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COMMITTEE V.8
RISERS AND PIPELINES

COMMITTEE MANDATE

Concern for the structural failure modes of risers and pipelines. Consideration shall be given to the dynamic response of risers under environmental conditions as well as pipe-soil interaction. Aspects related to the installation methods shall be considered. Attention is recommended for aspects related to maintenance, inspection and repair, especially in deepwater conditions.

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KEYWORDS

Flexible risers, hybrid towers, pipeline, dynamic response, *VIV*, soil-pipeline interaction, failure mode, installation, inspection and repair.

CONTENTS

1. INTRODUCTION

The immediately previous report regarding risers and pipelines is ISSC2000 Specialist Committee V.5 Structural Design of Pipeline, Riser and Subsea Systems. It represented the sequel to the report of Committee V.7 Structural Design of Pipeline Systems of the 1997 1SSC. The mandate of ISSC2000 report is as follows.

"Concern for the development of appropriate principles for life cycle—design of offshore pipeline, riser and subsea systems designed for the conveyance of fluids, including load and dynamic response. Consideration shall be given to inspection and monitoring procedures, and to the influence of operational decisions on safety."

Both reports dealt with the issues related to the structural design of pipeline, riser and subsea systems designed for the conveyance of fluids. There were two main factors driving pipeline and riser technologies during the preparation of ISSC2000 report. The first was the requirement of longer but reliable cost-reduced pipelines connecting wells and the production facilities. The second factor was the inexorable increase in water depths between 1700m and 2800m associated with the exploitation of offshore oil and gas. The contents of the report consist of load and load effect, capacity, installation, design criteria and inspection, repair and maintenance. The topics and brief outputs of the report are summarized below:

- Relatively matured subsea pipeline and riser technology with further work required for reeled steel catenary risers, deep-water flexible pipes, steel tube umbilicals, composite tubes and large bore coiled tubing for pipeline applications.
- Importance of accurate prediction of hydrodynamic loads with the aid of rapidly advancing Computational Fluid Dynamics (CFD).
- Attractive steel catenary risers for deep water applications with additional research for the in-service fatigue life of the welded joints.
- Maturity of global riser analysis except pipe-sea bed interaction.
- Necessity of challenge toVoltex Induced Vibration (VIV) especially at high Reynolds numbers and in deep water applications.

It has been fifteen years since the ISSC2000 report was published. However, the increase in water depths is still continuing and is an important factor. This increase in water depths can be located in the construction records of drilling ships. Associated with the exploitation of offshore oil and gas, Discoverer Enterprise was constructed in 1999 whose maximum water depth is 3,048m and Discoverer Clear Leader was constructed in 2009 whose maximum water depth is 3,658m. Furthermore, carbon fiber reinforced plastic (CFRP) risers for 4000–5000 m water depths are under development in the field of scientific ocean drilling to exploit the mantle (Watanabe et al. 2007). This ISSC2015 report is based on the research literature of the last ten years and describes new design concepts, dynamic response with emphasis on vortex-induced vibration, soil-pipe interaction, failure modes, installation and maintenance, inspection and repair regarding risers and pipelines.

Technical developments in this broad technical area since ISSC2000 are focused and reported from the research point of view. As a result, contents are more or less selective although the all technical fields were tried to be covered equally as much as possible.

2. NEW DESIGN CONCEPTS

2.1 Latest design practice of flexible risers

2.1.1 Present application envelope

The unbonded flexible riser is a key enabler for floating production of hydrocarbons thanks to its ability to absorb floater motions as well as direct wave and current loading by geometrical deflection of the configuration without compromising the structural integrity of the internal cross-sectional components. More than 3500 flexible pipes have been deployed over the last 40 years. This includes about 1900 flexible risers with an accumulated field experience of about 22000 years. The vast majority of flexible pipes are in the range of 4"–12" inner diameter with a few low pressure pipes up to 20". Most pipes are designed for a pressure of 3000–5000 psi, although some small diameter pipes have a design pressure up to 15000 psi. The design pressure time inner diameter is widely referred to as the performance capacity of flexible pipes. Current limit for the performance capacity is about 70000–80000 psi-inch.

The operating temperature is below 60˚C for half of the pipes, 5% of the pipes operate in a temperature range of 120–130˚C. At present, flexible risers are operating down to a water depth of 1800 m. However, roughly half of the flexible pipes are installed at a water depth less than 500m (Sparks 2003, Kenny 2010, 4subsea 2013).

2.1.2 Deep water

Weight reduction is a key design driver for deep-water application of flexible risers. This is twofold - to reduce hang-off loads as well as to improve fatigue performance as friction stresses increase with the tension in the pipe. New materials (e.g. carbon fiber) as an alternative to steel are introduced for tensile as well as pressure armors. Special challenges are related to deepwater sour service application (e.g. pre-salt petroleum production) limiting the use of high strength steel due to its limited ability to withstand the aggressive annulus corrosion environment (Paumier & Mesnage 2011, Lambert et al. 2012). A reactive polymer layer has been proposed (Epsztein et al. 2011) to eliminate H_2S in annulus and thereby allowing usage of high strength sweet service steel for applications with high H_2S content.

Segmented flexible risers are proposed to optimize deepwater flexible riser configurations. The idea is to apply different cross-section designs along the riser optimized for the main design driver at each water depth. This involves use of lightweight crosssections with high axial capacity in the upper part combined with crosssections with high collapse resistance for the lower part of the riser (Lambert et al. 2012, Rytter et al. 2002, Paumier & Mesnage 2011).

Carbon fibre tensile armours (CFA) consisting of unidirectional carbon fibres embedded in an epoxy matrix has been proposed for weight reduction as well as for improving fatigue performance as CFA is less prone to an aggressive annulus environment. As the CFA concept has limitations with regard to the compressive capacity, this can either be mitigated by riser segmentation (Lambert et al. 2012) or by combining steel and CFA by means of new profile shapes (Rytter et al. 2002) .

For deepwater risers, concerns are the dynamic axial stresses and fatigue resulting from the combined action of floater motion and riser mass. Since these stresses are transferred directly into the end-fitting, stress concentrations inside standard design end-fitting designs may cause fatigue failure (De Sousa et al. 2013). A new end fitting design has been proposed to solve this problem (Campello et al. 2012).

Another important effect is the torsion buckling phenomena that may occur due to the combined action of reversed end cap and cyclic loading either during installation or operation. This has traditionally been handled by DIP testing (Secher et al. 2011). However, a way forward with regard to faster technology qualification would be development of simplified material models that can be integrated into the global dynamic analysis. These models need to be capable of describing the coupled axial and torsion cyclic responses and may be obtained from either structure testing (Østergaard et al. 2011) or numerical analysis (Sævik 2014).

2.1.3 Shallow water

Design of flexible riser configurations for shallow water in combination with harsh environment is challenging. This is because it is difficult to obtain the required capability to absorb floater motions using traditional flexible riser configurations such as lazy wave and pliant wave. Another severe shallow water constraint is to avoid collision with adjacent structures. Use of multiwave configurations in combinations with clump weights and tethers has been proposed to achieve required static and dynamic behavior for shallow water applications, e.g. (Hanonge & Luppi 2010).

2.1.4 Singing risers

Singing risers resulting from high frequent vortices created in the corrugated profiles of flexible pipes during gas flow have been in focus in recent years. The problem is attributed to flow-induced pressure pulsations from the flexible riser's shackle-type carcass, which has a corrugated profile. When gas passes through the flexible riser, vortex shedding occurs at each of the internal corrugations, generating pressure pulsations. The pulsations are generated due to vortex shedding and shear layer instabilities at the corrugations. If a coupling occurs with an acoustic field, a feedback mechanism occurs where the acoustical field is amplified by the shear layer instabilities and the acoustical field itself magnifies the layer instabilities (Kristiansen & Wiik 2007). The result is a high amplitude tonal noise, which is called the singing behaviour of corrugated risers. No direct coupling to a mechanical eigenmode of the carcass is required to start this singing, although the acoustic-mechanic coupling can excite mechanical resonance modes. Due to the generated pulsations mechanical vibrations occur on the associated topside and subsea piping. The resulting piping vibrations could lead to fatigue failure, particularly in welded connections to the main piping. For at least one platform, this resulted in leakages in small bore side branches. Significant efforts have been made by the industry to mitigate the problem by means of new pipe concepts including new carcass designs (Belfroid et al. 2011).

2.1.5 Hybrid towers

(1) Overall layout of hybrid towers

Free standing hybrid riser technology has been introduced as a generic riser solution for development of deepwater hydrocarbon recourses (Fernandes 2003, Alliot & Legras 2005, Auperin et al. 2005, Pereira et al. 2005, Pereira, Morooka et al. 2006, Mello, Lacerda et al. 2011, Gueveneux & Le Buhan 2014, Luppi et al. 2014). The main components of hybrid riser systems are:

- A lower vertical riser section tensioned by a subsurface buoyancy module at upper end.
- Flexible jumpers to connect the upper end of the vertical riser section to the floater.

The main idea behind this solution is to obtain a cost-effective generic deepwater riser solution to the extent possible built on qualified riser technology. The lower vertical riser section has close similarities to conventional tension leg platform/spar riser solutions. The vertical section spans the main part of the water column. This allows for application of conventional flexible riser technology for the jumpers. The jumpers provide the required flexibility to absorb floater motions due to combined action of wind, waves and current. This arrangement is introduced to de-couple to the extent possible the floater motions from the vertical riser section.

The main drivers behind the development of hybrid riser systems system for deepwater floating production are (Luppi et al. 2014) related to small hang-off loads, riser disconnection in harsh environments, flow-assurance by insulation/active heating/gas lift in the vertcal riser section, small footprint, limited seabed interaction and schedule flexibility (tower pre-installation).

Free standing hybrid risers are commonly divided into two main categories depending on the cross-sectional layout of the vertical riser section:

Bundle Hybrid Risers (BHR) where the crosssection consists of multiple riser lines bundeled together in an integrated complex crosssection. Each riser line may be designed as single riser pipe or concentric pipe in pipe. Service lines and umbilicals may in addition be included in the crosssection. All lines may be enclosed in common insulation material to provide flow assurance and buoyancy during both tow-out and operating phases.

Single Hybrid Risers (SHR) where the crosssection consists of a single riser line. The riser line may be designed as single riser pipe or concentric pipe in pipe. In this case, the carrier pipe is the riser pipe itself.

(2) Buoyancy tank and interfaces

The buoyancy tank is a vital component of the hybrid riser system. The design is governed by redundant buoyancy and riser strength requirements which means that one or several redundant compartments are water-filled during normal operation. The redundant compartments allow for failure of one or several compartments due to e.g. dropped objects without compromising the overall riser system integrity.

(3) Seafloor interface

The main requirements to the seafloor termination of the vertical riser are to provide angular flexiblity, vertical anchoring and minimize the load transferred to the seafloor flow-lines. The load carrying element (carrier pipe) of the vertical riser is anchored to the foundation by means of a flex-joint, taper-joint or articulated pin-joint to minimize the bending of the vertical riser. The other riser lines are connected to the on-bottom flow-lines by spools. The required holding capacity of the foundation is achieved by means of piles, gravity base or a suction anchor. Combined pile/gravity foundation is also applicable.

(4) Installation

Installation is a crucial issue for cost-effective application of hybrid riser technology. The most challenging part is installation of the vertical riser and buoyancy tank. Possible installation scenarios proposed are offshore assembly of riser joints using offshore welding or threaded connectors and onshore assembly of the complete column and buoyancy tank. The entire structure is subsequently transported by tow-out to the field and installed by upending.

Offshore assembly is only applicable to SHR systems while tow-out/up-ending primarily is intended for installation of BHR systems but also applicable to SHR systems. Tow-out and up-ending has been introduced as a cost-effective installation method for BHR system. This allows for onshore fabrication and assembly of the riser column which is a great advantage for complex bundle cross-sections. The entire riser column is subsequently transported to the field by tow-out. The buoyancy tank arrangement may be installed on the riser column onshore prior to tow-out or connected offshore prior to up-ending. Installation by tow-out requires that the riser column is nearly neutrally buoyant.

2.2 Latest design practice of pipeline

The offshore and subsea industries recently experienced a technical revolution in the design process. Advanced methods and analysis tools allow a more sophisticated approach to design, which takes advantage of modern materials and revised design codes supporting the limit state design concepts and reliability methods. The new approach is called design through analysis (STA), where the finite element method (FEM) is used to simulate the global behavior of pipelines as well as the local structural strength. The two-step process is used in a complementary way to determine the governing limit states and optimize a particular design.

A pipeline is a primarily horizontal pipe lying on, near or beneath the seabed, normally used for the transportation of hydrocarbon products between offshore production facilities or between a platform and a shore facility (ABS 2006). Subsea pipelines are used for a number of purposes in the development of subsea hydrocarbon resources. A pipeline system can be a single-pipe, pipe-in-pipe, or bundled system. The design process for each type of line in general terms is the same, and it is this general design approach and new design concepts that are discussed in this chapter.

The general design of pipeline is performed in three stages: conceptual design, front end engineering design (FEED), and detail design. The objective and scope of each of these design stages varies, depending on the operator and the size of the project. The design approach for a pipeline is to determine, based on given operating parameters, the optimum pipeline size parameters. These parameters include pipeline internal diameter, pipeline wall thickness, and grade of pipeline material, type of coating-corrosion and weight, and coating wall thickness.

Three factors have a major influence on the final compressive strength of the pipeline: quality of plate feedstock, optimization of compression and expansion during pipe forming, and light heat treatment. By focusing on these factors together with improving the ovality of the final pipe, it is possible to obtain a collapse resistance comparable to that of seamless pipes.

A novel pipeline concept developed by Venas (2012), X-Stream, aims to solve the collapse challenge by limiting and controlling the external over-pressure. In a typical scenario, the pipeline is installed partially water-filled, thus becoming pressurized at large water depths. Then, to ensure that the internal pressure does not drop below a certain limit during the operational phase when it is filled with gas, it is equipped with a so-called inverse high integrity pressure protection systems (HIPPS). Studies undertaken during the development of X-Stream show that the weight increase due to flooding is more or less balanced by the reduction in steel weight. Some practical aspects need to be studied, such as how to install large valves in ultra-deepwater. Another aspect includes repair procedures and equipment, even though that should not be much different from normal ultra deepwater pipelines. There are also some optimizations to be performed with respect to pressure loss during operation and equalization of the pressure during shutdown. However, the potential benefits of the X-Stream concept to gas export and trunk lines at ultra deepwaters are quite significant, such as:

- Reduced steel quantity and associated costs.
- Use of standard pipe dimensions, even for ultra deepwater and large diameters, reduces line pipe costs.
- No need for buckle arrestors and for reserve tension capacity in case of accidental flooding.

When a pipeline is subject to high pressure and high temperature, its ends expanded longitudinally and exerts large forces and bending moments onto adjacent tied-in structures connected to it. The tied-in structures must be designed to withstand these expansions and forces. Dumping rocks along the pipeline or a giant spool installed at the pipeline end have traditionally been costly alternatives.

SliPIPE is a new concept developed to deal with pipeline expansion which works to reduce the end force expansion exerted at the tie-in by absorbing the end expansion through sliding within itself and simultaneously reducing or eliminating the effective axial compressive force in the pipeline (Yew 2013). The concept consists of an outer pipe connected alongside a pressure chamber and an inner pipe that can slide inside them. Seals are placed at the contacts between the pressure chamber and the inner pipe. The inner pipe slides in or out of the outer pipes in response to an axial stress that can either be more or less than a certain value. This value is predetermined in the design and causes an axial tension in the pipe wall to develop, which opposes the effective axial compressive force component arising from the inner fluid pressure. The axial tensile pipe wall force is produced by letting fluid pressure in. Between the outer pipe/pressure chamber and the inner pipe of the SliPIPE concept are two main seals, a partition wall seal, an environmental seal and a scraper seal. The seals are made of materials that allow them to function at high temperatures and pressures.

New concepts for submarine pipelines and risers have been proposed recently in order to achieve flow assurance in deepwater environments. It is the case of both pipe-in-pipe (PIP) and sandwich pipe (SP). The PIP product consists of the production pipeline being sleeved into an outer pipe with the annulus being maintained dry and filled with a high performance insulation material configured to meet the particular project thermal requirements. The outer pipe is designed to withstand both the hydrostatic pressure dictated by the project water depth and the installation methodology. The inner pipe can be located within the outer pipe by the use of centralizers clamped at discrete intervals along the inner pipeline, or as for high performance PIP system, without centralizers. The inner and outer pipe sizings are designed as a single system which is to be installed by the preferred installation method for each project–reeling, towing, S-lay or J-lay. The selection of the appropriate installation method depends on the characteristics of the field development and the dimensions of the PIP systems.

In the case of sandwich pipe (Castello & Estefen 2008), the annular layer characteristics differ from PIP by satisfying simultaneously mechanical and thermal requirements. Therefore, greater structural strength combined with adequate flow assurance can be obtained. Sandwich structures are a particular kind of composite characterized by the combination of different materials bonded together, contributing with their single properties to the global structural performance. Usually, the sandwich structure is divided in three layers: two external thin and stiff, and a central thick flexible core. The external layers are bonded to the core to allow the load transfer between the components. Numerical and experimental studies have been carried out to obtain data about the mechanical behavior of this kind of structure not very well understood so far, as done by Borselino et al. (2004) and Sokolinsky et al. (2002). Sandwich structures, i.e. light and stiff panels, have been employed in the naval industry mainly, searching the advantages associated with weight reduction, fuel economy, stability during navigation and corrosion resistance, as mentioned by Mouring (1999). It should be considered that various application of a sandwich pipes with experimental tests and numerical models for verifying the influence of the inter-layer adhesion on the ultimate strength under external pressure and longitudinal bending of new sandwich pipes.

3. DYNAMIC RESPONSE INVESTIGATION REVIEW

3.1 Riser

3.1.1 Wave load induced dynamic response

Dynamic response of risers induced by wave loads is a relatively mature topic, thus this section focusses on wave loads in conjunction with other considerations.

The simultaneous effect of local wind and swell conditions result in bimodal seas, which are observed in many locations such as Brazil and West Africa. Bimodal sea states lead to bimodal riser responses, which complicate the analysis since the regular wave approach cannot be directly applied. Tan et al. (2012) compared three methods for fatigue analysis of flexible risers subjected to bimodal seas: (1) irregular wave analysis using bimodal wave spectrum; (2) treating the swell and wind seas as separate cases and summing the damage; (3) regular wave analysis, using some equivalent wave height and period. It is found that the method (1) underestimates the fatigue damage compared to the method (2), while the method (3) over predicts the damage. Francis (2011) compared seven different methods for combining bimodal wave fatigue damage, as outlined in DNV-RP-F204 and RealLife JIP. These are the main conclusions: (i) The direct summation of fatigue damage due to swell and wind seas is generally more accurate than the DNV simplified method: (ii) Regular wave analysis is not always conservative compared to irregular wave analysis.

Using a unidirectional wave spectrum generally leads to overestimation of the mooring and riser dynamic response. Thus, proper consideration of the wave directionality and spreading is necessary for accurate assessment of the system response. Caire & Schiller (2013) investigated the effect of wave spreading on the mooring and riser systems of a spread-moored floating production, storage and offloading (FPSO) facility. The wave environment is represented as the sum of a unidirectional swell wave and multidirectional wind-generated waves with a cos-2*s* spreading function (*s* is the spreading parameter). The case studies suggested that first, the top tension of moorings are more influenced by the wave spreading compared to risers; and second, less spreading results in larger top tensions for both mooring and risers.

