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BEST PRACTICE FOR THE ASSESSMENT OF SPANS IN EXISTING SUBMARINE PIPELINES
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BOMEL LIMITED

Ledger House

Forest Green Road, Fifield

Maidenhead, Berkshire

SL6 2NR, UK

Telephone +44 (0)1628 777707

Fax +44 (0)1628 777877

Email info@bomelconsult.com

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VOLUME 2

US MINERALS MANAGEMENT SERVICE

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BEST PRACTICE FOR THE ASSESSMENT OF SPANS IN EXISTING SUBMARINE PIPELINES

EXECUTIVE SUMMARY

Although there is significant published guidance on the design of new pipelines that, as they are laid, may form spans as a result of topographical features, there is not presently available equivalent published guidance for the assessment of free spans which may form during the operating life of a pipeline system due to such processes as scour. This report therefore provides a foundation for an agreed industry wide consistent and standardised process for the assessment of such spans by presenting a review of the "state of the art" practice for the assessment of spans in existing submarine pipelines and giving recommendations for determining "best practice" in undertaking such assessments.

Section 1 of the report, following an introduction to the topic, gives the background to the work and details the scope undertaken in the present project. Section 2 reviews the various philosophical approaches that can be taken to the management of free spans in existing pipelines and suggests a framework with associated procedures and processes for the assessment of such spans.

Section 3 then reviews the issue of "uncertainty" in respect of pipeline free spans by considering both the resolution uncertainty in the data and the inherent temporal variability of the span itself. The sensitivity of the free span assessment outcome to the various input parameters is presented. The section concludes with a discussion of a risk based, reliability approach to the subject.

Section 4 is concerned with the data perceived as required for assessment of free spans and in particular the value of historic records to better understand such issues as span development, migration and elimination both by natural processes or intervention. Section 5 addresses pipeline surveys with regard to methods, frequencies and accuracy of the data obtained.

Section 6 is concerned with preliminary data to allow a review and comparison of the various analytical tools presently available.

Section 7 presents a critical discussion of the earlier sections to determine the recommended content of a "best practice" document, key technical obstacles to its production, consideration of the availability of appropriate historic data and the feasability of its use to improve the assessment process.

Recommendations for a "Way Forward" from this point to availability of "Best Practice" guidance are documented in Section 8 to conclude the report.

The Appendices contain detailed technical material associated with the report.

1. INTRODUCTION, BACKGROUND AND SCOPE OF WORK

1.1 INTRODUCTION

The primary duty of pipeline operators is to ensure the health and safety of individuals and the protection of the environment in respect of the pipelines under their control. In the United Kingdom (UK), up until the time of issue of the Pipelines Safety Regulations (SI 1996 No 825), the health and safety aspects of onshore and offshore pipelines were covered by various sets of regulations. Those applicable to offshore pipelines dated from the 1970s, were prescriptive, bureaucratic and encouraged a compliance culture (Bugler, J.,1996 and Thayne, A. T.,1996). The Pipelines Safety Regulations, 1996 represent a move away from prescription in that they are based on a goal-setting philosophy and therefore compatible with the overall UK offshore regulatory regime. The regulations recognise the need for different approaches for pipelines with different levels of risk and the UK Health and Safety Executive has thus developed a regime that is intended to be flexible in all aspects of pipeline design, construction and, particularly relevant in the present context, operation. The adoption of a risk based approach is also consistent with present international trends. New techniques and approaches are encouraged (Parkash, S., 1996); however, those that are developed within this framework must be soundly-based and achieve an equivalent or greater level of safety compared with present practice. Thus, the present safety regime throws down the challenge to operators to promote innovative technology and thinking, allowing them the freedom that the previous prescriptive legislation did not permit.

