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Subsea pipeline infrastructure monitoring: A framework for technology review and selection

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ABSTRACT

The level of inherent risk associated with subsea oil and gas pipelines has led to advances in non-invasive infrastructure monitoring technologies. However, from an asset owner's perspective, identifying those technologies that provide the highest value presents a significant challenge. In addressing this problem, this paper presents a technology selection framework that is comprised of three main stages. In the first stage, 'failure pathway' diagrams are developed that clearly illustrate the issues and interactions that conspire to cause deterioration and failure of subsea pipelines and related components in service. In the second stage, a set of candidate technologies are identified that can provide data/information to populate the failure pathway diagrams. This ensures that only relevant technologies are identified. Finally, a Multi Criteria Assessment (MCA) procedure is used to assess technologies against industry-agreed performance metrics. Using the framework, a prioritised subset of high-value technologies are identified to address erosion, corrosion, fatigue, deformation, blockage and flow control problems in subsea pipeline infrastructure.

1. Introduction

This paper presents a selection framework to assist in the identification and prioritisation of emerging inspection technologies using subsea pipelines and components as a case study. The paper provides an assessment of technologies that are potentially useful for assessing the condition of subsea pipelines. While methods to convert data gathered from these technologies to useful asset information relating to structural reliability, failure probability and risk are important, a review of these remains outside the scope of this initial study and will be addressed in future reviews. The selection framework presented in this paper is based on three main stages:

1) Identifying deterioration mechanisms and 'failure pathways' for subsea infrastructure types under consideration.
2) Matching currently available or emerging inspection technologies to identified infrastructure types.
3) Prioritising inspection technologies for further investigation and field trialling based on their perceived value.

Subsea oil and gas production pipelines and their related components represent critical infrastructure that can incur severe economic, social and environmental impacts should they fail (Taylor and Tran 1996; Ilman and Kusmono, 2014). Compared to other pipelines (i.e. water and wastewater), recorded failure rates in subsea oil and gas pipelines are relatively low. For example, the UK Offshore Operators Association estimate that a total of 1567 subsea pipelines operate in the North Sea, with a total length of 24,837 km and an exposure (or operating experience) of 328,858 km-yrs (PARLOC, 2001). Of these, a total of 542 historical failure events are reported to have occurred up to 2000, corresponding to an estimated average failure rate of 0.0017 events per km/yr.

However, while average failure rates in subsea pipelines are relatively low, their failure consequences can be higher than for other pipeline types Failure of a pipeline carrying hydrocarbons can result in significant environmental and reputational damage. In addition, loss of integrity in any subsea pipeline may result in deferred production costs while the failure is addressed. As an example, reported by Hovey and Farmer (1994) corrosion in a particular subsea oil pipeline in the USA led to a spill event and the need to shut down production. This incident reduced oil production of the United States by an estimated 400,000 barrels per day and in turn, hiked up world oil prices (Hovey and Farmer (1994)).

With subsea assets now being installed in offshore locations that are deeper (over 2000 m deep) and further (over 200 km from shore) than previously the complexity of monitoring and inspecting

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the integrity of permanently installed infrastructure has increased for asset owners. Consequently, the development of technologies for non-invasive, non-destructive monitoring of subsea infrastructure health is a developing area of subsea engineering research. From an asset owner's perspective, a key challenge is to identify which of the emerging technologies is relevant to the range of infrastructure types and deterioration modes and is most likely to provide the greatest benefit from investment.

The following subsea infrastructure types were considered within the scope of the study:

- Well jumpers.
- Spools.
- Pipelines.

2. Identifying infrastructure deterioration mechanisms and failure pathways

For any monitoring technology to be effective and provide benefit, it must be able to report on specific indicators relevant to the performance of the infrastructure under consideration. In collaboration with industry partners, failure modes were prioritised as those that would incur the highest consequences to infrastructure owners. For the subsea infrastructure types under consideration, the identified set of high priority failure modes were:

- piping, jumpers, spools and pipelines—containment failure (spill)