To ensure safe design of riser systems, it is crucial to include all relevant dynamic loads including slug flow, which can be combined with wave loads to exert a significant effect on the riser response. International standards e.g. ISO 13628-2 recommend that slug flow should be considered but provide no detailed guidance on how to incorporate slugging effects into riser analysis. Gundersen et al. (2012) developed a method to determine the remaining fatigue life of a riser subjected to combined excitation of slow flow, vessel motions and irregular wave loads. The slug loading parameters (i.e. density, length, velocity and period of slug) were obtained iteratively by calibrating riser responses with field observations. This study showed that slugging can reduce the riser fatigue life significantly (~50%). Ortega et al. (2013) investigated the effect of irregular slug flow and regular wave loads on riser dynamic response by coupling two in-house codes. One code is responsible for the global dynamic analysis, while the other code simulates the internal slug flow using a finite volume method. Information is exchanged between the two coupled programs, which are run simultaneously.

Predicting the extreme response and fatigue life of risers under wave loads is of significant practical interest. These tasks are also academically challenging. Due to the irregular nature of waves, probabilistic approaches are required to evaluate the dynamic response, and the stochastic simulations can be computationally demanding. Another complicated aspect is the non-linear and non-Gaussian characteristics of the wave loads and dynamic response. In addition, the long term variation of the sea state should be taken into consideration. Since the same scatter diagram is often used for both the fatigue and ultimate limit states of risers, an important question is whether there are overlapping sea states when evaluating the long-term extreme response and fatigue damage. In a case study by Martins et al. (2009), it is shown that there is no overlap between important regions for fatigue and ultimate limit states. The ultimate limit state is governed by extreme sea states, while the fatigue limit state involves moderate sea states.

Focusing on extreme response prediction, Passano & Larsen (2007) proposed an efficient method for predicting the short-term extreme response of a steel catenary riser (SCR) at the touchdown area. This method is based on using a small number of simulations to identify clear trends between the prescribed axial velocity at the top end and the riser responses (effective tension and bending moment) near the touchdown point. Time histories for the axial velocity at the top can be generated very quickly using transfer functions from the wave spectrum in conjunction with the fast fourier transform (FFT) technique. The effectiveness of this approach is demonstrated by comparison with longer simulations. In a sequel, Passano & Maincon (2011) proposed a fast approach for estimating the long-term extreme response of an SCR. This approach preselects the relevant sea states (23 in this study) that contribute most to the long-term extreme response. The approach compared favorably to analysis of the full scatter diagram. In addition, for each sea state considered, the relevant time intervals are identified, allowing for the simulation of relatively short time series to explore low probability events. The extreme response can also be estimated using a short-term approach by searching the 100-year $H_S - T_p$ contour for the most onerous response. Irregular time domain analyses are performed for discrete $H_S - T_p$ combinations along the contour line. This is the basis for establishing the extreme response distribution for a given duration, typically three hours. The extreme load effect is estimated as a percentile in the extreme value distribution in each sea state. Calibration against long-term response extreme value estimation suggests that a 90% percentile is applicable for flexible risers in harsh environment (Baarholm & Haver 2010). The appropriate percentile level will however depend on the riser system as well as geographical location and should be established by calibration against long-term response statistics for applications with no prior experience.

For long-term fatigue assessment under wave loads, one of the main challenges is the high computational cost of simulating all the sea states in the scatter diagram. A common approach used in industry, and is also recommended in design codes such as DNV-RP-F204, is to lump several sea states into a manageable number of blocks. The problem is that this relatively crude approach inevitably leads to errors, and there are no guidelines on effective blocking strategies. To reduce the computational cost, Sheehan et al. (2005) proposed to replace irregular wave analysis with regular waves of different wave heights and periods. The Longuet-Higgins distribution is applied to extract the regular waves from the stochastic wave scatter diagrams. Since the Longuet-Higgins distribution tends to overestimate the probability of waves occurring at long periods, waves with periods exceeding a cut-off value are disregarded. To avoid the need to select a cut-off frequency, De Sousa et al. (2013) suggested to select the regular waves by generating time series of the wave elevation from the wave spectra. Low & Cheung (2012) developed an asymptotic approximation approach for fast evaluation of the long-term fatigue damage. The asymptotic approximation is based on a second-order Taylor expansion of the logarithm of the integrand about the maximum point. The integrand refers to the product of the fatigue damage response function and the joint probability density of the significant wave height and peak period. The asymptotic approximation is found to yield reasonable estimates of the long-term fatigue damage compared to the consideration of the full scatter diagram. Perdrizet & Averbuch (2008) outlined an efficient method to evaluate the nonlinear extreme response of a riser. The first order reliability method (FORM) is used to solve the short-term extreme, while the response surface method (RSM) is used to obtain the long-term extreme response.

The excitation force from irregular waves, in conjunction with vortex-induced vibrations and wake-induced oscillations, may cause collisions between risers in close proximity, resulting in damage. He & Low (2010) developed an approach for predicting the probability of riser collision, taking into consideration the uncertainty from irregular waves. The approach is based on the crossing rates of a parameter that characterizes the critical gap between two risers. In a sequel, He & Low (2013) extended this approach to consider various parametric uncertainties, in particular the current, drag coefficient, vessel RAO and riser mass.

3.1.2 VIV

Hydrodynamic current vortex-induced vibration (VIV) among other environmental loads, such as waves and those coming from the motions of the floating production unit dynamics are the other constraints that limit viability of risers and systems. (Chaplin et al. 2005)

In this scenario, deepwater risers and novel systems have been proposed and applied last years. However, many uncertainties still remain on the design of those systems, particularly related to the VIV. Procedures established by classification societies and commercial software to estimate service life due to VIV are available (Vandiver & Li 1999, Larsen et al. 2000). Those procedures are developed, in general, based on a specific background scenario of vertical pipes or horizontal ones, although they take data from real scale measurements as the basis. Otherwise, design simulations are based on restricted data from the VIV phenomena observed in laboratory scale.

VIV is a complicated structure-fluid coupled response. In the early days of the study, understanding of the phenomenon and derivation of non-dimensional parameter were investigated based on simple model, for example spring supported cylinder in a uniform flow. In parallel to the VIV study, efforts were made to develop dynamic analysis codes of a riser under current and wave load mainly for development and design purpose of deepwater riser and SCR.

Development of VIV analysis code has soon started and some codes which use the empirical VIV force model have been developed. Now they are the standard analysis codes used in industry, but improvement and development are continuing.

The study today might be categorized into two categories a) one is research into physical phenomena oriented study, more or less scientific, and b) another is a design oriented study. Design of riser which goes into deeper water presents pressing design issues and efforts to develop more advanced analysis codes are demanded.

(1) Physical phenomenon oriented scientific research

Most of the VIV research is related to fundamental studies. A large number of numerical studies are available in the literature, sometimes with analytical evaluations as can be observed in Williamson & Govardhan (2008). Those investigations are oriented to understand the physical phenomenon which the VIV involves, and they are conducted by laboratory experiments and/or numerical simulations by use of the computational fluid dynamics (CFD). Computational work can be based on commercial computer codes, and sometimes is based on in-house developing programs. Navier Stokes equations are used to model the flow around long pipe, and in general, viscous effects are represented by turbulence models by Reynold Averaged Numerical Simulation (RANS), Large Eddy Simulation (LES) which takes into account the turbulence scale, and Direct Numerical Simulations (DNS) in which a fine mesh is usually required.

Experiments in a water channel facility were conducted with stationary and yawed cylinders to investigate effects of the inclination in the force coefficients and in the vortex-shedding frequency. Force coefficients and Strouhal number were evaluated by assuming the Independence Principle by Franzini et al. (2014). Irregular vortex shedding regime was observed when the cylinder is inclined with 45 degrees. And, they observed lift force spectra as well as the mean drag coefficient different when the cylinder is yawed with upstream or downstream orientation, respectively, due to asymmetrical end conditions performed by the cylinder. Gonçalves et al. (2013) investigated the VIV on a very short length cylinders with two degrees of freedom. Experiments were conducted with Reynolds range from 6000 up to 70000. Three small mass ratios (m^*= 1.00, 2.62 and 4.36) and small aspect ratios ($0.3<L/D<2.0$) were considered. The author reported the maximum amplitude of motion in cross-flow direction (A/D=1.5) and the response amplitude for in-line direction was A/D=0.4.

Sanaati & Kato (2013) conducted an experimental study to investigate the effects of pre-tension and axial stiffness on the VIV of a horizontally mounted flexible cylinder. Tests covered a subcritical Reynolds number range from 1000 up to 16,000. Results showed that high pre-tension can raise the lift coefficient. Also observed was that the lock-in bandwidth of amplitude response narrowed with increase in pre-tension. They also concluded that the higher the applied tensions are, the lower the vibration amplitude will be, and it could significantly raise the hydrodynamic lift force coefficient but higher applied tensions generate narrower lock-in bandwidths. In a further research, Sanaati & Kato (2014) investigated effects of proximity interference on the hydro-elastic responses of two pre-tensioned flexible cylinders in side-by-side vertical arrangement. They observed for larger separation distances between cylinders that no synchronization is observed for very small amplitudes of vibration, and the mean drag and fluctuating components of the drag and lift forces of both cylinders showed quite different behaviors.

In a series of publications, R. Bourguet et al. (2013a, 2013b, 2012) uses DNS to simulate and analyze VIV of a long flexible tensioned cylinder in shear flow for a Reynolds numbers ranging from 110 to 1100. The cylinder is allowed to vibrate in cross-flow (CF) and in line (IL) directions, and transition to turbulence in the wake is taken. Lock-in drivers to the VIV of the tensioned cylinder are investigated. Standing and travelling waves pattern in both direction as well as synchronization of the vortex shedding with the cross-flow vibration in the high oncoming velocity region, over at least 30% of the cylinder length were observed. On the other hand, in multi-frequency response, synchronization of vortex shedding exhibits in all vibration frequencies is observed. Finally, different behavior for spanwise patterns of the forces and added mass coefficients are observed within the lock-in versus the non-lock-in region.

An innovative approach for the VIV calculated from numerical simulation of the flow around a solid cylinder with movement was shown in Hirabayashi & Suzuki (2013). Numerical simulation is shown for a cylinder with movement by the Lattice Boltzmann method, and a good result was obtained for the drag force in comparison with the literature. In a further study, Miyamura et al. (2014) obtained good result for a surface piercing floating structure when the same procedure was applied and movement of the free surface was introduced to approach to the vortex-induced motion. It was concluded that the lattice Boltzman method can also represent the motion of water surface motion accurately than conventional methods. The new approach demonstrates good potential for applying to VIV in long free surface cylinders such as marine risers.

Based on a series of previous studies, Pontaza & Menon (2013) predicted VIV response of a pipeline span. A Fluid Structure Interaction (FSI) model is described by coupling a three-dimensional viscous incompressible Navier–Stokes solver with a beam finite element solver in time domain. Euler–Bernoulli beam element and instantaneous flow-induced forces are taken and solution is reached through a finite element basis functions in space and an unconditionally stable Newmark-type discretization scheme in time domain.

A selective review of recent research on vortex-induced vibrations of isolated circular cylinders and the flow and vibration of circular cylinders in a tandem arrangement has been presented by Bearman (2011).The influence of Reynolds number on the response of isolated cylinders is presented and recent development using forced vibration is discussed. Huang & Larsen (2011) made a numerical simulation on vortex-induced vibration of an elastically mounted circular cylinder with two degrees-of-freedom Two-dimensional numerical simulation using incompressible flow with RANS was carried out to obtain forces and responses associated with vortex induced vibration of an elastically mounted circular cylinder with two degrees-of-freedom. Vandiver (2012) defined a dimensionless damping parameter, $c^* = 2\omega / \rho U^2$, for cylinders experiencing flow-induced vibrations and characterized VIV for all reduced velocities in the lock-in region. Generalized the c^* parameter to characterize the response of flexible cylinder in sheared and uniform flow. Data base available from three independent outsources are used to illustrate the applications of the c^* parameter.

The hysteresis effect on the VIV on an elastically mounted rigid circular cylinder has been investigated by Wanderley et al. (2012). Numerical solution of the two-dimensional Reynolds averaged Navier-Stokes equation was obtained for this purpose.

Numerical investigation of two-degree-of-freedom VIV of a circular cylinder in oscillatory flow was shown by Zhao et al. (2013). RANS equations were used and simulations are carried out for the Keulegan–Carpenter (KC) numbers of 10, 20 and 40 and reduced velocities up to 30 with the Reynolds number ranging from 308 to 9240. From results, it was observed that the amplitude of the primary frequency is larger than other frequency components at KC=10. For KC=20 and 40 most vibrations presented multiple frequencies. Maximum amplitude occurs for reduced velocities between in-phase regime and anti-phase regime, in both the x- and the y-directions. They also combined steady and oscillatory flows, respectively, to simulate by RANS the VIV in a circular cylinder with constant KC=10 and flow ratio ranging 0 to 1. In a combined flow domain, they observed a wider lock-in region compared with that one for a pure oscillatory flow. At the flow ratio equal to 0.8 the maximum amplitude in the cross-flow direction was reached (A/D=1.5), and the widest lock-in regime occurs at flow ratio ranging 0.4 to 0.6, about twice in the pure steady or pure oscillatory flow case.

Kang et al (2013) compared experiments, one with two cylinders in tandem arrangement, and the other with a single cylinder, both exposed to an incident fluid flow. Cylinders have low mass and damping ratio. Wake induced vibration (WIV) is found, and it was observed in the near wake interference, both are exposed to VIV, but the amplitudes of upstream and downstream cylinders, respectively, both are less than that observed for the single cylinder, for cross-flow and in-line directions.

Fu et al. (2013) verified VIV in a flexible cylinder through tests performed with a harmonically forced oscillation, for combinations of amplitude and period. VIV responses in CF are investigated using modal decomposition and wavelet transformation. The results show that no VIV oscillatory flow is quite different from the steady flow. New features denominated as “intermittent VIV”, amplitude modulation and the mode transition was observed. Development process of the VIV, including its “Building-up”, “Lock-in”, and “Die-out” in oscillatory flow are defined and analyzed.

Carmo et al. (2013) performed numerical simulations in two and three-dimensional flow, around two circular cylinders with tandem arrangements. The Reynolds number was varied from 100 to 645, and results confirmed that the presence of the wake upstream of the cylinder lead to higher amplitudes of vibration when compared to VIV.

Fundamental experimental research (Assi 2012) for curved cylinder in convex and concave configurations to investigate the two-degrees-of-freedom VIV response with low mass-damping ratio was conducted. Experiment Reynolds number ranged from 750 up to 15,000. Results for those curved cylinders showed lower vibration amplitudes when compared with a straight one. On the other hand, concave cylinder configuration showed higher amplitudes of vibration than the convex one. Assi et al. (2013) investigated by experiment, into pair of cylinders in tandem, how the cylinder responds to excitation caused by wake-induced vibrations (WIV) due to the interaction with vortices coming from the upstream cylinder, characterizing the amplitude and frequency of response.

Srinil et al. (2013) presented an experimental and numerical investigation of a two-degree-of-freedom VIV of a flexibly mounted circular cylinder with variable in-line-to-cross-flow natural frequency ratio. Tests were carried out in a towing tank and subjected to a uniform steady flow in a subcritical Reynolds number range from 2,000 to 50,000. The numerical prediction was based on Duffin-Van der Pol (structure-wake) oscillators. The maximum achieved cross-flow and in-line amplitudes was 1.25–1.6 and 0.5–0.7, respectively, depending on the level and combination of the x-y structural damping ratios.

Rahmanian et al. (2012) investigated VIV of two side-by-side cylinders of different diameters in steady flow with the diameter ratio of cylinders of 0.1, and Reynolds number of 5000 considering the larger cylinder diameter. Two dimensional Reynolds-averaged Navier Stokes equations are solved by FEM, by using the Arbitrary Lagrangian Eulerian scheme with a SST k-ω turbulence model. Numerical method was validated with experimental results. It was verified that collision of cylinders is dependent on the difference of the natural frequencies of each cylinder.

(2) Riser VIV and computer code

Laboratory experiments as well as in situ monitoring of risers are essential to develop and to have a reliable riser model for designing purpose, as well as, for understanding of the riser VIV phenomena in sufficient manner to build a calibrated theoretical and numerical model. In this manner, few works have been published in the literature (Vandiver & Li 1999, Larsen et al. 2000, Nozawa et al. 2010). Recently, great effort is being conducted to describe as much as possible the VIV in risers, to develop reliable computational tools for designing riser for the VIV. They ally theoretical analysis, reduced scale laboratory model tests, development of numerical procedures and computational fluid dynamics (CFD).

A truncated steel catenary riser (SCR) model was experimentally tested in the ocean basin (Wang et al. 2014) by oscillating the top end of the model to simulate the heave and surge vessel motion in order to investigate the vortex-induced vibration (VIV) features. Out-of-plane VIV responses were generally analyzed revealing that although the root mean square (RMS) strain distributed rather a broad band, the displacement was quite consistent within a narrowband from 0.2D to 0.3D, and the touch down point (TDP) area was found not to be the place suffering the maximum out-of-plane VIV response due to near wall effects.

CFD simulations of VIVs and wake-induced vibrations (WIVs) for two vertical risers in tandem and side-by-side arrangements were performed in Chen et al. (2013). Both risers have the same outer diameter of 0.016 m, and the same total length of 1.5 m (L/D = 93.75). Numerical simulations used the unsteady RANS method. The riser inline and cross-flow motion responses were calculated using a tensioned beam motion equation.

A numerical simulation procedure based on a semi-empirical VIV model to predict dynamic response of a pipeline with free span and risers was introduced by Tsukada & Morooka (2013). Computations were carried out in time domain using finite element method, and the VIV forces are calculated based on hydrodynamic coefficients such as the added mass, lift and drag coefficients. Furthermore, the laboratory experiment in a towing tank with reduced scale model of a steel catenary riser (SCR) was described in Morooka and Tsukada (2013). The main objective of the experiment was to obtain an improved understanding of the overall dynamic behavior due to VIV in a catenary-shaped riser. A large scale model (1:250) was considered, with very low mass and stiffness for the riser model with the Reynolds number ranging from 400 to 600.

Pereira et al. (2013) conducted a reduced scale model experiment of a catenary riser, and the vortex self-induced vibrations (VSIVs) were observed experimentally. The study verified the nonlinear dynamic behavior of risers through experimentally validated analytical and numerical models.

Cheng & Vandiver (2012) presented a theoretical formulation of the dynamic stiffness method and combined the dynamic stiffness method with the WKB theory to investigate riser dynamic analysis.

Resvanis et al. (2012) explores the dependence of the Reynolds number on VIV of flexible risers. Emphasis is placed on trends existing between the Strouhal number and the Reynolds number, and between the dimensionless amplitude (A/D) and Reynolds number. Data are derived from recent experiments conducted in a towing tank that used flexible cylinders of three different diameters, in sheared and uniform currents.

Shi et al. (2012) examined the characteristics of the VIV response of a long flexible cylinder (model riser) placed in uniform or sheared currents by employing real scale measurement of strains and accelerations available from the Norwegian Deepwater Programme (NDP) experiments on an instrumented riser. The measured data was used to describe the complexities inherent in riser motions accompanying VIV. They discussed how such data sets can be used effectively in predicting fatigue damage rates.

(3) Suppression devices and fatigue

When it is not possible to avoid the VIV phenomena, suppression devices are needed at least partially along the all riser length. Many kinds of VIV suppressors have been reported in the literature discussing the effectiveness of each solution presented.

Allen & Liaps (2014) combined results from two testing programs on long cylinders towed at high Reynolds numbers to assess the performance of helical strakes with differing conditions along the cylinder length. The results show that the coverage length, density, and location of the helical strakes have a substantial effect on both the local and global response of the tubular.

Tests conducted at the MARINTEK basin by Shell Company is described by Resvanis et al. (2014). The tests involved towing densely instrumented flexible cylinders at Reynolds numbers up to 220,000, and experimental results were described to show the effectiveness of different amounts of strake coverage and to explore the influence of simulated marine growth. All results are compared with the bare cylinder cases which will be used as a reference to determine how effective the strakes are in suppressing VIV and how this effectiveness can be affected by marine growth.