In addition to compliance with the regulatory framework, a further business driver for pipeline operators is cost management. Cost savings are being sought in all areas including the operation, maintenance and assessment of pipeline systems (Kaye, D., 1996). Operators have a clear responsibility to the public, regulators, customers and shareholders to prevent integrity breakdown adversely influencing pollution, personnel safety, security of supplies and the reliability or economic value of the asset. Operating companies are thus under continually increasing pressure to develop and manage pipeline integrity programmes in a responsible and cost-effective manner so as not only to ensure safety but also to increase the business emphasis on the reliability of pipeline systems. Maintaining the integrity of a pipeline system during its operational life has significant benefits in financial and environmental aspects in addition to safety considerations (Henderson, P.A., 1996).

As stated above, the Pipeline Safety Regulations,1996 are goal-setting; they therefore require the operator to demonstrate the integrity of the pipeline but do not specify the methods to be used. This permits the choice of any rationally engineered strategy and thus opens the route to more efficient and cost-effective integrity management. However, such strategies must be recognised as being more 'scientific' than used previously; they thus rely for their efficacy on the availability of good information (Robertson et al ,1995 and Ellinas et al, 1995), and data associated with the uncertainties involved in the operation of pipelines (Tviet, O. J., 1995). The desire to utilise more sophisticated approaches to the integrity management of pipelines imposes pressures all the way through the process and is dependent on the inspection technology to detect anomalies (Jones, D.,1996 and Bruce, J.,1994) and provide the quality of information that such technology requires (Lilley, J. R., 1996).

1.2 BACKGROUND

A key element in the integrity management of submarine pipelines is the detection, characterisation, assessment and, if necessary, correction of pipeline free spans. Submarine pipeline spans have received a great deal of attention in terms of research in recent years. Acronyms for research projects abound, including SVSP, MASPUS, GUDESP (Tura et al 1994), SUPERB (Sotberg et al, 1996) and the MULTISPAN project (Mørk, K. J., Vitali, L. and Verley, R., 1997). Despite these intensive efforts, and the fact that many of the pieces of work were Joint Industry Projects (JIPs), many of the findings generated have not directly found their way into the public domain and, therefore, are not used on an industry-wide basis. In practice pipeline operators, or consultants acting on their behalf, have developed and applied different procedures and criteria depending on individual company philosophy and standards. A whole range of methodologies and bespoke software has evolved (some of it commercially available) based on differing interpretations of research, guidelines and rules. However, the degree of divergence or convergence between the different approaches is not presently known quantitatively because, until now, there has been no opportunity to compare and contrast the strengths and applicability of the various methodologies.

Discussions with various industry stakeholders have indicated that there is a strong consensus that insufficient attention has been paid to, and that the principal outstanding problem is one of, the assessment of spans as *unplanned-for defects* in existing pipelines (formed as a result of seabed material transport) rather than design for spans in new pipelines. With existing pipelines there are greater uncertainties and less-detailed knowledge of many factors, as compared with the design situation where spans are formed on known topography. This, coupled with the strong influences of inherent time-dependent aspects, and the reliance on survey data (with its associated uncertainties) means that the problem presents serious impediments to the use of modern, complex and sophisticated analytical tools. While it is commendable that much high-quality and rigorous research work has been incorporated into the DNV Recommended Practice DNV-RP-F105 - Free Spanning Pipelines (DNV, 2001), this document remains biased towards design analysis and, whilst it recognises that time-dependence is one key aspect of spans by the use of the so-called temporal classification, gives little other definitive guidance for spans that develop while the pipeline is in service. Furthermore, although some research recognises that uncertainty is a key aspect of the general problem of addressing pipeline spans, and advocates the use of reliability methods, it is still strongly felt within the industry that insufficient attention has been paid to providing definitive guidance for pipeline spans as unplanned-for defects.

This present report therefore specifically addresses spans as unplanned-for defects in terms of the requirements for assessments and the constraints within which they must be performed. It addresses the perceived imbalance between designed-for and unplanned-for spans by providing a foundation for development of 'Best Practice' assessment guidance to provide acceptable levels of safety, coupled with appropriate cost-effectiveness, for spans that develop in existing pipelines.

