Abstract - The recent developments in offshore pipeline projects in Indonesian waters are showing a general trend towards deeper water, such as the West Seno Field in 1,000 m water depth. As the exploration is getting into deeper waters, or crossing a deepwater section, different design issues may become governing compared to shallow water.

"From Shallow to Deep - Implications for Offshore Pipeline Design" discusses a number of issues that need to be taken into account in the design of pipelines in deepwater. Aspects related to external pressure, material grade, fatigue, geo-hazards and design code selection are addressed. Installation, operability and repair aspects, which can also be different for shallow and deepwater, are excluded in this paper.

As a pipeline is installed in deeper water, the external pressure becomes dominant, and the wall thickness design is no longer governed by the pressure containment criterion. In most cases the local buckling criterion, composed of bending and collapse, becomes the governing design case. Buckle propagation is normally accommodated through the use of buckle arrestsors.

As consequence of the different governing design case, the required wall thickness may increase significantly. Wall thickness reductions are however possible through use of a higher material grade, additional fabrication requirements, and technology development such as collapse testing. Through the design process it should be realized that both the capabilities of the various pipe mills and of the available installation vessels may pose a boundary condition to the wall thickness design.

Because of the large unsupported pipe section between the touchdown point and the last support on the vessel both in length and time, a quasi static approach to the maximum stress during installation is no longer valid and a dynamic installation analysis is required. In addition, the vortex induced vibration (VIV) design for recent developments, allows the pipe to vibrate on the seabed. The fatigue design then needs to accommodate both fatigue during installation and fatigue during operation.

Deepwater pipelines become longer and are often used to connect developments beyond the continental slopes. Here the pipeline will encounter a complex seabed terrain, and geo-hazards become an important design aspect. Earthquakes, pockmarks (seepage of gas/liquids through seabed), faults, slumps/creeps (soil failure), slope instability, outcropping/sub-cropping and soil liquefaction need to be considered. These should not only be considered as individual hazards, but also interrelationships that may lead to a catastrophic event need to be investigated.

Through research and development the design philosophy of pipelines in deepwater has improved significantly over the last 20 years. Various available modern international industry codes are now able to satisfy the needs of deepwater pipeline designer, for example through limit state design, or the incorporation of technology development. For each project a coherent system of codes needs to be considered that allows the most suitable approach to the designer and the client to achieve the project objectives.

1. Introduction

Ever since the first pipeline was installed offshore, pipeline developments have been moving into ever-deeper waters. While in the early days of the offshore industry 100 m water depth was considered as deep, now pipelines are being installed in 2,000 m water depth or more. Until now, the deepest pipeline project that has been executed was the Bluestream project with a maximum water depth of 2,150m in 1994. Furthermore, the deepest pipeline project has ever been considered was the Oman-India Gas Pipeline Project in 1995 with a maximum water depth of 3,500m. Similarly, in Indonesia, more and more deep water prospects are being considered. At the time of writing the West Seno Field, located in approximately 1,000m water depth, 60 km East of Kalimantan, in the Makassar Strait, is Indonesia’s deepest deepwater development. However,
it is very likely that greater depths will be reached in the near future.

Considering this trend towards deeper water, this paper provides an overview of key pipeline design issues that need to be taken into account, and that are fundamentally different from shallow water. Let us therefore briefly consider what the most critical deep water design issues are.

• The first issue, the most obvious and the most influential, is the external pressure of the water on the pipeline. In particular as the pipeline is being installed empty, the external pressure will induce a large load on the pipeline, and can result in a different mode of failure. Even during operation the external pressure may still be larger than the internal pressure. As a consequence additional failure modes need to be considered not only for wall thickness design, but also for the on-bottom stress analysis.

• During the installation of the pipeline, the weight of the pipestring hanging of the laybarge increases with increasing depth. As a consequence more holding or tension capacity is required, and the capabilities of the available installation vessels need to be considered already in an early stage of the design.

• As the pipe joints are welded and lowered to the seabed, the duration that a pipe section is suspended between barge and seabed increases with water depth. Environmental loads on the pipe string can have a significant effect, and fatigue may become an important design issue. As such a dynamic analysis of the pipeline installation is required.

• The seabed onto which the pipeline is lowered may be fundamentally different from a shallow water seabed. While generally the seabed sediments are very soft, leading to settlement or sinkage of the pipe, often pipelines need to traverse continental slopes with a complex geomorphological behaviour and associated geohazards.