Rao et al. (2013) explored the competition of the VIV excitation in smooth and segments with fairings in a flexible pipe. An eight meters long tube model (divided into three sections) was used by evaluating amplitude and frequency of the response, in Reynolds number around 37000. In the study, the flexible tube was divided into three sections with and without fairings, to understand what portion of fairing or strake coverage may be lost or damaged, before the operator takes corrective measures. Furthermore, in Rao et al. (2014), a novel method to identify the power-in regions of long flexible cylinders subjected to VIV is presented. For pipes with partial coverage of suppression devices in uniform flow, the bare region is expected to be a power-in region, and the section with suppression devices, a power-out one. Experiments are used to benchmark the proposed power-in zone identification method, and the method is used to identify the power-in zones on a bare cylinder in a sheared flow. The occurrence of secondary power-in regions that may exist is explored when suppression devices are placed in the primary power-in zone.

Experiments were carried out in Cicolin (2014), with rigid circular cylinders fitted with three different types of permeable meshes, to investigate their effectiveness in the VIV suppression. Measurements of the dynamic response are presented for cylinders with low mass and damping which are free to respond in the cross-flow direction. Results for two meshes made of ropes and cylindrical tubes are compared with the VIV response of a bare cylinder and that of a known suppressor called the ventilated trousers (VTs).

A drilling riser VIV test has been conducted by Lie et al. (2013) to verify the possible VIV suppression to improve operability of retrievable riser systems with auxiliary lines by adding riser fins. The riser model was elastically mounted and towed over a reduced velocity range around 4–10 in two different Reynolds ranges 75.000 to 192 000 (subcritical regime), and 347.000 to 553.000 (critical regime). The results showed, in general, the slick joint riser configuration with kill and choke lines increased the displacements compared to displacements of the bare riser model.

King et al. (2013) described a recent large-scale experimental test conducted with a new VIV suppression device for cylindrical structures exposed to external fluid flow. The suppressor VT is a loose sleeve in the form of a flexible liquid light with full bobbins in a particular arrangement. It is unidirectional, robust and made with material compatible with the offshore environment.

An extensive program to study hydrodynamic models of a riser related to VIV from the database obtained by the Winter test of the Shell Oil Company was conducted (Lie et al. 2012). A new test rig was built and three different riser model prototypes, each 38 meters long, were towed horizontally at different advancing speeds, simulating uniform and linear varying current sliced flow. Bending strains and accelerations were measured for the in-line (IL) and cross-flow (CF) direction along the riser model.

Saint-Marcoux & Blevins (2012) present results for two sets of hydrodynamic tests at MARIN, in a tube fitted with helical 16D and 12D polyethylene boards, respectively. The first set of tests established the suppression efficiency for intact tablets configuration (no deformation), and the second set established the performance of the same board after passing a test roll in which fins and body boards suffered from permanent deformation due to a high contact load simulated in a sting roller during an S-lay installation.

Korkischko & Meneghini (2012) present experimental results for cylinder with the other two small rotating cylinders located along the main cylinder length which injects momentum in the flow boundary layer delaying the separation of flow around the cylinder surface. Consequently, the belt becomes narrower and the oscillating transverse velocity is reduced resulting in a free zone which prevents recirculation vortex formation. The main advantage of the moving surface boundary-layer control (MSBC) is the possibility of combining the suppression of vortex-induced vibrations (VIVs) and drag reduction vibrations. Experiments were performed on an installation of the water circulation channel with circular cylinders mounted on a lower base cushion air bearing with a degree of freedom in the flow channel transverse direction. The mass ratio is 1.8.

A dimensionless damping parameter is proposed in Vandiver (2012) which can be used to characterize all VIVs in a low speed lock-in range. The simple product of the maximum amplitude and damping are shown equal to the lift coefficient, thus providing a simple method for collection of data from response measurements. Mass damping parameters are not well adapted to the organization of the response of flexible cylinders in CFs or cylinders equipped with vortices suppressor or fairings. The dimensionless damping parameter is well suited to use in constant flow or the cylinder partially covered with vortex suppression fairings or data from three independent sources are used to illustrate the applications of the dimensionless damping parameter. It is shown that the method of modal analysis can be used to generalize the application of this parameter in flexible riser.

(4) VIV and fatigue

Besides the use of the suppression devices in the presence of the VIV, risers are exposed to fatigue. Then, fatigue life and reliability associated are essential to be verified in riser design. Several investigations have been conducted regarding the VIV fatigue and published in the literature in the past (Iranpour & Taheri 2006, Modarres-Sadeghi et al. 2010).

In a recent work of Passano et al. (2014), re-examination of the VIV fatigue is conducted with the basis of the Norweigian Deepwater Program through laboratory tests with a 38 m length riser pipe model. The observed response behavior is compared with the predicted VIV response and fatigue analysis result. Empirical coefficients from the experiment used to estimate riser behavior through a numerical simulation program such as VIVANA presented improved agreement with regard to amplitude and frequency of the response.

Comparative investigation is conducted in Jhingran et al. (2012) for the ability of helical straps and fairings, respectively, effectively suppress the VIV. Database from different test programs with a suppressor are classified, and performances observed for each suppressor device has been evaluated. Effects of the main parameters are analyzed, among those Reynolds number, surface roughness, interference, and coverage density.

Fontaine et al. (2011) demonstrated the calibration methodology to derive consistent values for the factor of safety (FoS). Evaluation used the most commonly used VIV prediction software by industry, and it was based on medium scale VIV available data. Results emphasize the need for a coherent approach to estimate the FoS, and software improvements on monitoring and measurement to reduce risk of failure if the influence of such improvements on the FoS is not quantified.

(5) VIV considerations for flexible risers

For dynamic risers, the governing load contributions result from wave and currents loads and associated floater motions. In addition VIV may also be a concern, especially for deepwater risers where high tensions and external pressure may limit the amount of hysteresis damping. It has not been possible to find references to documentation of field observations of VIV response of flexible risers in public domain. However, laboratory tests show that umbilicals with comparable structural damping may experience significant VIV response (Lie et al, 2007). As of today's practices, wave and VIV loadings are treated by separate models e.g. (Zhang & Tan, 2011). Whereas, the nature of wave responses includes large response amplitudes that requires a non-linear response model, empirical models such as Shear7 and Vivana assume a linear frequency domain model and small response amplitudes. In order to describe the extreme responses, the effect of VIV is included in the time domain model in terms of selecting the drag coefficient such that drag amplification from VIV is included. For fatigue calculations, the fatigue damage is obtained from separate models where the total damage is calculated as the sum of the wave and the VIV contributions. Significant uncertainties are present when applying these models with regard to the assumption of time and mode sharing as well as damping. For flexible pipes, the hysteresis damping will influence the dynamic response, and this is particularly the case for VIV calculations. In a time domain procedure this can be handled directly by applying an elastic-plastic material model for the pipe in bending (Smith et al. 2007). For VIV frequency domain response models, the equivalent damping coefficient related to each mode can be handled by iteration according to the procedure proposed by Sødahl et al. (2011). The moment curvature diagram needed for such procedures can be obtained from full-scale measurements or from FE models. Research is ongoing with regard to developing VIV time domain models that allows non-linear structure response effects to be included directly (Thorsen et al. 2014).

3.2 Free span VIV of pipeline

Vortex induced vibration (VIV) can lead to fatigue as well as ultimate stress-based failures at unsupported pipeline sections. Unsupported sections may exist directly after installation due to the seabed profile and/or develop with time due to soil movements. Two different types of VIVs (In-line and cross-flow) are mainly considered as shown in Figure 1.

In-line vortex-induced vibrations can lead to fatigue damage due to the high number of cycles. Cross-flow vibrations may also lead to fatigues damage. However, high stresses can also be induced due to the high vibration amplitudes which can be created by this type of vibration.

3.2.1 Assessment

The design against free span failure is an initial part of the design of an offshore pipeline. Most of the pipelines are designed using DNV RP F 105. This code provides easy, usable screening criteria for measured free span and comprehensive analysis methods like the force model and the response model.

Currently research is carried out regarding realistic soil parameter for the analyses (Yaghoobi et al. 2012), in which simplified approaches are proposed and the approaches are compared (Bai & Duffy 2014, dos Santos et al. 2014).

Additional codes are e.g. ABS Guidelines. Comparisons between the codes have been carried out (Bakhtiary et al. 2007). Besides this design codes, local requirements concerning e.g. the maximum allowable height in order to avoid hooking exists. Currently some joint industry projects (JIPs) are planed/running, e.g. for the Free Spans in Trenches (DNVGL), Understanding of VIV (BV), Free Spans (ITF).

Additional research is currently carried out concerning assessment of free spans in operation (Raposo et al. 2014) and combined effect like walking, lateral buckling and free spanning (Duan et al. 2014).

3.2.2 Mitigation

Regular surveys are normally performed, depending on the seabed activity, measuring the length and height of free span. If the length or height is above the acceptable criteria as described above, mitigation measures are taken. The mitigation of free span VIV is mainly done by seabed preparation, trenching, stones/gravel, installation of mitigation devices, see e.g. Wang et al. (2011) for details and mitigation assessment methods.

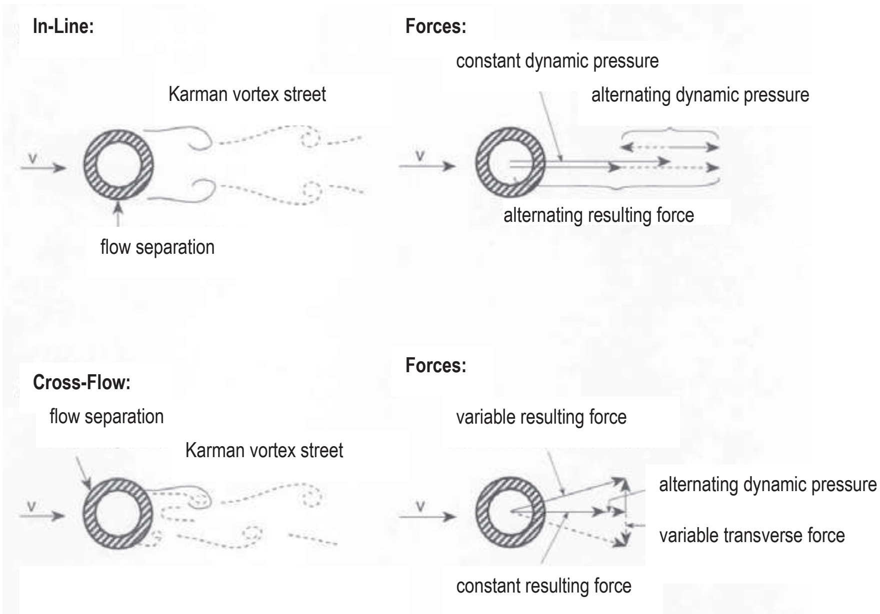

Figure 1. In-line and Cross-flow VIV.

4. SOIL-PIPELINE INTERACTION

4.1 Introduction

Pipelines are the arteries of offshore hydrocarbon development. They transport the hydrocarbon products and other fluids between wells and in-field processing facilities and also to shore. As the offshore pipelines are laid along the seabed, the pipeline-soil interaction and, in particular, the geotechnical issues must be captured adequately in the design process. Pipeline geotechnics is an emerging specialty that involves applications of geotechnical theory and practice unique to the construction of underwater pipelines. Existing pipeline design codes that are known to offshore industry, include API1111, DNV-OS-F101 and ABS *Subsea Pipeline Guide*.

For on-bottom pipelines, the geotechnical design inputs primarily relate to the interaction forces between the pipeline and the seabed in the vertical, axial and lateral directions. Numerical methods used to design against upheaval buckling require not only the ultimate capacity but also the displacement response to mobilize this capacity. Much less interest has been shown on uplift displacements to reach failure but Finch et al. (2000) proposed guidelines based on their experimental program.

Pipelines are laid on the seabed and may or may not be buried. When a pipeline is not buried, the interaction between the pipeline and the seabed results into many aspects of the pipeline design issues. One of the most difficult aspects in pipeline design, which is an increasing challenge as higher operating temperatures and pressure in deepwater applications, is the management of thermal- and pressure-induced loading. Large pressure and temperature changes during operating cycles generate high axial compressive stresses leading to buckling. Buckling is precipitated by axial stresses on the pipelines while axial and lateral resistance to pipeline movement comes from the soil. Uncontrolled buckling can cause serious damage to the pipeline. In shallow water conditions, pipelines are often laid in pre-dug trenches and buried to prevent bucking. However, this approach is not feasible in deep water. A cost-effective solution is needed to facilitate controlled buckling at prescribed locations along the pipeline, thereby relieving the axial stresses. Another major challenge for pipeline designers is progressive axial movement of the pipeline or pipeline walking, which is significantly influenced by lateral buckles along the pipeline. Pipeline walking is a phenomenon in which start-up/shutdown cycles cause a ratcheting response in the pipe axial displacement. Both controlled lateral buckling and pipeline walking are very sensitive to soil-pipeline interaction and there remains significant uncertainty associated with the characterization of the pipe-soil interaction forces in design. If the pipeline must be buried for stability or to avoid fishing gear, the shielding of the pipeline via the construction of a trench usually requires proper geotechnical design.

This document first introduced the typical soil behavior near the pipeline in Section 4.2. Then the state-of-art review of geotechnics for subsea pipeline is provided in two design scenarios. One is high operating temperatures and pressure pipe in deepwater application, where the management of the thermal- and pressure-induced expansion is a critical design issue. These include assessment of pipeline embedment (Section 4.3), lateral pipe-soil interaction (Section 4.4) and axial pipe-soil interaction (Section 4.5). Another design scenario is the on-bottom pipeline stability under extreme hydrodynamic loading from storm-induced currents and waves in shallow water. Geotechnics of pipeline trench construction by ploughing and jetting (Section 4.6) is reviewed as well as sediment transport and the liquefaction around the pipeline (Section 4.7).

4.2 Soil behavior near pipelines

The in situ soil shear strength profile is important for estimating the initial penetration of the pipeline and the soil resistance to the lateral displacement, both of which may involve cycles of remoulding and reconsolidation of soil. Flow-round penetrometers, such as T-bar or ball are superior to cone since they allow cyclic penetration and extraction tests to be undertaken. Laboratory testing of reconstituted material recovered from the seabed, is used to assess interface friction angles and remoulded strengths at the very low effective stress levels relevant for pipeline design. After comparison of tilt-table, shear box and ring shear test results on high plasticity clays from offshore West Africa for normal effective stress levels ranging from 2kPa to 300kPa, White & Randolph (2007) indicates a broad trend of residual friction coefficient. The simple expression given by Bolton (1986) to link stress level and peak friction angle in sands captured the same trend.

The pipeline geotechnical design requires determination of the geological history of the area, the seafloor soil characteristics from laboratory and in situ tests, and appropriate analysis to ensure that the pipelines can safely resist the operational and environmental forces. The seabed deposits are often normally consolidated and extremely soft and compressible near the seafloor. Some also exhibit unusual behavioral characteristics, e.g. calcareous sands or Arctic silts, and there is only limited experience with pipeline design in such soils. Current design approaches are only good if soil follows a certain pattern of behavior, e.g. they do not lose strength suddenly. Most pipeline laterally buckling/axial walking experimental studies were conducted in the centrifuge using kaolin, West African clays or silicone sand in the University of Western Australia and the large-scale pipe-soil test facility at the Norwegian Geotechical Institute (Langford et al. 2007). When calcareous sand was first encountered in offshore, people did not understand how it behaves, and this led to a lot of problems e.g. piles disappearing into the ground, loss of capacity etc. Also, the problems of pipeline behaviors under static and cyclic loading, although long recognized, continue to engage the attention of several research groups and to defy simple solutions.

4.3 Pipeline as-laid embedment and riser touchdown

Accurate prediction of the as-laid embedment is crucial to the assessment of pipe-soil resistance, pipeline lateral buckling formation due to initial load, the buckling response, end expansion and walking behavior due to system shutdown and restart cycles. The static pipeline embedment in fine-grained sediments has been well investigated/understood using plastic limit analysis solutions and finite element analysis (Murff et al. 1989, Aubeny et al. 2005, Randolph & White 2008a, Merifield et al. 2008). However, the observed as-laid embedment in soft soil is much greater than the penetration of the pipe into soil under its submerged weight even when the stress concentration created within touchdown zone by the catenary shape is considered (Lund 2000, Cheuk et al. 2008, Westgate et al. 2009).

The additional major embedment is due to dynamic lay effects which arise from oscillation of the suspended section of pipe, originating from the lay-vessel motion and hydrodynamic loading. The mechanisms that govern the dynamic embedment at the touchdown zone are not easy to quantify. The vertical pipe motions will raise the vertical pipe contact force associated with longitudinal translation of touchdown point accompanied by changes in pipe tension. The dynamic pipe moments soften and remold the surrounding soil, leading to the reduction in soil strength and bearing capacity. The horizontal motions also reduce the vertical bearing capacity due to the combined V-H loading imposed on the seabed (Merifield et al. 2008, Randolph & White 2008b, Cheuk et al. 2008). Moreover, a narrow trench will be created due to horizontal motions. As a result, in practice, a dynamic embedment factor f_{dyn} is commonly applied to the calculated embedment using plastic limit analysis solutions to account for dynamic effects. Previous studies have reported that the f_{dyn} factor is in the range of 2–10 (Lund 2000, Bruton et al. 2008). As a result, the prediction of as-laid pipe embedment can be associated with significant uncertainty. In order to reduce this uncertainty in design, the fully remoulded strength coupled with the static overstress is recommended (Westgate et al. 2010, SAFEBUCK Design Guideline 2011). It is also attractive to set the geotechnical components of pipeline analysis within a full probabilistic framework. This is consistent with the probabilistic structural reliability analyses that are increasingly performed during the assessment of pipeline on-bottom stability or lateral buckling (SAFEBUCK Design Guideline has adopt this novel approach).

4.4 Lateral pipe-soil interaction

Subsea pipeline behavior in deepwater has been studied over the past ten years in attempts to improve understanding of lateral buckling and pipeline walking. One such key research program is the SAFEBUCK Joint Industry Project (JIP) which was initiated in 2002. The SAFEBUCK JIP has been supported by a number of major oil and gas organizations worldwide. This program has led to new design guidelines for on-bottom lateral buckling covering single pipe and pipe-in-pipe systems (SAFEBUCK Design Guideline 2011). A significant part of SAFEBUCK involved research into pipe-soil interaction during lateral buckling, which is the largest uncertainty in design. This has led to a number of key insights into the fundamental pipe-soil behavior and the development of simple models to simulate this behavior (Cheuk et al. 2007, Bruton et al. 2008, Dingle et al. 2008, White & Cathie 2011).

The general form of the lateral response during the first load includes a breakout peak followed by a residual or plateau resistance. In clay soils, the breakout peak can arise from the loss of suction and therefore tensile resistance at the rear face of the pipe. After breakout, two characteristic types of lateral response ("light pipe" and "heavy pipe") can occur, depending on the ratio of pipeline weight to the seabed strength. For the clay soils, this ratio could be defined as V/suD; where V is the flowline weight, su is the soil undrained shear strength and D is the pipe diameter. Observing in centrifuge model tests conducted for the SAFEBUCK JIP (Bruton et al., 2008), values of V/suD<1.5 give a "light pipe" response, characterized by the pipe rising during the initial breakout. Values of V/suD>2 give a "heavy pipe" response, characterized by the pipe diving during the initial breakout. For "light pipe", as the pipe moves upwards the soil surface, the lateral resistance usually reduces from the breakout value to a steady residual value.

