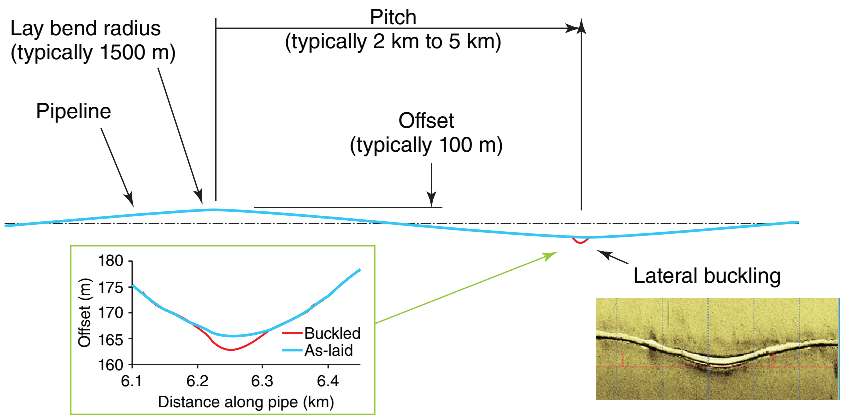

Figure 8. Typical snake lay configuration. (Reproduced with permission from Bruton *et al*. (2008) © Society of Petroleum Engineers, 2008.)

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sleeper, so that when the pipe buckles at the sleeper, it falls to the seabed, thus minimizing snagging or slugging issues.

4.3.3 Local weight reduction

Local Weight Reduction introduces a change in submerged weight and outside diameter. Two techniques have been employed:

- Distributed buoyancy
- Local weight coat removal

The concepts are similar although adding buoyancy increases the diameter while removing weight coat reduces the diameter. This initiation method works in several ways:

1. The buckle initiation force is reduced due to localized OOS, caused by the change in diameter and the reduction in submerged weight causing variations in local embedment.
2. The reduced submerged weight and reduced embedment result in a reduced lateral breakout resistance increasing buckle reliability.
3. The reduced submerged weight and reduced embedment will also reduce the residual lateral resistance in operation thus reducing the operating loading in the buckle.
4. The removal of concrete coating has the major advantage of removing the strain concentration associated with a concrete coating field joint.

The distributed buoyancy method uses discrete lengths of buoyancy applied to the pipe over a typical length of 60 m (200 ft) to 200 m (650 ft) to trigger buckling (Figure 10). It is important not to reduce the operational submerged weight so much that the pipe is buoyant at the minimum operating fluid density.

4.3.4 Zero radius bend or counteracts

For the ZRB (zero radius bend) or counteract technique (Peek and Kristiansen, 2008), a vertical trigger is preinstalled on the seabed and the pipeline is initially laid straight toward it. The straight lay continues until the pipe is seated on the trigger, at which point the lay vessel moves laterally and changes heading by a small angle. The lay vessel then continues laying in a straight line after the change in pipeline heading has been achieved.

This lay procedure creates a tight radius bend, concentrated within the span created by the trigger. Although referred to as a ZRB, the flexural rigidity of the pipe results in a bend radius that is nonzero but much smaller than that can be implemented in a convention route curve. This technique

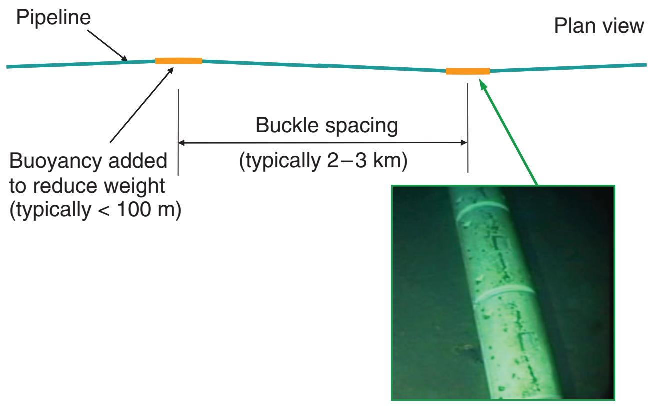

Figure 10. Buckle initiation using buoyancy. (Reproduced with permission from Bruton *et al*. (2008) © Society of Petroleum Engineers, 2008.)

significantly reduces the buckling force, which facilitates closely spaced buckling.

The lateral load imposed on the trigger during installation is small and can easily be reacted by incorporating a vertical post into the trigger. The ZRB technique has been employed to enhance the reliability of buckle formation on a number of projects and has significant advantages on long route curves, where the ZRB triggers can assist in maintaining a stable route curve under tension at shutdown.

4.3.5 Local residual curvature

Reel lay of pipelines involves straightening during offshore installation. The straightener system can be used actively during installation to create local residual curvature in the pipeline by not straightening the pipe at selected intervals. Pipeline local residual curvature could also be generated on S-lay vessels, by roller or stinger adjustment during laying. This residual curvature in the pipe may be used as a trigger to control lateral buckling. This approach has been used with a reel-lay vessel to realize very low critical buckling forces and successful buckle formation (Endal and Egeli, 2014).

4.3.6 Bathymetric features

The design can take advantage of significant vertical OOS, which can trigger buckles. These features can be incorporated into the buckle formation strategy as planned initiation sites. The reliability is evaluated within buckle formation analysis, in the same way as engineered triggers.