• Finally, operation, maintenance, and repair of a deep water pipeline pose their respective challenges. As these can be a subject of their own, these are not addressed in this paper.

The above items are discussed in more detail in the following section.

2. **External Pressure Effect to the Wall Thickness Design**

When the pipeline is considered from a purely theoretical point of view, it can be subjected to a limited number of loads. In order to understand the pipeline behaviour under these kinds of loads, cross sectional deformations just before failure of pipes subjected to these single loads are shown in Figure 1 (taken from [ref. 6]).

![Figure 1. Cross Sectional Deformation of Pipes Subjected to Single Loads](image)

From Figure 1, it can be seen that pipeline cross sections behave differently under different types of loads, these behaviours or combinations thereof are considered as pipeline failure modes.

During installation, hydrotest and operation, the offshore pipeline is subjected to the loads of internal pressure, external pressure, bending moment, and axial tension. In general, for shallow water pipelines, the failure modes of pressure containment and of combined bending and tension are considered, where generally pressure containment is governing.

For the pipeline design in deeper waters, four failure modes need to be assessed: design for pressure containment, collapse (external pressure), combined pressure and bending and buckle propagation. The last three designs are categorized as buckling phenomena, that have been discussed by several researchers [ref. 7,8,10,12,13,17]. Each of these failure modes will be discussed separately hereafter.

2.1 **Design for Pressure Containment**

The pressure containment criterion determines the minimum wall thickness required against the internal operating and hydrostatic test pressures. The external pressure is included in the pressure containment design, which provides a reduction to the total pressure in the pipe. To this aspect, the total pressure will be at its maximum at the zero water depth where the external pressure is zero. The pressure containment requirement is dominant for wall thickness design in shallow water pipeline.

2.2 **Design for Collapse (External Pressure)**

The design for pressure containment considers pressure both on the inside and the outside the pipe. During
installation, drying, or if the pipeline system is to be vented due to upset conditions, the pipeline is in an empty condition, i.e. no pressure inside the pipe. It means the internal pressure is zero.

As the pipe is moving into deeper water, the external hydrostatic pressure becomes higher and may collapse the pipe wall. The design for pressure containment does not include this condition, therefore the pipeline wall thickness need also to be designed for the hydrostatic collapse in which the governing load condition is at the maximum water depth.

2.3 Design for Combined Pressure and Bending Moment

The effect of external pressure acting alone in the pipeline has been covered by the design for collapse. However during installation, the pipeline experiences external pressure, axial tension and bending moment. The design against local buckling addresses these aspects.

The external pressure is induced by the external fluid around the pipe. The axial tension is induced by the tension applied at the tensioner of holding clamp of the installation vessel to maintain the catenary shape of the pipeline, and the bending moment is a result of the catenary shape of the pipeline. These conditions are shown in Figure 2.

![Figure 2: Installation Using J-Lay Method](image)

Figure 2 is a typical schematic of pipeline installation using the J-lay method. It can be seen that the pipeline section above the water level only experiences axial tension. As the pipeline moves down into the water line, it experiences axial tension and external pressure. There is no bending moment as the pipeline is still straight. As the pipeline approaches the seabed, it has to bend following the catenary shape. At this section, the bending moment, axial tension and external pressure are all acting together. The combination of these loads induces a compressive stress, which needs to be included in the wall thickness design. The buckling design due to combined bending (including the axial tension) and external pressure considers two components: the first part is the pressure term in which the external pressure is compared to the collapse pressure, the second part is the comparison of the bending loadings (including the axial tension) to the bending capacity. The combination of these then shall be smaller than a design factor $X$, which varies with the design condition (installation, flooded, hydrotest or operation).

2.4 Design for Buckle Propagation

During pipeline installation and operation, there is a possibility of pipeline damage due to local buckling. Once the local buckle has occurred, the buckle will propagate along the pipeline until the external pressure becomes less than the buckle propagation pressure. In other words, the buckle propagation may occur if the external pressure exceeds the propagation pressure for the pipeline. The buckle propagation phenomenon itself was discovered in 1970 by the Battelle Institute in Ohio [ref. 16] and in order to cope with buckle propagation without having to dramatically increase the pipeline wall thickness, the buckle arrestor was developed. Several methods to design buckle arrestors have been proposed [ref. 8,10,12,17].