Large amplitude cyclic model tests were carried out to investigate pipe-soil interaction during pipeline operating cycles (White & Cheuk 2008, Bruton et al. 2008). It is found that surface soil, swept ahead of the pipe on each cycle, builds up into soil berms at the extremes of the pipe displacement. The residual resistance during the first load controls the lateral displacement at which the first buckle stabilizes, defining the initial shape of the lateral buckle and the peak bending stress in pipe. While in "heavy pipe" case, the pipeline moves downwards after the initial breakout resistance is mobilized. This downward movement, coupled with the growth of a soil berm ahead of the pipe, leads to a steady increase in the lateral resistance. This hardening form of response could increase the loads in the buckle while simultaneously inhibiting lateral displacement. These soil berms offer significant resistance to pipe movement and define the shape of the buckle in operation. Same as lateral response in the first load, two characteristic types of lateral response ("light pipe" and "heavy pipe") can occur during start-up/ shutdown cycle. The 'light pipe' showed a similar lateral response as its first load response. The residual friction factor remained approximately constant throughout each cycle until the static soil berms were reached. The 'heavy pipe' showed a contrasting lateral response. During the first lateral sweep of 2-D amplitude the pipe embedded deeper than 1-D. This increasing pipe embedment depth caused a sharp increase in the lateral resistance and no steady residual value was reached.

For design purposes, the variation in lateral resistance can be estimated from a geotechnical analysis that considers in detail the mechanisms described above. Then, to incorporate the results into the pipeline structural analysis, they can be converted into simple relationships. Currently, the simple Coulomb frictional model based on total stress framework was adopted in design calculation. In latest SAFEBUCK GEO JIP (started in 2010), the lateral pipe-soil response has been addressed in design by a new 'force-resultant plasticity model' which captures results from modeling and testing of lateral pipe-soil inter action and is designed to be used with standard software packages (Martin 2013). However, the soil-pipeline contact is still modeled in total stress terms and pipeline-soil interface is assumed to be completely cohesive and is defined by a stress-independent and time-independent interface resistance. This clearly does not address the heaping and remoulding of the soil around and beneath the pipeline as well as the issue of generation and dissipation of excess pore pressure and its effect on the stiffness and strength of the soil over time.

4.5 Axial pipe-soil interaction

Axial response can vary significantly for different types of soil, weights of pipe, coating roughness and pipe velocity (in clay soils). Recent model tests indicate that axial friction is strongly influenced by pore pressure, consolidation and the level of drainage during sliding (White et al. 2011). In general, pipe displacement generates excess pore pressure (undrained condition). The excess pore pressure (normally positive) tends to increase with increasing pipe velocity, giving a low residual axial resistance. If pipe displacement is very slow such that excess pore pressure is dissipated as fast as it is generated, this fully drained condition will give a gradual increase to a significant high level of residual resistance. These undrained (fast) and drained (slow) responses generally represent the lowest and highest values of axial resistance. In typical field condition, the response is likely to lie between the undrained and fully drained conditions. Currently the important transition from undrained to drained condition is not well understood and conventional design calculations do not provide adequate predictions of the observed behavior.

A model for axial pipe-soil interaction using the critical state theory has been proposed based on current axial test database (Hill et al. 2012, White et al. 2012). The key feature in this proposed model is the consideration of excess pore pressure which significantly affects the axial resistance. However, this model is still in a descriptive stage; it is therefore not really useful from the design calculation purposes. It is also largely limited to undrained condition. Although a simpler model for the axial resistance prediction has been proposed (Randolph et al. 2012), it is based on a number of simplified assumptions such as 1-D consolidation, assumed depth of pore pressure influence and elastic consolidation. This simple model is unlikely to be applicable to more complex situations that involve buckling and axial displacement. Moreover, the current database is limited to a few high quality tests in very soft, high plasticity West African clays using some selective representative pipes (mainly 8’’ and 12’’ pipes). Influence of pipe diameter, permeable coating, soil properties and cyclic or repeated loading remains largely unknown. The currently limited axial test database also does not yet allow full validation of any proposed model.

4.6 Pipeline stability during trenching and backfilling

A pipeline trench may be carried out before the laying process or afterwards. Pipeline trenching was historically performed using jetting, but mechanical ploughing or cutting has become an increasingly common approach. Different trenching techniques are suited to different ground conditions. Recently a unique concept of the Arctic subsea bucket ladder trencher was developed which is suitable for Arctic conditions. Ploughing, cutting and jetting are often used in combination on a single machine. In shallow water, dredging technology may be used to create a trench. Studies were conducted to assess the ploughing resistance for sleds and ploughs. In dilatant sands, the ploughing force can be significantly increased if undrained or partially drained conditions prevail (Reece and Frinstead 1986). The mechanics of pipeline plough performance are described by Palmer et al. (1979) and recent studies have examined the performance of ploughs in uniform sand and in sand waves (Palmer 1999).

Jet trenching techniques use high-pressure jets of water from nozzles suspended beneath seabed level to cut, erode and fluidize soil. Then pipeline is lowed into the area cut or fluidized by the jets. For sandy soil, the trench walls are not stable and pipe lowing is dependent on the pipeline being heavier than the fluidized soil. Moreover, there must be sufficient weight margin to ensure that the lowing of the pipeline is not affected by the turbulence and upward flow of water behind the trencher. White & Cathie (2011) suggested a minimum specific gravity (or unit weight) is believed to be approximately 1.8. However, this is without conclusive experimental support. A mathematical model of the jet trenching process in sand has been developed by Berghe et al. (2008) and Peng & Capart (2008). This model is calibrated by a series of 1g model tests. Both the results from model tests and the mathematical model indicate the dependence of the progressive rates of jetting power and sand density, and capture the main phenomena of sidewall collapse and overspill. For clays, the soil is cut and broken up by jets. After that the essential mechanisms are similar as in sand except the clay is not fully disaggregated. To minimize the risk of floatation in clays, Powell et al. (2002) suggest that the pipeline specific gravity should be greater than the specific gravity of a liquefied clay at the onset of effective stress. However, Cathie et al. (2005) believes that the problem of pipeline lowing and stability in clays is mainly dependent on the amount of slurry left in the base of the trench. The suggestion by Powell et al. (2002) may not be useful as the design criterion as the pipeline specific gravity is normally greater than the specific gravity of most muds.

Large plough which is towed by a vessel is also used to create a pipeline trench. A typical pipeline plough comprises skids ahead of and behind a heavy ploughshare. For most ploughing cases, pipeline stability is not an issue since the pipeline is lowered into the cut trench as the plough moves forward.

However, Cathie et al. (1996, 1998) found backfill ploughing can lead to pipeline uplift. As suggested by Cathie et al. (1998) and Powell et al. (2002), there are several factors that combine to lead to the uplift. Flow of soil down the slope of the trench is an important cause of uplift since high transient uplift forces are generated when soil impacts the pipeline. A backfill plough creates turbulence and in-line water flow, and liquefaction of backfill can also cause uplift of a lightweight pipeline. Based on their model tests, Powell et al. (2002) found uplift does not occur if the pipe is sufficiently heavy. The suggested minimum specific gravity (or unit weight) is approximate equal to 1.8. Accurate prediction of pipeline plough performance is also critical for offshore design. The variation of tow force with plough weight and trench depth is reasonably well-known (Reece & Grinsted 1986). Since the plough velocity affects the tow force, the effect of plough velocity has been considered in the current prediction models (e.g. Cathie & Wintgens 2001). In the earlier prediction models, only basic theory and a limited data set of previous trenching were utilized for the calibration. In order to improve the understanding of plough resistance, further experimental and numerical studies have been carried out (Bransby et al. 2005, He et al. 2005, Lauder et al. 2008, Lauder 2010, Peng & Bransby 2011). The results show that the plough resistance is believed to have two components, which are static and dynamic components. This is broadly confirmed by the mode of Cathie & Wintgens (2001). The static component is approximated well in existing solutions, but the passive pressure coefficient and dynamic component may need further improvement.

Current researches on pipeline stability during trenching and backfilling are mainly on the 2-D aspects of the problem and only on soil mechanics. However, uplift limitation and propagation during trenching and backfilling is a 3-D problem and involves pipeline structural response, soil transport and deposition, and consolidation. All of these aspects need to be investigated integrally in the future.

4.7 Pipeline stability during sediment transport and liquefaction

In the shallow waters offshore Australia, the on bottom pipeline stability under hydrodynamic loading from storm-induced currents and waves is a significant design issue. The mobility of the seabed may appear in the form of sediment transport and liquefaction which is not considered in current design methods.

In order to improve design reliability through better underlying science, the physical modeling of wave-induced liquefaction and sediment transport has been carried out in the University of Western Australia (Henning et al. 2013). From their experimental results, it is found that different soils may become mobile due to sediment transport and/or liquefaction. Specifically, the selected North West Shell (NWS) sandy SILT and very silty SAND will both liquefy and move due to sediment transport forces in sufficiently large cyclonic events (i.e. 100 year return periods). In contrast, the laboratory SAND and the silty SAND will only succumb to sediment transport because these sediments dissipate excess pore pressures quickly and avoid full liquefaction. The weakest storm event showed no sediment transport and only full liquefaction for the sandy SILT. The laboratory observations of sediment transport show that these NWS sediments, particularly those with a significant fraction of fines, have a different mobility to that predicted using conventional methods calibrated to clean siliceous sands.

Henning et al. (2013) also suggested that the simple pore pressure model from Verruijt [4] can illustrate liquefaction trends very clearly, but shows several disadvantages which include an inflexibility that hampers accurate calibration of the model parameters and, hence, an inaccurate development of the excess pore pressure rate. Other models should be investigated to model liquefaction.

The investigation of wave-induced liquefaction and sediment transport is still ongoing, the future research will focus on better defining and quantifying the erosion mechanisms of sediments, particularly those which exhibit behavior described as 'cohesive', as well as clarifying the nature of the 'frictional' seabed shear stress required to drive erosion (Henning et al. 2013). A better understanding will allow for a more accurate prediction of the threshold shear stress and erosion. This is a particularly urgent need in regions such as the NWS, where there is no distinction between 'clean' and 'cohesive' sediments, but instead a continuous spectrum from coarse to fine soils, often poorly sorted with widely mixed particle sizes.

A joint industry project (JIP) is now being proposed which will aim at identifying state-of-the-art design methodologies for mechanically stabilizing pipelines and thereby controlling movement by Geomarine and Crondall Energy. The aim of the JIP is to streamline the selection and optimization of secondary pipeline stabilization schemes by providing design guidance and a framework for comparative assessments of different schemes. These schemes include the application of rock dumping, concrete mattress, block placement, suction anchors, small diameter driven piles, drilled and grouted micro-piles, etc.

5. FAILURE MODES OF RISERS AND PIPELINES

5.1 Steel riser and pipelines

Since the 1970s, offshore oil and gas development has gradually proceeded from shallow-water installations up to around 400 m to the ultra deep waters around 3,000 m that represent the maximum today. The main design challenge for development beyond 3,000 m is related to the high external pressure that may cause collapse of the pipeline. From depths of 900 m onwards, external over-pressure is normally the most critical failure mode for pipelines. The risk of collapse is typically most critical during installation when the pipe is empty and external over-pressure is at its maximum. In addition, the pipe will be exposed to large bending deformation in the sag bend during installation that may trigger collapse, and collapse may be relevant for operational pipelines subject to significant corrosion. This potential failure mode is dealt with by increasing the pipe wall thickness. But at ultra deepwater depths, this may require a very thick walled pipe that becomes costly, difficult to manufacture, and hard to install due to its weight (Lee et al. 2014). Currently, there is a practical limit on wall thickness that limits the maximum water depth for 42-in. pipes to around 2,000 m. However, for a 24-in. pipe this limit is approximately doubled to 4,000 m based on developed drilling and production capacity. Those factors will be a major influence on the final compressive strength of the pipeline.

Current deepwater gas pipelines have thick walls and, due to quality and safety requirements, the number of pipe mills capable of producing the pipe is limited. When installing pipelines, the heavy weights are difficult to handle and the thick walls are challenging to weld. The number of pipe-laying vessels for deepwater pipelines is limited, too. New offshore oil and gas fields are being developed in deeper and deeper waters and export solutions for the gas are critical. New exploration activities are also heading for ultra deep waters. According to new exploration, transporting oil and gas from high-pressure and high-temperature reservoirs through pipelines is also a major challenge. A pipeline laid on or buried in the seabed responds to high pressure and high temperature by expanding, resulting in axial displacement (also known as end expansion), lateral buckling, upheaval buckling, or a combination of these. Such pipeline movements can cause failures and are critical to the integrity of a pipeline.

The number of potential failure modes for a multilayer structure such as a flexible pipe is high. However, the number of different failure modes experienced in operation is more limited. API (2007), PARLOC (2001) and Cosham & Hopkins (2004) list and describe all of the most probable failure modes and defects for a pipe. The use of this reference is highly recommended to get a complete overview. The potential causes and effects of damage during installation phase of the pipelines are summarized in this section.

5.1.1 Buckling (buckle propagation), collapse and fatigue failure

Lateral (horizontal) and upheaval (vertical) buckling are possible in subsea pipelines. Lateral buckling is usually associated with unburied pipelines at areas where the alignment is curved, whereas upheaval buckling will be on buried pipelines at over bends, where the profile is convex upward.

The key integrity issues are structural over-stress and fatigue failure, short and long term. Offshore pipelines are required to operate at even higher temperatures and pressures (DNV-RP-C203 2005, DNV-RP-F108 2006). The resulting high axial stress in the pipe wall may lead to unexpected buckling, which may have serious consequences for the integrity of the pipeline if this is not taken into account during the design phase. Unexpected lateral buckling has been observed in several operating pipeline systems.

The offshore industry lacks a complete understanding of lateral buckling, and efficient tools for simulating buckling behavior early in the design phase would make a valuable contribution to our knowledge (Chiodo & Ruggieri 2009, Gong et al. 2013, Netto et al. 2005).

Uncontrolled global buckling can cause excessive plastic deformation of the pipeline, which could lead to localized buckling collapse or cyclic fatigue failure during operation due to multiple heat-up and cool-down cycles, if it is not properly managed. The most relevant failure modes of pipeline lateral buckling may include loss of containment, as result of fracture failure on the tensile side of the cross section, due to excessive utilization and low cycle fatigue under cyclic thermal loads. When a pipeline on the seabed is heated, it tends to expand, and the expansion is resisted by the friction generated by the seabed. When the pipeline is cooled, it contracts, but the seabed friction resists the moving pipeline's return to the original position. If heat-up/cool-down cycles involve significant thermal gradients, then axial ratching of the pipeline can occur, with displacement toward the cold end. Over a number of cycles, this movement can lead to very large global axial movement with an associated overload of the spool piece or jumper at the pipeline end. This cumulative axial movement is called pipeline walking (Bai & Bai. 2014). The phenomenon of lateral buckling and walking of pipeline has been widely investigated over the past decades.

Deepwater pipelines are normally subjected to external pressure and bending, and they are designed to prevent buckling and collapse failures. But a pipeline that is locally damaged may collapse and, if the hydrostatic pressure is high enough, the collapse may propagate along the pipeline. The collapse propagation pressure is the lowest pressure value that can sustain the collapse propagation. Since the external collapse propagation pressure is quite low in comparison with the external collapse pressure, it is necessary to install buckle arrestors, at intervals along the pipeline, with the purpose of limiting the extent of damage to the pipeline by arresting the collapse propagation (Netto & Estefen, 1996).

Buckle arrestors are devices that locally increase the bending stiffness of the pipe in the circumferential direction and therefore they provide an obstacle in the path of the propagating buckle. There are many different types of arrestors, but all of them typically take the form of thick-walled rings. The external pressure necessary for propagating the collapse pressure through the buckle arrestors is the collapse cross-over pressure. Previous studies presented finite element models that simulated the collapse and post-collapse behavior of steel pipes under external pressure and bending. Those finite element models were used to analyze the effect of different imperfections on the collapse and collapse propagation pressures of the steel pipes (Toscano et. al. 2008, Toscano et al. 2002, 2003, 2004, Ramasamy & Ya 2014, Gong & Li 2015).

Many experimental results are available in the literature for the cross-over of integral buckle arrestors under external pressure (Gong et al. 2012, Lee & Kyriakides 2004, Olso & Kyriakides 2003, Lee et al. 2008, Estefen 1999, Netto & Kyriakides 2000a, 2000b).

In deepwater applications the carrier pipe must be designed to resist collapse due to the ambient external pressure while the design of the inner pipe is primarily based on the pressure of the hydrocarbons it carries. The collapse of relatively thick pipes under external pressure has been studied extensively and is quite well understood. Moreover, the buckle propagation phenomenon in pipe-in-pipe systems under external pressure was studied in combination with hyperbaric chamber test, uniform ring collapse model, and numerical simulation (Kyriakides 2002, Kyriakides & Vogler 2002, Kyriakides & Netto 2002) which put forth an empirical formula of the buckle propagation pressure for two-pipe systems through the fit of limited test data. Lourenco et al. (2008) applied a non-linear three dimensional finite element model to conduct an extensive parametric dependence analysis of the quasi-static buckle propagation in sandwich pipes, and further investigated the actual contribution of the core material to the propagation pressure.

5.1.2 Corrosion

The corrosion phenomenon in the oil and gas pipeline system is a serious problem in the petroleum industry today. Previous reports (PARLOC 2001) have shown that failure mechanisms for offshore pipelines are strongly linked to damage caused by corrosion and external loads as shown in Table 1. Corrosion problems may occur in numerous subsystems within the offshore oil and gas production system, including the gas and oil pipelines. It is recognized as one of the most important degradation factors of pipeline metallic material and a great concern in maintaining pipeline integrity. Also, corrosion tolerance must be carefully considered in the design of a pipeline (Bai & Bai 2005, Bai & Bai 2014, Klever 1995, Mohd & Paik 2013).

Previous studies have assessed the importance of corrosion damage evaluation for numerous structures, including gas pipelines and offshore structures, and assessed their mathematical models (Gabor & Lazlo 2012, Kim et al. 2013, Kyriakides & Corona 2007, Mohd et al. 2013, Paik &Thayamballi 2007, Teixeira et al. 2008). Also, there are lots of methods (codes) in the engineering practice to determine the burst pressure of corroded pipes depending on the loadings and the scopes of the pipelines (Adib-Ramezani et al. 2006). These semi-empirical methods based on measurement data (ASME B31G, Modified ASME B31G, DNV RP101) consider only the length and depth dimensions of the simple 2-D geometrical shapes which are used to approximate the real corrosion failures.

Table 1. Allocation of failure mechanisms for offshore pipelines.

Failure mechanism	Distribution
Corrosion	36%
Material	13%
External loads causing damage	38%
Construction damage	2%
Other	11%

5.1.3 Crack

Stress corrosion cracking can be a serious threat to the integrity of natural gas and petroleum pipelines (Palmer& King 2004, Bai & Bai 2005, Oh et al. 2007). The pipeline industry responded to this threat by performing a comprehensive research program to determine the causes of the failures and investigate various techniques (Nyhus et al. 2005) for preventing future failures. A relatively concise list of discoveries has had a measurable impact on mitigation of the stress corrosion cracking threat. Specially, hydrogen sulphide is a highly toxic and corrosive gas, having effects at ppm concentrations. It is soluble in hydrocarbons and water and will partition between these depending on local pressure, temperature, and Palmer & King (2004) categorized into three cracking forms, namely, sulphide stress cracking (SSC), hydrogen-induced cracking (HIC) and stress-oriented hydrogen-induced cracking (SOHIC).

Internal and external corrosion mechanisms such as sulphide or chloride cracking need to be considered. Nickel content in the range 1-9% is perceived to reduce the resistance of the material to sulphide stress corrosion cracking. It is introduced as the addition of alloying elements alters the weld ability, sometimes adversely, the additional costs associated with special weld procedures should also be taken into account in the cost-benefit analysis of pipe material selection (Palmer & King 2004).

5.1.4 Erosion

Erosion has been long recognized as a potential source of problems in the hydrocarbon production system. Many dangerous elbow failures due to erosion have occurred on production platforms, drilling units, and other subsea equipment in the past decades. While the subject of erosion around subsea pipelines has been studied (Chen et al. 2004), a review shows a number of areas where relatively little existing published work has been presented, including the variation in seabed shear stresses around the shoulders of subsea pipeline spans.