Buckling from bathymetric features may involve initial movement in the vertical plane, so that pipe–soil stiffness could be critical and should incorporate an appropriate level of uncertainty. The final buckle will form in the lateral plane

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unless there is very significant lateral restraint at the lift-off points. If the bathymetric features are modest, it may still be possible to take benefit from them. For example, by locating engineered triggers at the bathymetric OOS, to improve the reliability of the trigger.

If the bathymetry leads to pipeline free spans, then the expansion behavior of the pipeline will be modified as the expansion feeds into the spanning sections. This will absorb some of the feed-in that would otherwise drive lateral buckling and is generally beneficial. However, significant lengths of span may be a challenge, as for sleepers. In this case, span rectification using rock or mattresses will modify the force profile and influence lateral buckling. For more information on pipeline spanning, *see* **Pipeline Spanning**.

5 PIPELINE WALKING

5.1 Pipeline walking mechanisms

Pipeline walking is a stepwise ratcheting displacement along the axis of the pipe that occurs during changes in operating conditions, particularly during shutdown and restart operations. Over a number of cycles, this movement can lead to very large global axial displacements, leading to growth of buckles or overloading of any connections. Walking is usually associated with pipelines laid on the seabed, although it has occurred on trenched pipelines. Cumulative end expansion due to walking may need to be controlled to prevent tie-in failures.

Pipeline walking can be caused by the following:

1. Seabed slope along the pipeline length;
2. Liquid dropout as the pipeline shuts down;
3. Steel catenary riser that applies tension to the end of the pipeline;
4. Thermal transients caused by sudden cooling or heating of the fluids in the pipe.

These walking mechanisms can be assessed simply using analytical modeling to establish the rate of walking (Carr *et al*., 2006; Bruton *et al*., 2010). Detailed walking analysis requires FEA (finite element analysis).

If there are no fully constrained sections along the pipeline, it will experience expansion and contraction along its full length. However, these walking mechanisms cause the virtual anchor locations to change from operation to shutdown. This eccentricity in virtual anchor locations and loading is what drives pipeline walking due to slope and walking due to liquid drop out and tension applied by a catenary riser. At each shutdown and restart, the pipe will incrementally move axially, at a rate that is dependent on the axial resistance, the angle of slope, the locations of liquid holdup, and tension applied. Walking due to transients is due to the initial, asymmetric localized expansion of the pipeline (at the end being heated) or contraction (at the end being cooled).

Long pipelines with regular lateral buckles will behave like a series of short pipeline with ends that are free, except for the small resistance provided by the lateral buckle. Thermal expansion and contraction occurs between the buckles, in a similar way to free ends. Consequently, a long laterally buckled pipeline can also undergo walking. In this case, the walking can also cause growth of vulnerable buckles, leading to an increase in strain and the potential for failure.

5.2 Mitigation of pipeline walking using anchors

When the predicted pipe walking displacements threaten system integrity, walking may be controlled by the use of pipeline anchors, typically installed at the end of the pipeline from which it is walking. It is easier to install an anchor at the end of a pipeline and, in principle, the installation startup pile could be used as an anchor. However, there may also be an advantage in installing a midline anchor or using a midline rock dump to control walking.

A number of deepwater projects have identified pipeline-walking issues in design that required mitigation, typically by installation of pipeline anchors, with a capacity of 50–350 tons. Design and installation of midline anchors with such a capacity raises a number of technical and structural challenges. Pipeline anchors create very high levels of tension at shutdown, which can lead to large radius route curves becoming laterally unstable. This route-curve pullout is usually overcome by increasing the route-curve radius, or removing route curves altogether by changing the field layout. For these reasons, the complex interaction between pipeline buckling and walking responses are key drivers in the layout of a field development.

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NOMENCLATURE

S	Effective axial force (tension positive) (N)
S_L	Residual lay tension (N)
S_0	Fully constrained effective axial force (N)
p_i	Internal pressure (N/m^2)

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p_{iL} Internal pressure during installation (N/m^2)
A_i Internal cross-sectional area of pipe (m^2)
A_s Steel cross-sectional area of pipe (m^2)
E Young's modulus (N/m^2)
α Coefficient of thermal expansion (/K)
W_P Submerged pipeline weight per unit length (N/m)
ε_A Axial strain
ν Poisson's ratio (−)
μ_a Axial friction factor (or equivalent friction coefficient) (−)
$\Delta\theta$ Change in pipeline temperature from installation to operation (°C)
p_e External pressure (N/m^2)
A_e External cross sectional area of pipe (m^2)
S_W Force in the pipe wall (N)

ENDNOTES

1. Expansion spools will provide a reaction to expansion, which means that the effective force at the end has a small compressive value.
2. A virtual anchor point may move prior to buckle formation and may also move between load and unload conditions.

GLOSSARY

Effective force	The total axial force in the pipeline that drives the structural response.
Lateral buckling	Global sideways buckling of a pipeline laid on the seabed.
Pipeline expansion	Axial growth and displacement of pipe due to changing operating conditions.
Management	The outsourcing of the management of a vessel or vessels to a qualified ship manager for an agreed fee.
Pipeline walking	Axial ratcheting displacement of a pipeline.
Upheaval buckling	Global upward buckling of a pipeline usually from within a trench.

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