Buckle propagation can be prevented by increasing the wall thickness to the buckle propagation thickness or by designing buckle arrestors spaced along the pipeline. The space between two buckle arrestors is defined based on cost and risk optimization. If the pipe will be installed by the J-lay method using a collar system, a hex joint may be the preferred spacing. For deep water pipelines it is common to use buckle arrestors, because the thickness required against buckle propagation is relatively high and will be too costly to use for the entire pipeline length. There are various types of external and internal buckle arrestors, such as integral ring, welded ring, welded sleeve, heavy-wall integral cylinder, and grouted free-ring buckle arrestors.

2.5 Comparison of Wall Thickness Design Criteria

In order to illustrate the interrelationships between the various design criteria, an illustrative wall thickness comparison is depicted in Figure 3 for a typical deep water pipeline. It can be seen that in shallow water
sections (in this case less than 100m), the wall thickness is governed by the pressure containment requirement.

For a section deeper than 100m, the buckling design criterion becomes governing. With increasing water depth the external pressure increases, and the load cases involving this external pressure become dominant.

Comparing the collapse, combined loading and buckle propagation criteria, it can be seen that the buckle propagation is the governing criterion. However, for deepwater pipelines the wall thickness will generally not be based on this criterion as the additional thickness required is quite significant or even outside the manufacturing capabilities, and would be very costly to use for the entire length of pipeline. For this reason, the wall thickness is generally designed for the local buckling case, consisting of combined pressure and bending moment. The buckle propagation load case is then prevented by buckle arrestors that are spaced along the pipeline, as explained in the previous section.

Figure 3. Typical Wall Thickness Comparison

From the above example it can be concluded that local buckling is generally the governing design case for deep water pipelines, but also that the wall thickness required is significantly higher than what is required for internal pressure containment. As such several explorations have been made into the factors that affect the local buckling case in order to allow further optimization of the wall thickness. As the load side of the local buckling criterion cannot really be influenced these explorations focus on the resistance side, i.e. the properties of the pipeline.

In a similar vein as for pressure containment the material strength is the primary factor on the resistance side. However, for the local buckling case it should be noted that the applied production process reduces the hoop compressive strength of the pipe, a fact which is incorporated through a fabrication factor. Improvements in this area have a direct effect on the local buckling resistance.

A second factor playing a role in the local buckling resistance is the dimensional tolerance of the pipeline, in particular the ovality, which is a measure of out-of-roundness. The ovality of the pipeline is directly linked to the collapse component of the local buckling criterion, and higher ovality will require additional wall thickness for collapse resistance [ref. 4,6,7]. In the opposite way, more stringent dimensional tolerances may lead to a wall thickness reduction.

The above pipeline properties are discussed in further detail in the following section on material selection.

3. Material Properties for Deep Water Pipeline

3.1 Fabrication Capabilities of the Pipe Mill

The wall thickness required for local buckling resistance can become quite significant, and as a consequence not all pipe mills may be capable of producing the line pipe as designed. For a deep water pipeline it is therefore important that parallel to the design process the actual capabilities of the various pipe mills are considered, to ensure that a realistic design is achieved. If a only a very limited number of pipe mills is capable of producing the line pipe, this could have a significant effect on the line pipe cost. If the designed wall thickness exceeds the current pipe mill capabilities it may be possible for the pipe mills to upgrade. However, again this will have an effect on the overall project economics. The D/t characteristics of a number of recent deepwater projects for large diameter pipelines depicted in Figure 4. This figure also shows an indicative UOE manufacturing curve within which several pipe mills are generally capable of producing the pipe. Since pipe mills will have different capabilities for different material grades and individual pipe mills have deviating specifications the actual capabilities may deviate for each project, and therefore need to be considered on a case by case basis.

Figure 4. Recent Large Diameter Projects and Mill Capacities

3.2 Material Grade Selection

The strength of the offshore pipeline is represented by the Specified Minimum Yield Strength (SMYS) and Specified Minimum Tensile Strength (SMTS). With
increasing material grade (e.g. X60, X-65 and X-70), the SMYS and SMTS increase.