There are two primary mechanisms of erosion. The first is erosion caused by direct impingement. Normally, the most severe erosion occurs at fittings that redirect the flow such as at elbows and tees. The particles in the fluid can possess sufficient momentum to traverse the fluid streamlines and impinge the pipe wall. The other mechanism is erosion caused by random impingement. This type of erosion occurs in the straight sections of pipe even though there is no mean velocity component directing flow toward the wall. Venkatech (1986) provides a good overview of erosion damage in oil wells.

Shear stress amplification was derived from experimental erosion rates using the approach of back-calculating an averaged value based on an assumed amplification zone. The validity and accuracy of published amplification factors is limited to the present level of knowledge on the topic of sediment transport. Shen et al. (2015) presents a comparison studied with physical test interpretation.

5.2 Flexible pipes

5.2.1 Failure modes

Flexible risers including end fittings have a complex mechanical behavior and are exposed to environmental loading from waves and floater motions, external hydrostatic pressure as well as pressure and temperature loading from the conveyed bore fluids. Identification of all relevant failure modes and loading mechanisms is essential to ensure the structural integrity of flexible risers. Design criteria for all known failure modes are given in (API 2008) which is the main design code for flexible risers. However, some concerns have been raised on the time lag between determination of root cause of new failure modes and revision of the standard (4subsea 2013). The most frequent failures for flexible pipes are related to outer sheath damage, carcass failure and ageing/abrasion/wear (Sparks 2003, Kenny 2010, 4subsea 2013). A major incidence rate of 1.5% per riser per operational year is reported to PSA Norway (4subsea 2013). A major incidence is defined as a high risk of injury or pollution mainly based on judgments by the operator.

5.2.2 Design analysis

The offshore field development trend in terms of deeper waters, increased reservoir pressures and temperatures as well as corrosive well stream conditions (H_2S and CO_2) in combination with the composite nature of flexible pipes that includes materials with different as well as time dependent mechanical properties, give significant challenges with regard to documenting sufficient service life. In addition for existing risers, where corrosion of the tensile armor due to increasing H_2S levels outside the original design envelope or seawater ingress from damaged outer sheaths may give a significant reduction of remaining service life for many risers (4subsea 2013). For deep water applications, collapse due to external pressure or caterpillar forces during installation as well as tensile armor buckling due to the reversed end-cap effect represent additional challenges to be addressed. From a design point of view, major challenges are related to the long term change in mechanical properties including creep of the plastic materials and reduced long term fatigue performance of the steel materials. In addition comes the long term buckling performance due to combined cyclic load action. Whereas ultimate strength and fatigue performance issues of intact pipes away from the end fittings may be dealt with by simplified local models, the structural behavior inside end fittings, exposure to caterpillar forces and damaged pipe scenarios may require full finite element (FE) analyses where all relevant structural details are captured. General FE software has therefore been increasingly used in recent years to address these issues. De Sousa et al. (2012) developed an ANSYS model that was used to correlate the tensile armor birdcaging failure to test data where good correlation was found. De Sousa et al. (2012) and Ji (2014) developed models for the corrosion fatigue scenario assuming a set of broken tensile wires to investigate the reduction in fatigue life. Sævik (2014) developed a model addressing the lateral transverse buckling scenario during cyclic loads. Good correlation was found with test data (Østergaard 2012) and a design criteria based on cyclic loading first yield was proposed.

In recent years several new failure modes have been experienced such as fatigue failure inside the end fitting for deepwater risers (Campello et al. 2012) and carcass failure due to collapse or tear out (Farnes et al. 2013). In both cases, FE models have been developed to document the performance or improving the design. For the carcass tear out case a viscoelastic model was applied describing thermal shrinkage and stress relaxation effects in the PolyVinylidene DiFluoride (PVDF) layers exposed to the transient operation load condition (Kristensen 2014). This points towards improved qualification procedures by means thorough failure mode identification, use of advanced finite element analyses in combination with material testing to avoid such failures in future applications.

For standard static stress analyses, i.e. load cases where the helical layers can be assumed to carry the imposed load by membrane action only consistent with the API approach of mean stresses (API 2008) there are already well established procedures used by the industry. However, facing the challenges from corrosion fatigue in the tensile armor, extra care needs to be taken when evaluating residual life since eventual fractured wires may cause local bending in the pressure armor leading to immediate failure. This requires FE models that adequately describe the bending behavior of the pressure spiral, i.e. the mean stress approach is no longer valid.

There are also well-established models for fatigue stress analysis of the tensile armor. This includes analytical models (Skeie et al. 2012), tailor made FE models (Sævik 2011) and application of general FE codes e.g. (Perdrizet 2011). Both the FE model approaches are capable of describing the boundary condition represented by the end fitting; however, the general FE approach e.g.(Perdrizet 2011) still requires long computing times that are not suitable for standard engineering calculations. Experience has shown that as long as the bend curvature load is introduced more than half tensile armor pitch length away from the end fitting, the boundary condition effect is normally not an issue for the moderate curvatures governing fatigue analyses. Significant efforts have also been made in recent years to provide input to the industry in terms of tensile armor SN-data for fatigue analysis in corrosive environments (Berge et al. 2009). This work is ongoing.

However, for large curvatures experienced either during extreme operation or installation conditions, both the end fitting and curvature gradient effects may introduce behaviors that require FE modeling. This is particularly the case during installation spooling operations where torsion may be introduced due to changing the direction of curvature. If the torsion causes locking between the tensile armor layers, the non-linear moment capacity of the pipe will increase and may ultimately cause birdcaging or transverse buckling failures in the tensile armor. To evaluate such scenarios, FE analysis is required using material models that allow updates of the layer locking mechanism.

5.2.3 Monitoring

In MARINTEK (2014), the flexible riser monitoring methods are grouped into; (a) commonly used methods such as hydro test and offshore leak tests according to (API 2008), internal pressure and temperature monitoring and bore fluid characteristics; (b) widely used methods including external visual inspection, in-line coupon monitoring, annulus (volume test, ventilation test, gas sampling) monitoring; (c) systems that are in some use including annulus vent, internal gauging, radiography and curvature monitoring; (d) systems that are in limited use or under development such as fibre optic monitoring, eddy current methods, laser leak testing, annulus temperature monitoring, ultrasonic inspection, X-ray tomography, torsion monitoring, acoustic emission, nonintrusive stress (magnetic) monitoring.

Based on the operation experiences revealing changes in the bore chemical composition during riser life and the complexities of failure modes encountered e.g. (Farnes et al. 2013), residual life evaluations will totally rely on how accurate load (environmental, pressure, temperature) and chemical condition histories that can be used as the basis for the evaluations. This is particularly the case for the corrosion fatigue issue, where the assumption with regard to annulus conditions totally determines remaining service life. All means of describing these conditions in detail contributes to reduce the uncertainties in residual life evaluations. However, considering the potential dramatic consequences of failure and the inherent uncertainties, systems that can predict wire failures are still needed. The development of fibre-optic systems e.g. (Weppenaar 2014) and nonintrusive stress monitoring systems that can sense single wire failures are promising technologies to meet these challenges.

6. INSTALLATION

6.1 Risers

In the past few decades, offshore engineering projects dedicated a great effort to develop innovative conceptual installation procedures for risers. This effort was not only for the riser itself onsite installation, but also for the transportation procedure of riser system and components from the land to offshore. Several engineering as well as scientific research investigation have been developed for this purpose.

Experience gained on installing subsea facilities including riser systems, in general, has been reported. Ultra deepwater field development pushed the oil industry to pursue frontiers of the technology to develop innovative solutions for riser system concept and installation, observing risks involved and cost reduction pressures. Engineering work as well as laboratory investigations evaluated feasibility of those operations facing challenges of the ultra deepwater depth beyond 3000 m. Improvements on the knowledge of installation procedures for new systems such as the Submerged Buoy for Supporting Risers (BSR) have been reported. Numerical and experimental investigations were conducted regarding system behavior during installation, involving several kinds of support vessels. A full-scale test has also been conducted to verify feasibility of the operation.

This section briefly pointed out some research works in the recent years that contributed to improve understanding of the riser installation process, related to system behavior to environmental loads by means of experimental, analytical or numerical analysis approaches.

In Franciss et al. (2011) and de Araujo et al. (2011), model test results are described to validate installation procedures to anticipate problems during on-site operation, and also discuss test of pull-in operations for two flexible risers after the actual buoy is installed. Design of monitoring systems to verify all forces and displacements during the installation is described. Results demonstrate technology development for petroleum production in ultra deepwater depths. Furthermore, in Saito et al. (2011) innovative fixed submerged supports of flexible risers for lazy-S configuration is presented. Installation procedures as well as discussion to reduce both construction and installation costs are discussed. Tolls for inspection and reliability of the structure are compared with other floating buoy solutions for risers.

Application of the nonconventional pendulous installation method (PIM) deepwater installation technology is introduced in Wang et al. (2013), and it describes how to install a 195-ton manifold in a water depth of 1,500 m. The analysis methodology and numerical findings of the PIM installation are presented for lifting off deck, overboarding, lowering through splash zone and water column and landing into the target box on the seabed.

Installation phases and analyses performed for the offshore operation during the transport and installation of three subsea templates at the North Sea is described in Mouhandiz and Troost (2013). A full-scale monitoring program was performed during the installation, and accuracy of the theoretical models have been observed.

J. L. Legras and B. Pillet (2013) presented the tethered catenary riser (TCR), a new riser concept for field development in deep and ultradeep waters. Steel catenary risers (SCRs) are supported by a subsurface buoy which is tethered down to seabed and anchored. Flexible jumpers are used to connect the buoy with the floating production unit (FPU). Installation studies showed its feasibility, since this operation could be undertaken following a similar other procedure already in use. The system is an option for use in deepwater developments all over the world.

6.2 Pipelines

For pipelines the installation is typically the most critical phase in their lifetime. High stresses and fatigue loads may occur. Therefore, special pipeline installation vessels have been developed since the beginning of the ‘70s as shown in Table 2. These vessels receive the pipeline sections with a typical length of 12.4 m, which are welded together in the firing line onboard the vessels.

Currently pipelines are installed in water depths up to 2,900m. For deeper water applications flexible pipelines are often used instead of rigid ones. Additional challenges arise during installation due to the combination of the installation loads together with the attached equipment, e.g. Pipeline End Terminations (PLETs).

Among different pipeline installation methods like reeling, S-Lay, J-Lay, the reeling method is common. The new Ceona Amazon has a unique configured G-Lay system (under patent application). Ceona (2014) and other new concepts of installation are coming up (Perez et al. 2014).

Before the installation, comprehensive installation analyses are carried out. Software tools based on the finite element method like OFFPIPE and Orcaflex are specialized for this purpose. Nevertheless, commercial general purpose software like ABAQUS, ANSYS etc. can be used (Dawood & Kenny 2013, Marchionni et al. 2011). Currently research work is carried out with respect to material behavior effects of reeling installation (Shitamoto et al. 2014, Sriskandarajah et al. 2013) and reeling simulation (Karjadi et al. 2013). Static analyses as well as dynamic analyses are carried out. The static results are typically assessed based on stresses and local buckling criteria e.g. according to DNV-OS-F101. Dynamic analyses cover fatigue and sometimes crack growth analyses.

The dynamic analysis is used to determine e.g. allowable weather windows for the installation and the allowable holding times in one position. Currently dynamic amplification factors, side current, are investigated in bigger JIP projects in cooperation between operator, installation and classification companies, e.g. JIPs around installation analysis launched by DNV GL (2014).

Table 2. Pipeline installation vessel (length over 190 m).

Name	Owner / Operator	Built in	Method	Diameter [in]	Water depth [m]	Length [m]
Solitaire	Allseas	1972	S	2–60	2,775	300
Castoro Otto	Saipem	1976	S&J	4–60		191
Saipem 7000	Saipem	1985	J	4–32	>2,000	198
Audacia	Allseas	2005	S (Bow)	2–60	1,050	225
Castorone	Saipem	2012	S&J	–60	3,000	330
Ceona Amazon	Ceona	2014/5	G	6–24	3,000	199
Pieter Schelte	Allseas	2014	S	6–68	> 2,775	382

7. INSPECTION AND REPAIR

7.1 Risers

Risers are generally designed to remain in service for the full field life of 20 or more years without little if any need for maintenance or repair. Integrity management programs that determine maintenance and inspection requirements are developed during detailed design, based on a risk assessment to identify degradation threats and methods of mitigation (Cook et al. 2006). The operating parameters that are monitored, methods of inspection and associated frequency of inspection are then defined according to the expected severity of operating conditions and response.

As a minimum, visual inspection is conducted regularly, typically every year. Subsea components are inspected by ROV and surface mounted equipment including flow control valves and trees and tensioning systems by maintenance/inspection personnel. In the presence of aggressive production or export fluids, corrosion coupons may be used or pigging of the riser conducted as an extension of pipeline inspection.

Findings from visual inspection have shown various forms of degradation including cathodic protection system failure through anode depletion and excessive marine growth which can be particularly detrimental to response when it occurs over strakes used for suppression of vortex induced vibration (Vadel 2013). These issues have been resolved through the provision of anode sleds for cathodic protection replenishment and jet washing to remove marine growth.

Fatigue is a key design driver for riser systems. Uncertainties exist in the prediction of wave, current and vessel motion induced fatigue for which monitoring systems have been implemented. Examples of successfully implemented systems include a stand-alone (offline) motion measurement system for top tensioned risers (Thethi et al. 2005) and an on-line strain and motion measurement system for steel catenary risers (SCRs) (Constantinides et al. 2011). A longer term program involving various deployments of standalone motion monitoring systems on drilling risers for VIV measurement and analysis calibration has also been conducted (Tognarelli et al. 2012).

Due to the differences in configuration and service requirements of different riser types, the methods of inspection, maintenance and repair adopted can vary considerably from one riser system to the next. The challenges and issues specific to different riser types are discussed below.

Fixed Platform Risers–Risers providing well access on shallow water production platforms can be subject to high levels of corrosion near and above the mean sea level due to wetting and drying action and the effects of condensation. Many such risers have been in service for 20 years or more and economics are driving a need to extend service lives. Inspection is generally focused on measurement of conductor corrosion, conducted using ultrasonic testing (UT) probes or various forms of eddy current devices (Reber 2012). Measurement of surface casing corrosion is also being conducted less widely (Munns et al. 2007). Methods of maintaining or improving integrity to provide extended service lives include the use of grouting the conductor-casing annulus and use of welded sleeves or clamps to effectively replace the corroded conductor (Ramasamy et al. 2014). For prevention of casing and conductor corrosion in the annulus, topping up the internal fluid with rape seed oil has been adopted (Munns et al. 2007).

Deepwater Dry Tree Risers–Vertical or (near) vertical top tensioned risers used on spar and tension leg production platforms provide direct well access and in some cases import or export of production fluids. The tension setting on these devices is critical to satisfactory riser response and is monitored by way of tensioner cylinder pressures, or load rings in the case of air-can tensioners on spar platforms. Provision is generally made for swapping out tensioner cylinders in the case of cylinder seal or rod damage. Uncertainties in current profiles that generate vortex induced motion of the vessel or vortex-induced vibration from direct action on the risers may warrant monitoring of dynamic riser response to calibrate analysis predictions (Thethi et al, 2005).

Steel Catenary Risers (SCRs)–The focal point of SCR inspection includes wall loss, fatigue damage and excessive trenching near the touchdown zone on the seabed and integrity of VIV suppression devices such as strakes or fairings. Failure of the flex-joints that connect the riser to the vessel have occurred (BSEE 2008) (J P Kenny 2007) resulting in the need for repair. This requires removal of the fixed piping and simply replacing the upper body (Selden 2009) or replacement of the complete flex-joint that involves a reversal of the final stage of the installation operation. High fatigue damage can be incurred in SCRs in a localized region around the touchdown point on the seabed. In the presence of aggressive production fluids, wall thickness measurements from this region, obtained from intelligent pigging, may be needed to enable qualification of long-term integrity (Urthaler et al. 2013). A means of managing SCR TDP fatigue has been proposed that involves movement of the platform position by adjustment of mooring lines, changing the location of fatigue damage concentration along the length of the riser in the process.

Hybrid Risers–Free standing hybrid risers that consist of a vertical steel riser pipe (or bundle) supported by a buoyancy tank with a flexible riser connection(s) to the vessel are used in West Africa, Brazil and the Gulf of Mexico. A comprehensive monitoring system has been implemented to confirm riser response (Zimmerman 2009), but typical monitoring and inspection activities are focused on the integrity of the buoyancy tank, which is critical to successful long-term performance. This is achieved by use of tension monitoring devices mounted on the riser or by taking measurements from the tank using remotely operated vehicles (ROVs) mounted flooded member detection devices. In the event of buoyancy tank compartment failure, integrity can be restored through the displacement of the ballast water in the reserve compartments in the base of the buoyancy tank using nitrogen.

Flexible Risers–External visual inspection is conducted for flexible risers in the same way as for metallic risers, with the added requirements that supporting structures and ancillary items such as buoyancy must be addressed and greater attention must be paid to the integrity of the surface condition of the external sheath. Minor surface damage may be reparable, subject to agreement between the vendor and operator. Numerous methods of monitoring and inspection are being developed for flexible risers and pipelines. These include annulus leak detection, fiber optics, included during manufacture, for measurement of curvature and temperature and various armor wire corrosion and breakage measurement systems such as the magnetic anisotropy and permeability system (MAPS), eddy current, radiographic, ultrasonic and acoustic emission

(Boschee 2012). A key area of potential failure for flexible risers is at the support near the surface, where fatigue loads and potential for damage tend to be greatest (Seaflex 2007). While it is generally considered that measurement of annulus condition to identify the presence and nature of fluids that have permeated through the layers provides a vital guide for inferring the fatigue performance of the armor wires, it has been found that this assumption and the assumed fatigue resistance of the armor wires may be overly conservative (Boschee 2012). In view of these uncertainties, amongst others, a combination of inspection methods tends to be recommended.

7.2 Pipelines

Pipeline systems shall be designed and operated safely, with respect to humans, the environment and the economy, to maximize the life cycle value. The process is a continuous process applied throughout design, construction, installation, operation and decommissioning phase to ensure that the system is operated safely (Bai & Bai 2005). It is better to understand the typical characteristics of pipelines for maintenance, and repair:

- Water depths are beyond diver limits and all activity is remote; wall thicknesses are typically high (material, welding, buckling).
- Operating pressures are typically very high or very low and ambient external pressures are high, commonly similar to internal operational pressures (coating and insulation degradation).
- High levels of insulation are commonly required (insulation degradation).
- Waters are typically cold approx. 4°C– 6°C (flow assurance, materials).
- Pipelines tend not to be protected by a concrete coating (damage) and geo-hazards can be significant (spanning, buckling, damage, bend stability, turbitity and debris flows).
- Slugging within produced fluids is common (spanning, fatigue).
- Greater tolerances (survey inaccuracy, installation accuracy).
- Metocean and environmental conditions tend to be benign (stability).
- Seabed mobility is less dominant (scour, spanning).
- Corrosion coatings tend to be of very high quality (corrosion, damage).

7.2.1 Maintenance

Normally subsea facilities, including the pipeline system, shall possess sufficient reliability to ensure availability throughout the field life. Subsea pipeline that is susceptible to failure should be designed to minimize the effort/costs required for replacement of the failed assembly (Bai & Bai 2005). Currently maintenance methods are categorized into preventive maintenance, routine maintenance, and corrective maintenance. Because of the high cost and potential delays associated with intervention, preventive maintenance should be eliminated at the design stage, wherever possible. Routine maintenance tasks are required where the elimination of specific intervention is uneconomically or technically problematic. Normally such maintenance would be undertaken during repair activity, or combined with planned inspection campaigns (ABS 2014). Intervention to rectify breakdown or degradation (Corrective Maintenance) is referred to as ‘Repair’.