Based on these prioritised asset types and failure events, “failure pathway” diagrams were constructed that identify and establish links between the issues that drive asset deterioration and failure by the modes of concern identified above. By identifying influences over the failure events in this way, elements in the failure pathway diagrams correspond to possible parameters that, by effective monitoring/inspection, would provide an early indication of asset distress and the opportunity to intervene prior to failure. Alternatively, monitoring those parameters identified in the pathway diagrams can also inform the decision to defer intervention by confirming adequate condition of the asset (Davis et al. 2013). Failure pathway diagrams therefore provide a basis for identifying candidate monitoring technologies to be reviewed in subsequent stages of the methodology (Davis et al. 2013). The relevant failure pathway diagrams have been developed for key infrastructure types/failure modes and are shown below. The individual elements in each diagram indicate those parameters (or distress indicators) that signal deterioration towards failure and can therefore provide useful information if monitored. The dark purple element in each diagram corresponds to the actual failure event of concern. Generally, those parameters shown towards on the outer ‘perimeter’ of each diagrams (in dark blue), correspond to the origin/initiation of asset deterioration, whereas those parameters towards the inner part of the diagram occur closer to the actual failure event. Dashed lines in each diagram indicate where multiple parameters combine to promote a subsequent stage of the asset deterioration and failure process. A more detailed description of identified deterioration and failure processes follows the diagrams below.

2.1. Pipelines: loss of containment

Reference to the literature for subsea pipeline deterioration suggests a wide range of possible failure mechanisms and modes, which have been used to construct the failure pathway diagram in Fig. 1. The individual elements in the diagram indicate those parameters (or distress indicators) that signal deterioration towards failure and could therefore provide useful information if monitored.

2.1.1. Internal corrosion

Nyborg (2005) describes how small changes in the corrosivity of internal fluids that are transported by subsea pipelines, can lead to increase in the observed pitting corrosion rates on internal pipe surfaces. Dugstad et al. (1994) suggest empirical observations of the limiting factors (i.e. temperature, CO_2 partial pressure, flow velocity etc) that control internal corrosion in oil and gas pipelines. Such parameters may be useful in establishing surrogate indicators for monitoring internal corrosion levels in subsea pipelines.

2.1.2. Internal erosion

Sand erosion is commonly anticipated in the oil and gas industry and severe damage to facilities can be encountered if sand events are not handled properly (Kulkarni et al., 2012). Problems arising from high sand production can exacerbate corrosion problems. Typical problems include erosion of production choke valves leading to replacement; erosion/wear/blockage of production pipelines.

Sand produced with oil and gas is normally filtered down-hole, with sand screens to limit the size and amount of sand that can move through into production pipelines. The type of pipeline material strongly influences the extent of sand erosion. Erosional allowances are calculated and prepared for with erosion resistant inlays and cladding being common in subsea production lines. Based on the literature (Meng and Ludema, 1995), it appears that there are four primary mechanisms by which solid particle erosion occurs:

- Cuttings wear (defined as the indentation of material surface by a sharp solid particle followed by fracture of the material).
- Cyclic fatigue.
- Brittle fracture (“non-cyclic failure”).
- Localised melting of the material.

For sand erosion encountered in the oil and gas industry, the important system parameters that are thought to contribute to this deterioration process are: sand particle impact velocity and angle; pipeline material hardness and sand particle size and sharpness (Kulkarni et al. 2012). Although fine sand was previously not thought to present an erosion problem, recent evidence Kulkarni et al. (2012) suggests that in some cases, these fines can cause severe erosion damage. As described by Kulkarni et al. (2012), fines are almost inevitable in oil and gas production since they can escape through most sand screens.

2.1.3. External vibration, Deformation and cracking

Changes in the subsea infrastructure external environment can also increase failure likelihood. As described by Natarajan et al. (2007) major contributors to fatigue of subsea infrastructure (flowlines and risers) are related to changes in motion from interactions with fluid flow and interactions between infrastructure and the seabed. For example, Xiao and Zhao (2010) discuss how seawater current flow across free spanning lengths of subsea pipeline can lead to Vortex Induced Vibration (VIV). In those cases where pipelines are lowered from lay barge to the sea bottom without burial, free spans or suspended spans (i.e. sections of pipeline that are not in contact with the seabed) can form due to irregularities of the seabed and/or scouring underlying seabed material. Currents flowing across free spans of pipeline can cause the formation and shedding of localised circular flow patterns