For shallow water application, low material grades are often used, especially for lower pressure pipelines. However, for the deepwater offshore pipelines the common used material grade are X60, X-65 or X-70. The higher yield strength, the thinner the required wall thickness. Therefore, the total required steel volume is reduced. In the ultra deepwater installation especially for large diameter linepipe, the reduction of wall thickness significantly reduces the top tension. Nowadays the welding of Grade X-70, both longitudinally in the pipe mill and offshore girth welding during pipe lay, is well established.

In addition, X70 material can be fabricated to exhibit adequate fracture resistance at both longitudinally in the pipe mill and girth welds to avoid ductile/brittle failure at the minimum design temperature. The use of X80 material has been considered and may be suitable especially for very deep water, but is currently still considered in experimental stage.

3.3 Compressive Hoop Strength and Collapse Tests

As mentioned earlier the pipe manufacture process (i.e. UOE, TRB, etc), will reduce the compressive hoop strength of material, generally translated into the design through a fabrication factor. For large diameter, heavy walled linepipe in deepwater, the UOE pipe manufacturing process is the general method applied by pipe mills. During the UOE forming process, the cyclic cold working of the material causes variations in material strength due to the Bauschinger effect. The analyses of Kyriakides et al. [ref. 7] established that this effect degrades the hoop compressive strength of the material as well as the associated collapse resistance of the pipe.

The reduction of the hoop compressive strength, as depicted in Figure 5, is a key issue for deepwater collapse. It is incorporated in the DNV OS-F101 design code [ref. 4] in the form of fabrication factor $\alpha_{fab}$ which is a factor of material strength. For different fabrication process this factor has different values. For the UOE process the standard factor has a value of 0.85, or a reduction of the material strength of 15%.

From above discussion it becomes clear that for optimizing the wall thickness design most can be gained by improving the knowledge of the material behaviour. Three major collapse test campaigns have been performed, all under INTEC supervision: for the Oman-India Project [ref. 14,15], the Bluestream Project, and a recent deep water trunk line project in the Gulf of Mexico (GOM), each of these campaigns taking the status of technology further. Where the Oman-India testing was primarily focused on a good understanding of collapse (although other aspects such as thermal aging were already identified), the Bluestream testing was undertaken primarily to understand combined collapse and bending.

![Figure 5. Compressive Hoop Strength Reduction due to UOE Forming](image)

As a result of the Bluestream collapse testing, the resistance of the pipe for combined collapse and bending can be better estimated. This has led to an increased value of $\alpha_{fab}$ and a corresponding saving on pipeline wall thickness (the testing results remain confidential).

A second aspect that can be verified by collapse testing is the effect of thermal aging. Thermal aging is the process whereby the compressive hoop strength reduction from UOE forming process can be recovered. By thereby verifying this phenomenon for the project pipe this recovery can be demonstrated to be significant, and further wall thickness reductions can be achieved resulting in significant project savings.

3.4 Linepipe Quality and Dimensional Tolerances

In addition to the material hoop compressive strength, the local buckling resistance is affected by the quality of the line pipe, as discussed earlier in Section 2.5. Some codes such as DNV allow the use of less conservative safety factors in case the line pipe quality is more stringently controlled, through so-called supplementary requirements. The two most commonly used supplementary requirements for deep water are the requirement ‘U’, which relates to improved confidence in the yield stress of the material, and the requirement ‘D’ which ensures enhanced dimensional properties. While the application of these supplementary requirements may have an effect of the line pipe material costs, it can also result in significant wall thickness savings. For example, the DNV supplementary requirement ‘U’ results in a 4% improvement on the design yield strength through the Material Strength Factor. The DNV supplementary requirement ‘D’ has a direct relationship with the collapse part of the buckling equation. While typical
shallow water pipelines can have an ovality of 3%, for deep water pipelines this is generally restricted to 1%.

4. Installation Vessel Capabilities

During installation of the pipeline, the weight of the pipe string hanging of the laybarge increases with increasing depth as can be seen in Figure 6. As a consequence more tension capacity is required to maintain the pipe string in its configuration. These required tensions can become so high that they may not be achievable by various installation vessels, and in a worst case scenario it may be found that there are no vessels available that are capable of installing the pipeline as designed. For this reason it is necessary that the capabilities of the available installation vessels are considered already in an early stage of the design.