7.2.2 Inspection

Pipeline inspection is a part of pipeline integrity management for keeping the pipeline in good condition. The rules governing inspection are the pipeline safety regulations (DNV-RP-F116 2010, PETRONAS 2011). Inspection campaigns are an integral part of the IMR strategy, the purpose of the inspections being to monitor pipeline system integrity over time and to monitor the impact of the subsea and production environments on the pipeline (Anderson 2005). Understanding and confirming design assumptions, routine inspections may indicate a requirement for more specific investigations involving detailed or specialist techniques. The normal physical inspection tasks undertaken on the deepwater pipelines can be split into locations internal and external to the pipeline. Internal and external locations are typically periodically inspected by pigging and ROV/AUV methods respectively.

(1) Deepwater pig inspection

Pig inspection of offshore pipelines tends to look for internal problems (Bai & Bai 2005). Generally running pigs in offshore pipelines is very similar to running in onshore lines, after the wall thickness and higher pressures are taken into consideration. The most favored inspection methods are either ultrasonic or magnetic flux inspection. Magnetic flux is limited by magnet strength, i.e. get enough magnetism in the wall of the pipe to enable good results to be obtained. Ultrasonic can inspect very thick wall pipe, but ultrasonic has to be run in a liquid medium. The main difference between offshore and onshore is the length of run between pig traps, as offshore pipelines tend not to have intermediate compression stations with conveniently located pig traps. The pig must not get stuck in the pipeline as retrieving it will be much more expensive than from an onshore pipeline. The pig must stay alive and recording data (battery duration may be an issue).

(2) Deepwater ROV inspection

Traditionally, external inspection of deepwater pipelines is performed using work ROVs deployed from DP ROV support vessels (McStay et al. 2005). These vessels are expensive, and they may not be available when they are needed most. In deep waters, ROVs become heavy to handle from these vessels, because of long umbilicals, thus becoming prone to breakdowns. ROV inspections of long transmission lines can be very slow and may take many months to complete end-to-end. Weather downtime is also an issue for ROV support vessels when working in harsh and hostile environments.

(3) AUV based inspection

AUV-based inspection in deepwater fields may provide dramatic improvements in cost, performance, safety and reliability.

- Large DPII vessels with high-end ROV spreads would no longer be required for simple inspection.
- AUVs have demonstrated solid performance requiring simple autonomy for missions such as bathymetric survey and high resolution sonar imaging.
- AUVs can be deployed from small utility vessels, and are capable of operations in higher seas without the operational limitations and equipment hazards imposed by umbilical and tether management systems.
- Reduction in equipment complexity, vessel size and crew size would also result in improved safety, reliability and lower environmental impact.
- In the future AUVs would become "field resident", residing in the subsea field for periods of months. The end state of "Vessel Independent Operations" will achieve further reductions in cost while improving performance and safety.

(4) Optimization of Routine/Scheduled Inspection

An optimum IMR plan aims to strike an appropriate balance between the following objectives:

- Maximizing the availability of the pipeline system during its operating life by maintaining and preserving its integrity, thus maximizing revenue.
- Minimizing inspection, intervention and rectification measures through the life of the pipeline system, thus minimizing through-life IMR related costs.
- Reducing to as low as is reasonably practicable all risks to people, the environment and assets, in accordance with legislative, societal and business requirements, thus minimizing the costs of failures.

Permanent monitoring methods also exist and are becoming more commonplace. The designers have probably planned for the worst case, but if things are not that bad and/or the operational approach changes this can result in very different results to those planned and designed. The requirement for and frequency of inspection will most commonly be determined using risk-based techniques (Bai & Bai 2014, Seo et al. 2015).

7.2.3 Repair

Damage to a subsea pipeline can be repaired in different ways, depending on the water depth and the type and extent of the damage. This section describes the various types of conventional methods currently available for repairing a damaged subsea pipeline (Manelli & Radicioni 1994). The minimum functional requirements identified for an emergency repair system listed in several operable and capable items: Operable at water depths up to deepest water of the pipeline, on pipe size (internal diameter) of pipelines, with steel wall thickness up to maximum and relevant coatings, on soft seabed soils (soft calcareous clay and silt), on seabed slopes, and capable of providing a repair capability extending from minor dents to replacement of multiple pipe joints.

While not mandatory, it is advantageous if the system(s) and equipment also exhibit the following characteristics: Modular and/or lightweight, minimum number of components, incur minimal shut down and/or reduction of operation, minimum CAPEX investment. An overall pipeline repair system to install a clamp or spool requires an extensive array of equipment to conduct a repair operation. The repair systems generally perform tasks from the following list:

- Metrology of the pipeline damage and repair site
- Isolation of the damaged section of pipe with internal plugs if required
- Soil excavation
- Pipeline lifting, locally at the repair site or completely to the surface
- Pipe coating removal
- Pipe cutting
- Removal of damaged section
- Pipe end surface preparation
- Metrology of the pipeline for clamp and spool piece preparation
- Transport and positioning of clamps, spool pieces and connectors
- Closing and sealing clamps and connectors
- Testing the repair
- Lower the pipeline to the seabed
- Removal of repair system equipment.

Damage scenarios during installations and operation pose differing levels of risk. The most significant potential damage scenarios during the installation phase are dry and wet buckles. The technology and methodologies required for rectification of installation phase damage (i.e. buckles) are a direct extension of techniques used for similar events in shallow water, and currently exists with installation contractors and specialist equipment suppliers.

Several potential damage scenarios exist during the operational phase. The most significant are those where a damaged section of pipeline needs to be reinforced, replaced or cleared of a hydrate blockage. Where a replacement pipeline section is required, the length could vary significantly depending on the nature of the event causing the damage (a few meters to several kilometers in the event of a geohazard (i.e. slope instability). There is a wide range of qualified or nearly qualified equipment for the subsea repair, both currently available and under continual development. The equipment exists both as individual components (equipment, tools and fittings) and full systems. Some repair systems are owned and operated on a "club" basis, by a group or consortia of pipeline operators. The clubs at present operate in specific geographical locations. The need to access the pipeline at both ends for the purpose of recommissioning (i.e. flooding, cleaning, dewatering, etc.), is inherent in many of the repair scenarios. Access facilities and the provision of adequate space for equipment (particularly dewatering) are significant.

8. CONCLUSIONS

Technology challenges for flexible risers are indispensable for floating oil and gas production systems. Several hybrid riser concepts have been introduced, combining proven rigid and flexible riser technologies. Several installations have been performed in benign environments whereas the major design challenge in harsh environments is related to fatigue during installation.

Pipeline technology has experienced revolutionary advances in the design process through analysis. Several new pipeline concepts have been introduced with using numerical analysis, analysis tools, modern materials and revised design codes. Further challenging pipeline concepts for ultra deep waters will be expected with using them.

Evaluation of fatigue and extreme response is crucially important to ensure safety and serviceability of risers. Although the dynamic response is a rather matured topic, breakthrough developments are rarely seen, but efforts are continued to develop the analysis method and improve accuracy of analysis. Dynamic response under combined action of wind, wave, current and other relevant dynamic loads such as slug flow is an example of effort.

An important challenge in this area of research is non-linearity. Non-linearity makes perspective of phenomena worse and interpretation more difficult. A typical example is VIV. This is partly the reason why the large efforts are made to the scientific investigation of the phenomenon. On the other hand development of analysis codes used in design are continued in responding to the needs of design. Development of VIV suppression devices are continued as before.

In the past decades the computer has shown dramatic developments in performance and capacity, but high computational load is still a main challenge for numerical simulation of hydrodynamic phenomena and hydroelastic response.

The statement on soil-pipe interaction in ISSC2000 was limited to the pipeline scoring. Since then, a large progress has been accomplished on the soil-pipe interaction, and issues such as pipeline as-laid embedment, pipe-soil interaction and pipeline stability have been stated in this report. Lateral buckling and pipeline walking are the main themes of subsea pipeline behavior in deepwater. SAFEBUCK Joint Industry Project (JIP) which was initiated in 2002 has led to new design guidelines for on-bottom lateral buckling and development of simple models to simulate this behavior. However, challenges are needed to develop better models because the simple models have been proposed under some assumptions.

A model for axial soil-pipe interaction using the critical state theory and a simpler model for the axial resistance prediction have been proposed, which are based on a number of simplified assumptions. The development of more sophisticated models than these simple models is requested to be applicable to more complex situations that involve buckling and axial displacement.

Pipeline trenching was historically performed using jetting, but mechanical ploughing or cutting has become an increasingly common approach. Current researches on pipeline stability during trenching and backfilling are mainly on 2-D aspects of the problem and only on soil mechanics. However, uplift propagation during trenching and backfilling is a 3-D problem and involves pipeline structural response, soil transport and deposition, and consolidation. All of these aspects need to be investigated integrally in the future.

The physical modeling of wave-induced liquefaction and sediment transport has been carried out in the University of Western Australia, but the investigation of wave-induced liquefaction and sediment transport is still ongoing. The future research will focus on better defining and quantifying the erosion mechanisms of sediments, particularly those which exhibit behavior described as 'cohesive', as well as clarifying the nature of the 'frictional' seabed shear stress required to drive erosion.

A new joint industry project (JIP) is now being proposed which will aim at identifying state-of-the-art design methodologies for mechanically stabilizing pipelines and thereby controlling movement.

The number of potential failure modes for steel pipes is smaller than that for flexible pipes. Most probable failure modes for steel pipes are buckling, collapse, fatigue, corrosion, stress corrosion cracking and erosion. Regarding the buckling of steel pipes, FEM has been widely used and will be more important in the future.

Identification of all relevant failure modes and loading mechanisms is essential to ensure the structural integrity of flexible risers. The most frequent failures for flexible pipes are related to outer sheath damage, carcass failure and aging/abrasion/wear. Flexible risers in deep waters are exposed to high pressure and temperature and corrosive environments. Design criteria for all known failure modes are given in (API 2008) which is the main design code for flexible risers. However, new failures modes and loading mechanisms have to be identified with experiments and analyses, with the development of fibre-optic monitoring systems. With the increase of water depths, failures modes and loading mechanisms would become more complex and the FE analysis models considering the geometrical, material and boundary non-linearities would be indispensable.

Ultra deepwater field development pushed the oil industry to pursue frontiers of the technology to develop innovative installation procedures for riser systems, observing risk involved and cost reduction pressures. The experimental, analytical and numerically analytical tools seem to be getting matured and their utilization has been enabling to develop innovative conceptual installation procedures for riser systems including the transportation procedure of riser system and components from the land to offshore. What is expected in the years ahead is to develop more reliable and cost-effective installation procedures for ultra deepwater riser systems and improve their accuracy based on the comparison of the procedures with the data obtained from the monitoring program for the in situ riser system installation.

Pipeline installation gives the most critical time to its strength. Accordingly, comprehensive installation analyses are carried out before the installation using FEM-based software tools. One of recent JIPs is concerned with dynamic installation analysis to investigate dynamic amplifications factors, side current etc. and is ongoing. An important challenge is to give new pipe lay barges multipurpose, multiwater depth abilities.

As evidenced by the recent research literature, these fifteen years have given a great progress to the field of maintenance, inspection and repair of risers and the technologies for them are almost mature. Integrity management programs that determine maintenance and inspection requirements for a riser life of 20 or more years are developed during detailed design, based on a risk assessment to identify degradation threats and methods of mitigation. The operating parameters that are monitored, methods of inspection and associated frequency of inspection are then defined according to the expected severity of operating conditions and response for respective riser systems. Fatigue is a key design driver for riser systems and deployments of monitoring systems for the prediction of wave-, current- and vessel motion-induced fatigue are successful in recent years. However, more efforts are desired to improve such monitoring systems especially effective for VIV-induced fatigue prediction. Maintenance, inspection and repair of deepwater and ultra deepwater pipelines are challenging. Inside inspection of deepwater pipelines is executed with pigs. However, if the inspection run between pig traps becomes even longer, then that cost and reliability will be future issues to address. Their external inspection is performed with ROVs and AUVs. In deeper waters, AUVs provide dramatic improvements in cost, performance, safety and reliability compared to ROVs. More sophistication of AUV inspection will be a future issue.

REFERENCES

4subsea. 2013. PSA-Norway–Un-bonded Flexible Risers - Recent Field Experience and Actions for Increased Robustness.

ABS. 2014. *Guide for building and classing subsea pipeline systems.* Houston: American Bureau of Shipping.

Adib-Ramezani, H., Jeong, J. & Pluvinage, G. 2006. Structural integrity evaluation of X52 gas pipes subjected to external corrosion defects using the SINTAP procedure. *International Journal of Pressure Vessel and Pipeline* 83:420–32.

Allen, D.W. & Liapis, S. 2014. The Effect of Coverage Length and Density on the Performance of Helical Strakes. Paper No. 23107, *Proc. OMAE,* June 2014.

Alliot, V. and Legras, J. L. 2005. Lessons Learned From The Evolution And Development of Multiple-Lines Hybrid Riser Towers For Deep Water Production Applications. *Proc. OTC,* May 2005.

Anserson, C. 2005. *Pipeline inspection*. Aberdeen: HydroFest. (Available at: www.ths.org.uk)

API. 2008. API 17J Specification for unbonded flexible pipe.

API. 2007. Specification for line pipe. Washington: American Petroleum Institute.

ASME B31G. 2009. *Manual for determining the remaining strength of corroded pipelines*. A supplement to ASME B31G Code for Pressure Piping. New York:USA.

Assi, G.R.S., Srinil, N., Freire, C.M. & Korkischko, I. 2012. Experimental Investigation of the Vortex-Induced Vibration of a Curved Cylinder. Paper No. 83016, *Proc. OMAE,* June 2012.

Assi, G.R.S., Bearman, P.W., Carmo, B.S., Meneghini, J.R., Sherwin, S.J. & Willden, R.H.J. 2013. The Role of Wake Stifness on the Wake-induced Vibration of the Downstream Cylinder of a Tandem Pair. *Journal of Fluid Mechanics*. 718. 210–245. Cambridge.

Aubeny, C. P., Shi, H. & Murff, J.D. 2005. Collapse Loads for a Cylinder Embedded in Trench in Cohesive Soil. Paper No. 19493, *Proc. OTC*, May 2005.

Auperin, M., et al. 2005. Lessons Learned From Development And Installation of Injection Single Hybrid Risers–Application to Production, Test Pipe-in-Pipe SHRs. *Proc. OTC,* May 2005.

Baarholm, G. S. & S. Haver 2010. Application of environmental contour lines on a flexible riser. Paper No. 20860, *Proc. OMAE,* June 2010.

Bai, Y. & Bai, Q. 2005. *Subsea pipelines and risers*. MA: Elsevier Science.

Bai, Y. & Bai, Q. 2014. *Subsea pipelines integrity and risk management*. MA: Elsevier Science.

Bai, Q. & Duffy, B. 2014. Analytical Approach for Mechanical Responses of Spanning Pipelines. Paper No. 24524, *Proc. OMAE,* June 2014.

Bakhtiary et al. 2007; Analysis of Offshore Pipeline Allowable Free Span Length; International Journal of Civil Engineerng. Vol. 5, No. 1

Bearman, P.W. 2011. Circular Cylinder Wakes and Vortex-Induced Vibrations, *Journal of Fluids and Structures.* 27 (5–6). 648–658. Elsevier.

Belfroid, S. P. C., et al. 2011. Application of a new carcass design for prevention of singing behaviour in flexible risers. *American Society of Mechanical Engineers, Pressure Vessels and Piping Division* (Publication) PVP.

Berge, S., et al. 2009. Environmental effects on fatigue strength of armour wire for flexible risers. Paper No. 80262, *Proc. OMAE,* June 2009.

Borsellino, C., Calabrese, L., Valenza, A. 2004. Experimental and Numerical Evaluation of Sandwich Composite Structures. *Composites Science and Technology*. 64(10–11).1709. Elsevier Ltd.

Boschee, P. 2012. Best Practices for Flexible Pipe Integrity Evolve. *SPE Oil and Gas Facilities Magazine*, February 2012.

Bourguet, R. Lucor, D. & Triantafyllou, M.S. 2012. Mono-and Multi-Frequency Vortex-Induced Vibrations of a Long Tensioned Beam in Shear Flow. *Journal of Fluids and Structures*. 32. 52-64.

Bourguet, R. Karniadakis, G.E. & Triantafyllou, M.S. 2013a. Multi-Frequency Vortex-Induced Vibrations of a Long Tensioned Beam in Linear and Exponential Shear Flows. *Journal of Fluids and Structures*, Vol. 41, pp. 33–42.

Bourguet, R. Karniadakis, G.E. & Triantafyllou, M.S. 2013b. Distributed Lock-In Drives Broadband Vortex-induced Vibrations of a Long Flexible Cylinder in Shear Flow. *Journal of Fluid Mechanics*. 717. 361–375.

Bransby, M.F., Yun, G.J., Morrow, D.R., & Brunning, P. 2005. The performance of pipeline ploughs in layered soils". *Frontiers in Offshore Geotechnics* I.

Bruton, D.A.S., White, D.J., Marr, M. & Cheuk, C.Y. 2008. Pipe-Soil Interaction during Lateral Buckling and Pipeline Walking: the SAFEBUCK JIP. Paper No. 19589, *Proc. OTC,* May 2008.

Caire M. & Schiller R.V. 2013. The effect of wave energy spreading on the mooring and riser system response of a spread-moored FPSO. Paper No. 10675, *Proc. OMAE, June 2013.*

Campello, G., et al. 2012. A novel concept of flexible pipe end fitting: Tensile armor foldless assembly. Paper No. 83511, *Proc. OMAE, June 2012.*

Chaplin, J.R., Bearman, P.W., Cheng, Y., Fontaine, E., Graham, J.M.R., Herfjord, K., Huera Huarte, F.J., Isherwood, M., Lambrakos, K., Larsen, C.M., Meneghini, J.R., Moe, G., Pattenden, R.J., Triantafyllou, M.S. & Wilden, R.H.J. 2005. Blind Predictions of Laboratory Measurements of Vortex-induced Vibrations of a Tension Riser, *Journal of Fluids and Structures* (21): 25–40. Elsevier.

Carmo, B.S., Assi, G.R.S. & Meneghini, J.R. 2013. Computational Simulation of the Flow-Induced Vibration of a Circular Cylinder Subjected to Wake Interference. *Journal of Fluids and Structures.* 41, 99–108. Elsevier.

Castello, X. & Estefen, S.F. 2008. Sandwich Pipes for Ultra Deepwater Applications. Paper No. 19704, *Proc. OTC,* May 2008.

Cathie, D.N., Machin, J. & Overy, R.F. 1996. Engineering appraisal of pipeline floatation during backfilling. Paper No. 8136, *Proc. OTC,* May 1996.

Cathie, D.N., Barras, S. & Machin, J. 1998. Backfilling pipelines: state of the art. *21st offshore pipeline technology conference*, Oslo.

Cathie, D.N., & Wintgens, J.F. 2001. Pipeline trenching using plows: performance and geotechnical hazards. Paper No. 13145, *Proc. OTC,* May 2001.

Cathie, D.N., Jaeck, C., Ballard, J.-C. & Wintgens, J.F. 2005. Pipeline geotechnics–state-of-art. *Frontiers in Offshore Geotechnics* I. 95–113.

Chen, E., Mclaury, B.S. & Shirazi, S.A. 2004. Application and Experimental validation of a computational fluid dynamics (CFD)-based erosion prediction model in elbows and pluged tees*.* *Computers & Fluids.* 33: 1251–1272.

Chen, H.C., Chen, C.R. & Huang, K. 2013. CFD Simulation of Vortex-induced and Wake-induced Vibrations of Dual Vertical Risers. *Proc. ISOPE,* June-July 2013.

Cheuk, C.Y., White, D.J. & Bolton, M.D. 2007. Large-scale modelling of soil-pipe interaction during large amplitude cyclic movements of partially embedded pipelines. *Canadian Geotechnical Journal*, Vol. 44, 977–996.

Cheuk, C.Y. & White, D.J. 2008. Centrifuge modeling of pipe penetration due to dynamic lay effects. Paper No. 57923, *Proc. OMAE,* June 2008.