![Figure 6. Required Top Tension in Empty and Flooded Condition](image)

As part of this evaluation of installation capabilities two design conditions; empty and flooded are considered. The empty condition relates to normal installation, while for the flooded condition the vessel is required to be able to hold a flooded pipe, for example in case of a wet buckle. As the water depth increases, the top tension to maintain the sag bend configuration will be even higher, especially in flooded condition. This can be seen in Figure 4.1 for a typical deep water pipeline, where the required top tension for flooded condition increases by about a factor of 2.8 from the empty condition. To demonstrate the difference, for a typical pipeline the required top tension for empty and flooded conditions in 100m water depth are 650 kN and 1740 kN respectively, and in 2000m water depth are 4000 kN and 11500 kN respectively.

Other vessel characteristics need to be considered. For example, deepwater installation vessels typically require a dynamic positioning system for station keeping. A conventional mooring system, consisting of eight to fourteen mooring lines which works well in shallow water, is not very suitable for deepwater installation, since the anchor reset speed could become slower than pipeline fabrication speed [ref.11]. Nowadays, most modern installation vessels are equipped with such a dynamic positioning system.

5. Pipeline Loading During Installation

In shallow water installation analysis the pipeline is generally analyzed in its static installation configuration. The maximum stress during installation is then obtained through the application of a stress multiplication factor.

In deep water installation this approach is no longer valid. The unsupported pipe section between the touchdown point and the last support on the vessel will be both in length and in time longer than in shallow water, and fatigue needs to be addressed. A dynamic analysis is a must to obtain the fluctuating stress that occurs during installation. Especially for large diameter pipelines, the total mass of the pipeline and the associated added mass have a significant effect on the behaviour of the pipeline and tensioner system. These will result in higher stress fluctuations.

The results of this need to be combined with the fatigue analysis of the pipeline in its installed condition, in particular if the pipeline is spanning. Recent code developments allow the pipeline to undergo vortex induced vibrations (VIV) as long as the fatigue life is not exceeded. The fatigue design then needs to accommodate both fatigue during installation and operation.

For pipelines in the installation condition, the girth welds are the main area of concern for fatigue [ref. 13]. The girth welds are under stress in the transversal direction of the weld during the lay operation as a result of axial stress fluctuations in the pipeline. For this reason, the fatigue analysis is performed for the girth weld locations only.

Generally the fatigue analysis for pipelines during installation is performed as a time domain analysis, considering the wave loads acting on the pipeline and the vessel behaviour, characterized by the Response Amplitude Operator (RAO). To conduct the time domain fatigue analysis, first the fluctuating stresses on each girth weld between the stinger and touchdown points need to be obtained, which can be done by a dynamic pipeline lay software. The next step is to use the S-N curves in conjunction with Miner’s cumulative damage rules to compute the fatigue life. The total fatigue life considers the contribution of all fatigue damage in each girth weld between the stinger and touchdown points.

6. Consideration of Geo-Hazards

When traversing deepwater and in particular continental slopes, route selection becomes more critical as the pipeline may experience typical deepwater and seismic...
geo-hazards such as slope instability, turbidity flows, lateral and vertical faults or a combination of those. Minimizing such geo-hazards, compromising the shortest pipeline route, could ultimately reduce overall project costs significantly. However, it is not always possible to avoid such hazardous areas due to existing constraints (multiple hazards at the field location, limited lay corridor, nature of seabed topology and requirement to achieve shortest possible route, etc.). This section shortly describes an engineering approach to assess the integrity of the pipeline for a few common encountered deepwater geo-hazards.

![Figure 7. Tectonic Plates](image)

The majority of earthquakes are due to shifts in tectonic plates (Figure 7) although some are caused by volcanic activity. Pipelines in seismic active areas may be subject to fault movements. Faulting is the displacement associated with the relative movement of adjacent parts of earth’s crust. The movement can occur suddenly during an earthquake or accumulate gradually over a period of time.

The behaviour of the pipeline to such movements of the underlying seabed is generally evaluated with a finite element program such as ANSYS. Required for the analysis are the geometry of the faults, width of fault zone, type of fault, direction of movement and displacement of the planes, which suddenly occurs during an earthquake or which could gradually accumulate over a long period of time (creep).