Cheuk, C.Y. & White, D.J. 2011. Modelling the Dynamic Embedment of Seabed Pipelines. *Geotechnique* 61(1): 39–57.

Chiodo, M.S.G. & Ruggieri, C. 2009. Failure Assessments of Corroded Pipelines with Axial Defects using Stress-based Criteria: Numerical Studies and Verification Analyses. *Int. J. of Pressure Vessels and Piping*. 86(2–3):164–176.

Cicolin, M.M. & Assi, G.R.S. 2014. Response of a Circular Cylinder Fitted With Permeable Meshes Acting as VIV Suppressors. Paper No. 24709, *Proc. OMAE,* June 2014.

Constantinides, Y., Chen, J., Tran, L., Enuganti, P. & Campbell, M. 2011. Comparison of SCR Field Response with Analytical Predictions. Paper No. 50150, *Proc. OMAE*, July 2011.

Cook, H., Dopjera, D, Thethi, R & Williams, L. 2006. Riser Integrity Management for Deepwater Developments. Paper No. 17891, *Proc. OTC*, May 2006.

Cosham, A. & Hopkins, P. 2004. An Overview of the Pipeline Defect Assessment Manual (PDAM). *4th International Pipeline Technology Conference*, May 9–13, Ostende: Belgium.

Dawood and Kenny 2013. Finite element method simulating the pipeline mechanical response during reel-lay simulation. Paper No. 10555, *Proc. OMAE,* June 2013.

de Araujo, J.B., de Almeida, J.C.L. & Fernandes, A.C. 2011. Installation of a Submerged Buoy for Supporting Risers (BSR) System in Campos Basin Site. Paper No. 50167, *Proc. OMAE, June 2011.*

de Sousa F.J.M., Rebello A.M. & Sagrilo L.V.S., 2013. An alternative methodology to evaluate the fatigue life of risers based on regular waves. Paper No. 10914, *Proc. OMAE,* June 2013.

de Sousa, J. R. M., et al. 2013. A FE model to predict the stress concentration factors in the tensile armor wires of flexible pipes inside end fittings. Paper No. 10995, *Proc. OMAE,* June 2013.

de Sousa, J. R. M., et al. 2012. Fatigue analysis of a 6" flexible pipe with broken tensile armor wires. Paper No. 83532, *Proc. OMAE,* July 2012.

de Sousa, J. R. M., et al. 2012. An Experimental and numerical study on the axial compression response of flexible pipes. *Journal of Offshore Mechanics and Arctic Engineering* 134(3).

Dingle, H.R.C, White, D.J. & Gudin, C. 2008. Mechanisms of pipeline embedment and lateral breakout in soft clay. *Canadian Geotechnical Journal* 45(5): 636-652.

DNV-OS-F101. 2007. *Submarine pipeline system*. DNV.

DNV-RP-C203. 2005. *Recommended practice for fatigue design of offshore steel structures*. DNV.

DNV-RP-F101, 2004. *Recommended Practice-Corroded Pipelines*. DNV.

DNV-RP-F108. 2006. *Fracture control for pipeline installation methods introducting cyclic plastic strain*. DNV.

DNV-RP-F116. 2010. *Intergrity management of submarine pipeline*. DNV.

dos Santos, M., et al. 2014. A Comparitive Study of a Free Span Pipeline Through Numerical Simulations. Paper No. 24069, *Proc. OMAE,* June 2014.
Duan, G., et al. 2014, Finite Element Analysis of global walking with spanning and lateral buckling. Paper No. 24159, *Proc. OMAE,* June 2014.
el Mouhandiz, A. & Troost, S. 2013. Subsea Templates Installation at North Sea using HLV THIALF. *Proc. ISOPE,* June-July 2013.
Epsztein, T., et al. 2011. Towards an H2S free environment in flexible pipe annulus thanks to a new Anti-H2S polymer layer. Paper No. 49664, *Proc. OMAE,* June 2011.
Estefen, S.F. 1999. Collapse Behaviour of Intact and Damaged Deepwater Pipelines and the Influence of the Reeling Method of Installation. *Journal of Constructional Steel Research*. 50(2): 99–114.
Farnes, K. A., et al. 2013. Carcass failures in multilayer PVDF risers. Paper No. 10210, *Proc. OMAE,* June 2013.
Fernandes, A. C. J. P., Vardaro, E., Franciss, R. & Almeida, J.C. 2003. Sub-surface buoy hybrid riser system for deepwater application. Paper No. 37412, *Proc. OMAE,* June 2003.
Fontaine, E., Marcollo, H., Vandiver, K., Triantafyllou, M., Larsen, C. Tognarelli, M., Constantinides, Y. & Oakley, O. 2011. Reliability Based Factors of Safety for VIV Fatigue Using NDP Riser High Mode VIV Tests. Paper No.49820, *Proc. OMAE,* June 2011.
Francis, K. 2011. Fatigue analysis of flexible risers due to bimodal waves. *Proc. ISOPE,* June 2011.
Franciss, R., Gonzales, E.C., de Almeida, J.C.L., de Araújo, J.B. & Fernandes, A.C. 2011. Alternative Method of Buoy Supporting Riser (BSR) Installation. Paper No. 49862, *Proc. OMAE,* June 2011.
Franzini, G.R., Gonçalves, R.T., Meneghini, J.R. & Fujarra, A.L.C. 2014. Experimental Investigation into the Flow around a Stationary and Yawed Cylinder under Asymmetrical End Conditions. *Proc. ISOPE,* June 2014.
Fu, B. & Batte, A. 1999. An overview of advanced methods for the assessment of corrosion in linepipe. *Offshore Technology Report*-OTO 1999 051.
Fu, S., Wang, J., Baarholm, R. Wu, J. & Larsen, C.M. 2013. VIV of Flexible Cylinder in Oscillatory Flow. Paper No. 10348, *Proc. OMAE, June 2013.*
Gabor, F. & Laszlo, V. 2012. The effect of the width to length ratios of corrosion defects on the burst pressures of transmission pipelines. *Engineering Failure Analysis* 21: 21–30.
Gong, S.F. & Li, G. 2015. Buckle Propagation of Pipe-in-pipe Systems under External Pressure. *Engineering Structures*. 84: 207–222.
Gong, S.F., Sun, B., Bao, S. & Bai, Y. 2012. Buckle Propagation of Offshore Pipelines under External Pressure. *Marine Structures*. 29(1): 115–130.
Gong, S.F., Ni, X.Y., Bao, S. & Bai, Y. 2013. Asymmetric Collapse of Offshore Pipelines Under External Pressure. *Ship and Offshore Structures*. 8(2): 176–188.
Gueveneux, H. & Le Buhan, P. 2014. Hybrid riser tower design: Evolution, operational efficiency and compliance to ultra deep offshore challenge. Paper No. 23882, *Proc. OMAE,* June 2014.
Gundersen P., Doynov K. & Andersen T. 2012. Methodology for determining remnant fatigue life of flexible risers subjected to slugging and irregular waves. Paper No. 83412, *Proc. OMAE,* June 2012.
Hagatun, K. S., O.; Lie, H. 2010. Hybrid Riser Solutions for Harsh Environments. DOT 2010.
Hanonge, D. & Luppi A. 2010. Challenges of flexible riser systems in shallow waters. Paper No. 20578, *Proc. OTC,* May 2010.
He, J., Vasblom, W.J., & Miedema, S.A. 2005. FEM analyses of cutting anisotropic densely compacted and saturated sand. *Western Dredging Association Conference*, New Orleans, USA.
He J.W. & Low Y.M. 2010. Probabilistic assessment of the clashing between flexible marine risers. Paper No. 20046, *Proc. OMAE,* June 2010.
He J.W. & Low Y.M. 2013. Predicting the probability of riser collision under stochastic excitation and multiple uncertainties. Paper No. 10381, *Proc. OMAE,* June 2013.
Henning, M., Scott, D. & White, D. 2013. Free field sediment mobility on Austrian's north west shelf. Paper No. 11490, *Proc. OMAE,* June 2013.
Hill, A.J., White, D.J., Bruton, D.A.S., Langford, T., Meyer, V., Jewell, R. & Ballard, J-C. 2012. A new framework for axial pipe-soil resistance, illustrated by a range of marine clay datasets". Proc. International Conference on Offshore site investigation and geotechnics. SUT, London.
Hirabayashi, S. & Suzuki, H. 2013. Numerical Study on Vortex Induced Motion of Floating Body by Lattice Boltzmann Method. Paper No. 11045, *Proc. OMAE,* June 2013.
Huang, Z. & Larsen, C.M. 2011. Numerical Simulation on Vortex-Induced Vibration of an Elastically Mounted Circular Cylinder with Two Degrees-of-Freedom. Paper No. 49573, *Proc. OMAE, June 2011.*
Iranpour, M. & Taheri, R. 2006. The State-of-the-Art Review of Risers' VIV Fatigue. *Proc. OMAE,* June 2006.
Jhingran, V., Zhang, H., Lie, H., Braaten, H. & Vandiver, J.K. 2012. Buoyancy Spacing Implications for Fatigue Damage Due to Vortex-Induced Vibrations on a Steel Lazy Wave Riser (SLWR). Paper No. 23672, *Proc. OTC,* May 2012.
Ji, G. L., B.J., Sævik, S., Klæbo, F., Axelsson, G. & Fergestad, D. 2014. Integrity assessment of damaged flexible pipe cross-sections. Paper No. 24155, *Proc. OMAE,* June 2014.
J P Kenny BSEE 2007. Deepwater Riser Design, Fatigue Life and Standards Study. *Project. Report for MMS*, Project No. 572.
Kang, Z., Liu, W. & Qin, W. 2013. Vortex-Induced Vibration Experiment Research of Two Cylinders in Tandem Arrangement. Paper No. 10471, *Proc. OMAE,* June 2013.

Karjadi et al. 2013. Development on Aegir Reeling Pipeline Analyses Simulation by Test Validation. Paper No. 10365, *Proc. OMAE,* June 2013.

Kenny, M. 2010. Oil & Gas UK - State of the art report on flexible pipe integrity. Aberdeen, MCS Kenny.

Kiefner, J. & Vieth, P. 1989. A modified criterion for evaluating the strenght of corroded pipe. *Final report for PR 3-805 project to the Pipeline Supervisory Committee of the American Gas Association*, Battelle. Ohio: UK.

Kim, D.W., Mohd, H.M., Lee, B.J., Kim, D.K., Seo, J.K., Kim, B.J. & Paik, J.K. 2013. Investigation on the burst strength capacity of aging subsea gas pipeline. Paper No. 10267, *Proc. OMAE,* June 2013.

King, R., Brown, A., Braaten, H., Russo, M., Baarholm, R. & Lie, H. 2013. Suppressing Full-Scale Riser VIV with the VT Suppressor. Paper No. 11642, *Proc. OMAE,* June 2013.

Klever, F.J., Stewart, G., & Valk, C.A.C. 1995. New developments in burst strength predictions for locally corrodes pipelines. *Proc. OMAE, June 1995,* 5:161–173.

Korkischko, I. & Meneghini, R.R. 2012. Suppression of Vortex-Induced Vibration Using Moving Surface Boundary-Layer Control. *Journal of Fluids and Structures*. 34. 259–270. Springer.

Kristensen, C. E. M., J., Skeie, G., Skjerve, H. & Sødahl, N. 2014. Carcass tear out load model for multi-layer pressure sheath risers. Paper No. 24129, *Proc. OMAE,* June 2014.

Kristiansen, U. R. & G. A. Wiik 2007. Experiments on sound generation in corrugated pipes with flow. *Journal of the Acoustical Society of America* **121**(3): 1337–1344.

Kyriakides, S. 2002. Buckle Propagation in Pipe-in-pipe Systems.: Part I. Experiments*. International Journal of Solids and Structures*. 39(2): 351–366.

Kyriakides, S. & Corona, E. 2007. *Mechanics of offshore pipelines-Volume1: buckling an*d collapse, 1st Ed. MA: Elsevier Science.

Kyriakides, S. & Netto, T.A. 2004. On the Dynamic Propagation and Arrest of Buckles in Pipe-in-pipe Systems. *Int J Solids Struct.* 41 (20): 5463–5482.

Kyriakides, S. & Vogler, T.J. 2002. Buckle Propagation in Pipe-in-pipe Systems. Part II: Analysis. *Int. J. Solids Struct*. 39 (2): 367–392.

Lambert, A., et al. 2012. Qualification of unbonded dynamic riser with carbon fiber composite armours. Paper No. 83130, *Proc. OMAE,* June 2012.

Langford, T.E., Dyvik,R. & Cleave, R. 2007. Offshore pipeline and riser geotechnical model testing: practice and interpretation. Paper No. 29458, *Proc. OMAE,* June 2007.

Larsen, C.M., Vikestad, K., Yttervik, R. & Passano, E. 2000. VIVANA Theory Manual. *MARINTEK*. Trondheim, Norway.

Lauder, K., Bransby, F., Brown, M., Cathie, D., Morgan, N., Pyrah, J. & Steward, J. 2008. Experimental testing of the performance of pipeline ploughs. *Proc. ISOPE,* July 2008, 212–217.

Lauder, K. 2010. Perdition pipeline plough performance by scale model testing. *Presentation to CTC*, University of Dundee.

Lee, L.H., Kyriakides, S., Netto, T.A. 2008. Integral Buckle Arrestors for Offshore Pipelines: Enhanced Design Criteria. *International Journal of Mechanical Sciences*. 50(6): 1058–1064.

Lee, L.H. & Kyriakides, S. 2004. On the Arresting Efficiency of Slip-on Buckle Arrestors for Offshore Pipelines. *International Journal of Mechanical Sciences.* 46(7): 1035–1055.

Lee, S.E., Paik, J.K., Ha, Y.C., Kim, B.J., & Seo, J.K. 2014. An Efficient Design Methodology for Subsea Manifold Piping Systems based on Parametric Studies. *Ocean Engineering*. 84:273–282.

Legras, J. & Pillet, B. 2013. Tethered Catenary Riser: A New Deepwater Concept. Paper No. 11102, *Proc. OMAE,* June 2013.

Lie, H., et al. 2007. Free-span VIV testing of full-scale umbilical. *Proc. ISOPE,* July 2007.

Lie, H., Braaten, H. and Kristiansen, T. & Nielsen, F.G. 2007. Free-Span VIV Testing of Full-Scale Umbilical. *Proc. ISOPE,* July 2007.

Lie, H., Braaten, H., Jhingran, V.G., Sequeiros, O. & Vandiver, J.K. 2012. Comprehensive Riser VIV Model Tests in Uniform and Sheared Flow. Paper No. 84055, *Proc. OMAE,* July 2012.

Lie, H., Braaten, H., Szwalek, J., Russo, M. & Baarholm, R. 2013. Drilling Riser VIV Tests with Prototype Reynolds Numbers. Paper No. 11643, *Proc. OMAE,* June 2013.

Lourenco, M.I., Pasqualino, I.P. & Palermo, T.D.S. 2008. Core Material Performance on the Propagation Pressure of Sandwich Pipes. Paper No. 57507, *Proc. OMAE,* June 2008.

Low Y.M. & Cheung S.H. 2012. Evaluating the long-term fatigue response of mooring lines using an asymptotic approximation. Paper No. 83612, *Proc. OMAE,* July 2012.

Lund, K.M. 2000. Effect of Increase in Pipeline Soil Penetration from Installation. Paper No. PIPE-5047, *Proc. OMAE,* February 2000.

Luppi, A., et al. 2014. Deep water hybrid riser systems. *Proc. OTC,* May 2014.

Manelli, G., & Radicioni, A. 1994. Deepwater Pipeline Repair Technology: A Gernal Overview. *Proc. OMAE,* 1994.

Marchionni et al. 2011. Offshore Pipeline Installation - 3-Dimensional Finite Element Modelling. Paper No. 49832, *Proc. OMAE,* June 2011.

Marintek. 2014. Handbook on Design and Operation of Flexible Pipes, Marintek Report, MT 2014-F-001.

Martin, C.M. 2013. SAFEBUCK GEO Joint Industry Project-Task 4: User Element Development. University of Oxford (Confidential to JIP Participants)

Martins M.A.L., DÓria A.S. & Silverira E.S.S. 2009. Long-term fatigue and extreme design of steel risers. Paper No. 79272, *Proc. OMAE,* May-June 2009.

Maschner, E.A. & Abdalla, B. 2012. On pipeline lateral buckling: lessons learned and current design challenges. Paper No. 83413, *Proc. OMAE,* July 2012.

McStay, D., McIlroy, J., Forte, A., Lunney, F., Greenway, T., Thabeth, K. & Dean, G. 2005. A new tool for the rapid remote detection of leaks from subsea pipelines during remotely operated vehicle inspections. *Journal of Optics A: Pure and Applied Optics*, 7(6): S346-S351.

Mello, V. C., et al. 2011. Roncador P-52 Hybrid Riser Review: Key Concepts, Construction and Installation Challenges. *Proc. OTC,* May 2011.

Merifield, R.S., White, D.J. & Randolph, M.F. 2008. The Ultimate Undrained Resistance of Partially Embedded Pipelines. *Geotechnique* 58(6): 461–470.

Miyamura, A., Hirayabashi, S. & Suzuki, H. 2014. Numerical Simulation of Vortex-Induced Motion with Free Surface by Lattice Boltzmann Method. Paper No. 24302, *Proc. OMAE,* June 2014.

Modarres-Sadeghi, Y., Bourguet, R., Triantafyllou, M.S., Tognarelli, M. & Beynet, P. 2010. Re-Evaluation of VIV Riser Fatigue Damage. Paper No. 21043, *Proc. OMAE,* June 2010.

Mohd, M.H., Kim, D.K., Kim, D.W., & Paik, J.K. 2014. A time-variant corrosion wastage model for subsea gas pipelines. *Ships and offshore structures*. 9(2):161–176.

Mohd, M.H. & Paik, J.K. 2013. Investigation of the Corrosion Progress Characteristics of Offshore Subsea Oil Well Tubes. *Corrosion Science.* 67:130–141.

Morooka, C.K. & Tsukada, R.I. 2013. Experiments with a Steel Catenary Riser Model in a Towing Tank, *Applied Ocean Research*. 43. 244–255. Elsevier

Mouring, S.E. 1999. Buckling and Postbuckling of Composite Ship Panels Stiffened with Preform Frames. *Journal of Ocean Engineering*. 26.793–803.

Munns, I., Crouzen, P., Rea, T, Hunt, R. & Reid, D. 2007. Inspection of Offshore Platform Well Surface Casings and Conductors. *SPE Applied Technology Workshop on Well Integity*. Barcelona, November 2007.

Murff, J.D., Wagner, D.A. & Randolph, M.F. 1989. Pipeline Penetration in Cohesive Soil. *Geotechnique* 39(2): 213–229.

Netto, T.A. & Estefen, S.F. 1996. Buckle Arrestors for Deepwater Pipelines. *International Journal of Marine Structures.* 9: 873–883.

Netto, T.A., Ferraz, U.S., & Estefen, S.F. 2005. The Effect of Corrosion Defects on the Burst Pressure of Pipelines. *J. of Constructional Steel Research*, 61(8): 1185–1204.

Netto, T.A. & Kyriakides, S. 2000a. Dynamic Performance of Integral Buckle Arrestors for Offshore Pipelines. Part I: Experiments. *International Journal of Mechanical Sciences.* 42:1405–1423.

Netto, T.A. & Kyriakides, S. 2000b. Dynamic Performance of Integral Buckle Arrestors for Offshore Pipelines. Part II: Analysis. *International Journal of Mechanical Sciences*. 42:1425–1452.

Nozawa, T., Suzuki, H., Ohta, M. 2010. Numerical Prediction and Suppression of VIV of Deepwater Riser. Paper No. 20135, *Proc. OMAE,* June 2010.

Nyhus, B., Ostby, E., Knagenhjelm, H.O., Balck, S. & Rostadsand, P.A. 2005. Fracture control offshore piplines: experimental studies on the effect of crack depth and asymmetrical geometries on the ductile tearing resistance. *Proc. OMAE,* June 2005.