To achieve a balanced risk design for the oil or gas pipeline system, it is desirable to know the recurrence interval for a given earthquake-induced fault displacement. Therefore, part of deepwater pipeline projects involving pipelines beyond the continental slopes, is a probabilistic seismic hazard analysis (PSHA). In a PSHA all relevant geotechnical and seismic hazards are identified and ground-motions such as the fault direction and displacements are quantified for different return periods [ref. 3,9]. Provided this information, it is possible to engineer the pipeline to resist fault displacements and to comply with codes and standards. Pipeline integrity for example is determined using the local buckling criteria from DNV OS-F101 [ref. 4].

Other typical deepwater geo-hazards that could impact the integrity of the pipeline are gravity flows, slope stability, turbidity (mud or debris) flows and liquefaction. Gravity flows for example are triggered by density or temperature gradients and could produce an increased load on the pipeline. Often, for a pipe lying on the seabed, the frictional resistance of the soil can accommodate this increased load. At spans, however, this increased load will reduce the maximum allowable span length, which may lead to mitigation measures in the form of extra supports of the pipeline at the exposed span locations.

Slope stability has to be investigated in detail as failure of the slope could lead to failure of the oil and gas pipeline system. Slope instability could be triggered by natural sources, e.g. earthquake activity, toe erosion, rapid sediment deposition leading to excess pore pressure conditions or by human activities such as drilling of wells, mooring or anchoring forces and installation activities. In case of an earthquake triggering mechanism, the stability of the slope can be related to the local peak ground accelerations (PGA) and seabed slope angles. Applying ground mechanics, slope instability can be predicted. Evidence of recent mass sediment movement observed in the route survey data can indicate instable slopes. In some cases it is possible to trigger potentially unstable slopes to fail (e.g. with explosives or drilling) creating smoother stable slopes, however, this is often not desirable regarding the risks and environmental impact.

In general, potentially instable slopes are being avoided selecting alternative pipeline routes. However, the indirect effect of slope failure, the generation of turbidity and debris (mud) flows, could still impact the pipeline. Geotechnical investigation should identify and determine the direction, width and loads of possible turbidity flows on the pipeline during its operational life. Minor impact is experienced when debris and turbidity flows run along the pipeline in longitudinal direction. Significant impact on the integrity of the pipeline can be expected for large lateral debris and turbidity flows. Lateral curves along the pipeline route have to be assessed to ensure that they remain stable while the pipeline is exposed to debris flow along the pipeline. Where large flows are expected to reach the pipeline, trenching could be an option to ensure the pipeline is protected. For seismic active areas this option has to be carefully evaluated as ground motions at for example the trench transition area could introduce high bending moments and unacceptable stresses in the pipeline.

### 7. Design Code Selection

As part of the pipeline design exercise a design code needs to be selected that sufficiently covers all relevant design aspects of the project. Particularly for deepwater pipeline designs, the critical aspects as mentioned in the
foregoing sections need to be addressed by such code. As these are not always fully covered by all design codes, the code selection becomes an important aspect of the design process.

For the overall pipeline mechanical design, the first aspect to be considered is the wall thickness design and material grade selection. This aspect influences other design aspects; on-bottom stability, vortex induced vibration, cathodic protection, install ability, and fatigue life. Because of the various interrelations between these items a good design code should be able to give complete guides and references in a consistent manner.

The following modern international industry codes have been considered in the code comparison for offshore pipeline mechanical design:
- ASME B31.8 Gas Transmission and Distribution Piping Systems, 1999 [ref. 1]
- EN 14161 Petroleum and Natural Gas Industries – Pipeline Transportation Systems, 2003 [ref. 5]
- DNV OS-F101 Submarine Pipeline Systems, 2000 [ref. 4]

ASME B31.8 was not particularly developed for the offshore pipeline design. As its name, this code gives guidance for designing a gas transmission (onshore and offshore) and piping systems. Section VIII of ASME B31.8 discusses the offshore gas transmission. In this section, the wall thickness is calculated based on traditional Allowable Stress Design (ASD), in which design stresses are compared to a factorized yielding stress level. While this method is relatively easy to use not all the capabilities of the pipeline are fully explored, generally resulting in a more conservative design. Related to the other design aspects, this code does not give clear explanation on how to assess and what to refer to. Therefore these aspects have to be referred to other design codes.

EN 14161 Petroleum and Natural Gas Industries is the European standard and was published in 2003. Based on this code, principles of reliability-based limit state design methods may be applied but shall not be used to replace the requirement for the hoop stress due to fluid pressure. This means that the traditional Allowable Stress Design (ASD) format is still applied in the wall thickness calculation. Similar to ASME B31.8, the other design aspects are not fully explained, and are referred to other design codes.

API RP1111 is an American standard based on Limit State Design. This means that the design codes are based on the probability of failure and the structural reliability of the pipeline for different limit states. As a consequence of this method, safety design factors are applied for the loads and the characteristic resistance. API RP1111 wall thickness design is limited in that the bending safety factors are not defined. The designer then is forced to use his experience, which results in a subjective approach. For design aspects other than wall thickness references to other design codes are given; some are referring to DNV recommended practices.

Similar to API RP1111, DNV OS-F101 is based on the Limit State Design. The difference between DNV and API is that DNV provides more options and more complete design guides. Related to the other design aspects, DNV OS-F101 refers to relevant DNV recommended practices, resulting in a cohesive code structure for the complete design. In addition, this code is able to document sufficient safety for the system. The safety factors for different design conditions are well presented. Finally, this code allows the incorporation of technology development through the various resistance factors, as illustrated by the research into collapse testing and thermal ageing.

8. Conclusions

While pipeline developments reach larger water depths, the governing design criteria change from those commonly known from shallow water developments. In this paper the most important deepwater pipeline design aspects have been described, and the conclusions can be summarized as follows:

- The wall thickness design of deepwater pipelines is generally not governed by internal pressure containment but by external pressure and bending, as combined under the local buckling criterion.
- The resistance against local buckling is not only determined by the material grade, but also by the fabrication process and the dimensional tolerances of the pipe, in particular the ovality. This allows further optimization of the wall thickness design.
- A significant wall thickness reduction can be achieved by investigating the effect of the fabrication process on the collapse resistance through collapse testing. INTEC has been involved in three major collapse test campaigns, as a result of which the required wall thickness could be significantly reduced on each project.
- The capabilities of the various pipe mills in terms of D/t ratio and material grade and the capabilities of available installation vessels in terms of tension capacity for holding the pipe impose boundary conditions on the diameter and wall thickness that can be applied. These capabilities should therefore be assessed in parallel with the design, in an early phase of the project.
- The common material grades for deepwater pipeline projects are X60, X65 and X70. However for large diameter pipeline and ultra deepwater projects, X70 is often preferred as it will reduce the requirements for the capabilities of the installation vessel.
Because of the large unsupported span between vessel and seabed and the long duration before a pipe section reaches the seabed a dynamic installation analysis is required, in combination with a fatigue analysis. The fatigue analysis during lay should particularly focus on the girth welds, while the fatigue damage incurred during lay should be included in the life time fatigue analysis of deep water spans.

Geohazards that are encountered when laying pipe beyond the continental slopes, need to be considered in order to ensure the integrity of the pipeline during its operational life. Typical deepwater geohazards are seismic activity (in combination with fault movements), slope stability and turbidity flows.

A careful code selection is required to ensure sufficient safety for the system. Particularly for deepwater pipeline designs, the design code needs to be carefully reviewed to ensure that all critical deep water design aspects are suitably be addressed.

9. References


7. Biographies

Satio Braskoro was born in Semarang, Indonesia, on February 6, 1976. He is a senior pipeline engineer at INTEC Engineering BV, The Netherlands. He has been involved in many pipeline and riser projects in the North Sea and in the Mediterranean Sea. Prior to joining INTEC Engineering, he has been involved in vessel structural modifications and FPSO fatigue assessments. Braskoro holds a MSc in offshore technology from Delft University of Technology and a BS in ocean engineering from Institut Teknologi Bandung.

Thomas D.T. Dronkers is a senior pipeline. He has been involved in major pipeline projects from a conceptual level up to installation and commissioning. Prior to joining INTEC Engineering, he obtained a MSc degree in Civil Engineering at the Delft University of Technology and completed a paper at Delft Hydraulics, which was published by Coastal Engineering (Elsevier).

Martijn van Driel is a senior lead engineer. He has been involved in many of INTECs recent trend-setting deep water projects, such as the Shell Malampaya, Bluestream, Medgaz, Galsi, and IGI pipeline projects. He has detailed knowledge of the various deep water design issues, including local buckling design and collapse testing, deep water installation issues, and geohazards. He holds a MSc in offshore technology from Delft University of Technology.