Oh, C.K., Kim, Y.J., Baek, J.H., Kim, Y.P., & Kim, W.S. 2007. Ductile Failure Analysis of API X65 Pipes with Notch-type Defects using a Local Fracture Criterion. *Int. J. of Pressure Vessels and Piping.* 84(8): 512–525.

Olso, E. & Kyriakides, S. 2003. Internal Ring Buckle Arrestors for Pipe-in-pipe Systems. *International Journal of Non-Linear Mechanics*. 38(2): 267–284.

Ortega, A., et al. 2012. On the dynamic response of flexible risers caused by internal slug flow. Paper No. 83316, *Proc. OMAE,* June 2012.

Ortega A., Rivera A. & Larsen C.M. 2013. Flexible riser response induced by combined slug flow and wave loads. Paper No. 10891, *Proc. OMAE,* June 2013.

Paik, J.K. & Thayamballi, A.K. 2007. *Ship-shaped offshore installations design, building and operation*. Cambridge: Cambridge University Press.

Palmer, A.C.,Kenny, J.P., Perera, M.R. & Reece, A.R. 1979. Design and operation of an underwater pipeline trenching plough. *Géotechnique* 29(3):305–322.

Palmer, A.C. 1999. Speed effects in cutting and ploughing. *Géotechnique* 49(3):285–294.

Palmer, A.C. & King, R.A. 2004. *Subsea pipeline engineering*. PennWell Corporation. Oklahoma: USA.

PARLOC. 2001. *The update of loss of containment data for offshore pipelines*. Mott MacDonald Ltd..

Pasqualino, I.P. & Estefen, S.F. 2001. A Nonlinear Analysis of the Buckle Propagation Problem in Deepwater Pipelines. *International Journal of Solids and Structures*. 38(46–47): 8481–8502.

Passano E. & Larsen C.M. 2007. Estimating distributions for extreme response of a catenary riser. Paper No. 29547, *Proc. OMAE,* June 2007.

Passano E. & Maincon P. 2011. Estimating long-term distributions of extreme response of a catenary riser. Paper No. 50151, *Proc. OMAE,* June 2011.

Passano, E., Larsen, C.M., Wu, J. 2014. On the Prediction of Fatigue Damage from VIV. Paper No. 24217, *Proc. OMAE,* June 2014.

Paumier, L. & Mesnage O. 2011. Psi armour wire for high collapse performance of flexible pipe. Paper No. 49257, *Proc. OMAE,* June 2011.

Peng, A.T.H. & Capart, H. 2008. Underwater sand bed erosion and internal jump formation by travelling plane jets. *Journal of fluid mechanics*, 595:1-43.

Peng, W. & Bransby, M.F. 2011. Numerical modelling of soil around offshore pipeline plough shares. *Frontiers in Offshore Geotechnics II*. 877–882.
Perdrizet, T. L., J.M., Barbin, N., Le-Corre, V., Charliac, C. & Estrier, P. 2011. Stresses in armour layers of flexible pipes: comparison of Abaqus models. *2011 SIMULIA Customer Conference*. Barcelona, Spain.
Perdrizet T. & Averbuch D. 2008. Long term failure probability calculation method applied to riser design. Paper No. 57876, *Proc. OMAE,* June 2008.
Pereira, F.R., Gonçalves, R.T., Pesce, C.P., Fujarra, A.L.C., Franzini, G.R. & Mendes, P. 2013. A Model Scale Experimental Investigation on Vortex-Self Induced Vibrations (VSIV) of Catenary Risers. Paper No. 10447, *Proc. OMAE,* June 2013.
Pereira, P. S. D., et al. 2005. Experimental study on a self standing hybrid riser system throughout tests on a deep-sea model basin. *Proc. OMAE,* June 2005.
Pereira, P. S. D., et al. 2006. Self standing hybrid riser system in waves and current. *Proc. OMAE,* June 2006.
Perez et al. 2014, Moonpool Effect Assessment During Structure Installation. Paper No. 23373, *Proc. OMAE,* June 2014.
PETRONAS. 2011. *Pipeline inspection report. Petroliam Nasional Berhad (*Petronas). Kuala Lumpur: Malaysia.
Pontaza, J.P. & Menon, R.G. 2013. Prediction of Vortex-induced Vibration Response of a Pipeline Span by Coupling a Viscous Flow Solver and a Beam Finite Element Solver. *Journal of Offshore Mechanics and Arctic Engineering*, 135 (3). ASME.
Powell, T.R., Fisher, R., Phillips, R. & Jee, T. 2002. Reducing backfilling risks. *Proc. International Conference on Offshore site investigation and geotechnics*–Diversity and sustainability. SUT.
Rahmanian, M., Cheng, L., Zhao, M. & Zhou, T. 2012. Vortex-Induced Vibration of Two Side-by-Side Circular Cylinders of Different Diameters in Close Proximity in Steady Flow. Paper No. 83223, *Proc. OMAE,* June 2012.
Ramasamy, R. & Ya, T.M.Y.S.T. 2014. Nonlinear Finite Element Analysis of Collapse and Post-collapse Behaviour in Dented Submarine Pipelines. *Applied Ocean Research.* 46: 116–123.
Ramasamy, R., Al Jaberi, M. & Al Junaibi, H. 2014. Ageing Offshore Well Structural Integrity Modelling, Assessment and Rehabilitation. Paper No. SPE-171741, *Proc. ADIPEC*, October 2014.
Randolph, M & White, D.J. 2008a. Pipeline Embedment in Deep Water: Quantification and Processes. Paper No. 19128, *Proc. OTC,* May 2008.
Randolph, M & White, D.J. 2008b. Upper Bound Yield Envelopes for Pipeline at Shallow Embedment in Clay. *Geotechnique* 58(4): 297-301.
Randolph, M. F., White, D. J. & Yan, Y. 2012. Modelling the axial soil resistance on deep-water pipelines. *Geotechnique* 62, No. 9, 837–846.
Rao, Z., Vandiver, J.K., Jhingran, V. & Sequeiros, O. 2012. The Effect of Exposure Length on Vortex Induced Vibration of Flexible Cylinders. Paper No. 83273, *Proc. OMAE,* July 2012.
Raposo, C., et al. 2014. On the Challenges With Pipeline Free Spans in Operational Phase. Paper No. 23403, *Proc. OMAE,* June 2014.
Reber, K & Boenisch, A. 2012. Advanced Electromagnetic Technology and Tools for Subsea Inspection. *SubseaUK, Subsea Pipelines Integrity Management Conference*, London, December 2012,
Reece, A.R. & Grinsted, T.W. 1986. Soil mechanics of submarine ploughs. Paper No. 5341, *Proc. OTC,* May 1986.
Resvanis, T.L., Rao, Z. & Vandiver, J.K. 2014. Effects of Strake Coverage and Marine Growth on Flexible Cylinder VIV. Paper No. 24462, *Proc. OMAE,* June 2014.
Rytter, J., et al. 2002. A Novel Compression Armour Concept for Unbonded Flexible Pipes. *Proc. OTC,* May 2002.
SAFEBUCK III "Safe Design of Pipelines with Lateral Buckling Design Guideline" 30 August 2011.
Saint-Marcoux, J.F. & Blevins, R.D. 2012. Accounting for VIV in Wake Induced Motion of Risers In Tandem At High Reynolds Number. Paper No. 22951, *Proc. OTC,* May 2012.
Saito, D., Cordeiro, L.R.S., Castro, F.A., Medeiros Jr., C.J. & Ribeiro, G.D. 2011. Innovative Supports of Risers and Corresponding Installation Procedures. Paper No. 50011, *Proc. OMAE,* June 2011.
Sanaati, B. & Kato, N. 2013. Vortex-induced Vibration (VIV) Dynamics of a Tensioned Flexible Cylinder Subjected to Uniform Cross-Flow. *Journal of Marine Science and Technology*. 18 (2). 247-261. Springer
Sanaati, B. & Kato, N. 2014. A Study on the Proximity Interference and Synchronization between Two Side-By-Side Flexible Cylinders. *Ocean Engineering*. 85. 65–79. Elsevier
Seaflex. 2007. Flexible Pipes–Failure Modes, Inspection, Testing and Monitoring. *Project Report for Petroleum Safety Authority*, Norway, December 2007.
Secher, P., et al. 2011. Lateral buckling of armor wires in flexible pipes: Reaching 3000m water depth. Paper No. 49447, *Proc. OMAE,* June 2011.
Selden, R. A. 2009. Innovative Solution for Emergency Repair of a Deepwater Riser (Avoiding Flooding and Re-Commissioning, Minimising Lost Production) A Case Study of Independence Hub Flex-Joint Repair. Paper No. 20154, *Proc. OTC*, 2009.
Seo, J.K., Cui, Y., Mohd, M.H., Ha, Y.C., Kim, B.J., & Paik, J.K. 2015. A risk-based inspection planning method for corroded subsea pipelines. *Ocean Enigneering* (in press).
Sheehan J.M., Grealish F.W. & Smith R.J. 2005. Characterization of the wave environment in the fatigue analysis of flexible risers. *Proc. OMAE,* June 2005.
Shen, W., Griffiths, T., Zan, Z., & Leggoe, J. 2015. Shear stess amplification around subsea pipelines: Part 3, 3D study of spanning pipelines. *Proceedings of the 7th International Conference on Scour and Erosion*. London: Taylor & Francis Group.

Shitamoto et al. 2014. Effect of Reeling Simulation on the Mechanical Properties of New Duplex Stainless Steel for Line Pipe. Paper No. 23694, *Proc. OMAE,* June 2014.

Skeie, G., et al. 2012. Efficient Fatigue Analysis of Helix Elemenets in Umbilicals and Flexible Risers: Theory and Applications. *J. of Applied Mathematics*(246812).

Smith, R., et al. 2007. Computational tool for the dynamic analysis of flexible risers incorporating bending hysteresis. Paper No. 29276, *Proc. OMAE,* June 2007.

Sparks, C. M., A., Rishoj, N., Deserts, L., Périnet, D., Hansen, N.O., Sele, A., Grealish, F., Riber, H., Boulliat, V., Chomard, A. & Cunff, C.L. 2003. *RISER TECHNOLOGY* – STATE OF THE ART REPORT.

Srinil, N., Zangneh, H. & Day, A. 2013. Experimental Investigation of Two-Degree-Of-Freedom VIV of Circular Cylinder with Low Equivalent Mass and Variable Natural Frequency Ratio. Paper No. 10239, *Proc. OMAE,* June 2013.

Sriskandarajah et al. 2013. Effect of Reeling Installation on Welding Residual Stress in Pipeline Girth Welds. Paper No. 11502, *Proc. OMAE,* June 2013.

Sævik, S. 2011. Theoretical and experimental studies of stresses in flexible pipes. *Computers and Structures* **89**: 2273–2291.

Sævik, S. J., G. 2014. Differential equation for evaluating transverse buckling behaviour of tensile armour wires. Paper No. 24158, *Proc. OMAE,* June 2014.

Sødahl, N., Steinkjer, O, Gjølmesli, E. & Hansen-Zahl, K. 2011. Consistent VIV Fatigue Analysis Methodology of Umbilicals. Paper No. 49459, *Proc. OMAE,* June 2011.

Sokolinsky, V.S., Frostig, Y. & Nutt, S.R. 2002. Special Behavior of Unidirectional Sandwich Panels with Transversely Flexible Core under Statical Loading. *International Journal of Non-Linear Mechanics*.37. 869–895.

Tan Z.M., Hou Y.C. & Zhang John, 2012. Irregular wave simulation and fatigue damage evaluation of a flexible riser subjected to bi-modal sea states. Paper No. 83386, *Proc. OMAE,* July 2012.

Teixeira, A.P., Soares, C.S., Netto, T.A. & Estefen, S.F. 2008. Reliability of Pipelines with Corrosion Defects. *International Journal of Pressure Vessels and Piping.* 85(4): 228–237.

Thethi, R., Howells, H., Natarajan, S. & Bridge, C. 2005. A Fatigue Monitoring Strategy & Implementation on a Deepwater Top Tensioned Riser. Paper No. 17248, *Proc. OTC*, May 2005.

Thorsen, M.J. Sævik, S. & Larsen, C.M. 2014. A Simplified Method For Time Domain Simulation of Cross-Flow Vortex-Induced Vibrations. *Journal of Fluids and Structures*. 49 (Aug 2014): 135–148. Elsevier.

Tognarelli, M., Taggart, S. & Campbell, M. 2008. Actual VIV Fatigue Response of Full Scale Drilling Risers: With and Without Suppression Devices. Paper No. 57046, *Proc OMAE*, June 2008.

Toscano, R.G., Amenta, P.M., Dvorkin, E.N. 2002. Enhancement of the Collapse Resistance of Tubular Products for Deep-water Pipeline Applications. *Proceedings 25th Offshore Pipeline Technology Conference*, Amsterdam, Netherlands.

Toscano, R.G, Mantovano, L.O., Amenta, P.M., Charreau, R.F., Johnson, D.H., Assanelli, A.P., Dvorkin, E.N. 2008. Collapse Arrestors for Deepwater Pipelines. *Cross-over mechanisms, Computers & Structures.* 86 (7–8): 728–743.

Toscano, R.G., Mantovano, L., Dvorkin, E.N. 2004. On the Numerical Calculation of Collapse and Collapse Propagation Pressure of Steel Deep Water Pipelines under External Pressure and Bending: Experimental Verification of the Finite Element Results. *Proceedings 4th International Conference on Pipeline Technology*. Belgium.

Toscano, R.G., Timms, C., Dvorkin, E.N., DeGeer, D. 2003. Determination of the Collapse and Propagation Pressure of Ultra-deepwater Pipelines. *Proc. OMAE,* June 2003.

Tsukada, R.I. & Morooka, C.K. 2013. A Numerical Simulation Procedure for Vortex-induced Vibration of Pipelines with Free Span. Paper No. 10964, *Proc. OMAE,* June 2013.

Urthaler, Y., Cerkovnik, M., Yin, F., Saldana D. & Gordon R. 2013. An Investigation of the Tolerance of Riser Fatigue to Corrosion Pitting. Paper No. 11015, *Proc. OMAE*, France, June 2013.

Vadel D. 2013. Interpretation of Subsea Inspection Data. Decom World. *Subsea Integrity Management Summit*, Houston, September 2013.

Vanden Berghe, J.-F., Capart, H. & Su, J.C.C. 2008. Jet induced trenching operations: mechanisms involved. Paper No. 19441, *Proc. OTC,* May 2008.

Vandiver, J.K. & Li, L. 1999. SHEAR7 Program Theory Manual. *Department of Ocean Engineering, MIT*. Boston, USA.

Vandiver, J.K. 2012. Damping Parameters for Flow-Induced Vibration. *Journal of Fluids and Structures*. 35. 105–119. Springer.

Venas, A. 2012. Taking deepwater pipelines to the X-Stream, DNV has a safe and cost-effective concept in the pipline. *Pipeline update 1-2012*: DNV-GL publication.

Venkatesh, E.S. 1986. Erosion damage in oil and gas wells. SPE paper 15183, *Rocky Mountain Regional Meeting of the Society of Petroleum Engineers*, Billings, MT.

Wanderley, J.B.V., Sphaier, S.H. & Levi, C. 2012. Two-Dimensional Numerical Investigation of the Hysteresis Effect on Vortex Induced Vibration on an Elastically Mounted Rigid Cylinder. *Journal of Offshore Mechanics and Arctic Engineering. 134(2), 021801*. ASME

Wang, A.M., Zhu, S., Zhu, X., Xu, J., He, M. & Zhang, C. 2013. Pendulous Installation Method and its Installation Analysis for a Deepwater Manifold in South China Sea. *Proc. ISOPE,* June-July 2013.

Wang, J., Fu, S. & Baarholm, R. 2014. Vortex-Induced Vibration of Steel Catenary Riser under Vessel Motion. Paper No. 23584, *Proc. OMAE,* June 2014.

Wang et al. 2011. Advanced FEA for Span Mitigation Analysis. Paper No. 50239, *Proc. OMAE,* June 2011.

Wang, D., White, D.J. & Randolph, M.F. 2010. Large-deformation finite element analysis of pipe penetration and large-amplitude lateral displacement. *Canadian Geotechnical Journal*, Vol. 47, 842–856.

Watanabe, Y., Suzuki, H. & Tamura, K. 2007. Optimization of a Fitting Structure of CFRP Riser Pipe for Deep Sea Drilling. Paper No. JSN-464, *Proc. ISOPE,* July 2007.

Weppenaar, N. A., B. 2014. Investigation of tensile armor wire breaks in flexible risers and a method for detection. Paper No. 23103, Proc. OMAE, June 2014.

Westgate, Z.J., White, D.J. & Randolph, M.F., 2009. Video Observations of Dynamic Embedment during Pipe laying on Soft Clay. Paper No. 79814, *Proc. OMAE,* May-June 2009.

Westgate, Z.J., White, D.J., Randolph, M.F. & Brunning, P. 2010. Pipeline laying and embedment in soft fine-grained soils: field observations and numerical simulations. *Proc. OTC*, May 2010.

White, D.J. & Dingle, H.R.C. 2011. The mechanism of steady friction between seabed pipelines and clay soils. *Geotechnique*, Vol. 61, No. 12, 1035–1041,

White, D. J., Ganesan, S. A., Bolton, M. D., Bruton, D.A.S., Ballard, J-C. & Langford, T. 2011. SAFEBUCK JIP-Observations of axial pipe-soil interaction from testing on soft nature clays. *Proc. OTC*, May 2011.

White, D.J. & Cathie, D.N. 2011. Geotechnics for subsea pipelines. *Frontiers in Offshore Geotechnics II*. 87–113.

White, D.J., Campbell, M.E., Boylan, N.P. & Bransby, M.F. 2012. "A new framework for axial pipe-soil resistance, illustrated by shear box tests on carbonate soils". *Proc. International Conference on Offshore site investigation and geotechnics.* SUT, London.

Williamson, C.H.K. & Govardhan, R. 2008 A Brief Review of Recent Results in Vortex-Induced Vibrations. *Journal of Wind Engineering and Industrial Aerodynamics*. 96. 713–735. Elsevier.

Yeganeh et al. 2012. Determining Natural Frequency of Free Spanning Offshore Pipelines by Considering the Seabed Soil Characteristics. *Journal of the Persian Gulf (Marine Science)*, Vol. 3, No. 8

Yew, C.C. 2013. SliPIPE-new pipeline expansion concept. *Pipeline update* No.1-2013: DNV-GL publication.

Zhang, Y. & Tan, Z. 2011. An Investigation of Fatigue Damage due to VIV in Flexible Riser with Different Methodologies. Paper No. 49036, *Proc. OMAE,* June 2011.

Zhao, M., Tong, R. & Cheng, L. 2012. Numerical Simulation of Two-Degree-Of-Freedom Vortex-Induced Vibration of a Circular Cylinder between Two Lateral Plane Walls in Steady Currents, *Journal of Fluids Engineering*. 134(10), 104501. ASME.

Zimmermann, C., Edwards, R., Talmont, P., Duley, D., de la Cruz, D. & Maroju, S. 2009. Recent Experience with a Comprehensive Riser Tower Monitoring System. *Proc. DOT*, New Orleans, February 2009.

Østergaard, N. H. 2012. On Lateral Buckling of Armouring Wires in Flexible Pipes. Aalborg, Denmark, Aalborg University.

Østergaard, N. H. et al. 2011. On lateral buckling failure of armour wires. Paper No. 49358, *Proc. OMAE,* June 2011.

OTC= The Offshore Technology Conference.
OMAE= The International Conference on Offshore Mechanics and Arctic Engineering.(∼2007)
The ASME International Conference on Offshore Mechanics and Arctic Engineering.(2008)
The ASME International Conference on Ocean, Offshore and Arctic Engineering.(2009∼)
ISOPE= The International Society of Offshore and Polar Engineers Conference.

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