The availability of such guidance will promote:

- consistent and standardised practice across the industry
- the ability to make rational span acceptance decisions that are informed by:
  - quantified levels of safety or probability of 'failure'
  - collective expertise and experience
- rationalised inspection, maintenance and repair strategies, with potential cost savings
- avoidance of pipeline failure (and all its potential consequences) with confidence
- an holistic view of the problem, rather than addressing isolated technical aspects
- a coherent research strategy - directing resources towards the quantifiably important aspects of the problem.

1.3 SCOPE OF WORK

The fundamental issues associated with the assessment of unplanned-for free spans in existing pipelines can be summarised as follows:

1. There are greater uncertainties and less detailed knowledge of many factors (compared with the design situation). It may even be the case that certain information is not available owing to the age of the pipeline.

2. There is a temptation to use the more complex and sophisticated analytical tools that are available on the basis that they are 'better' by some subjective judgement. However, these tools are diverse, and their usage may require the precise

specification of many data items. If information is scant, subjective engineering judgement is necessary to assign values to parameters; these may be over-conservative or under conservative and any advantage gained from using the sophisticated tool may be lost, or the level of safety unquantified.

3 In using data or information that is available, specific issues may be raised as to their applicability and relevance to the present problem (as compared with the design situation).

4 There is strong reliance on survey data, which is obtained by remote or indirect means, very often under difficult conditions, and thus may be imprecise or subject to interpretation. This data relates to fundamental parameters of the problem, e.g. observed span length and gap beneath span.

5 Underlying and strongly influencing the whole of the problem are the time-dependent aspects. The problem is one of dealing with the mechanics of a structure that may change its geometry, sometimes rapidly, with respect to both time and space. Results from an individual survey only represent a "snapshot" at a particular time.

Whereas much past research has concentrated, almost exclusively, on quantitative engineering analysis tools, the scope of work undertaken in this project has been formulated by taking a holistic and systemic view of span assessment as a management process that involves:

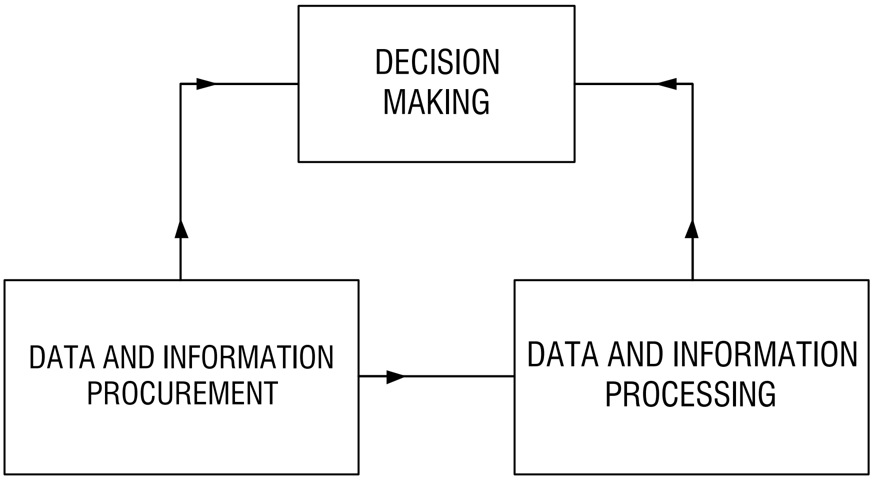
- data and information procurement
- data and information processing
- decision making.

And thus seeks to determine:

- what informs decision making? (whether to leave a span or intervene with remedial measures?)
- what are the means of data / information processing? (analytical / engineering assessment tools?)
- what data / information is required? (including survey data?)

Uncertainty is treated as an integral part of the assessment process.

The above issues, which are expanded in Table 1.1, interact systemically thus:



With regard to 'decision making', it is self-evident that at a very early stage a conclusion has to be reached about the overall philosophical approach that needs to be taken to the problem. Given the inherent uncertainties, it is suggested that the philosophy adopted should lean towards the probabilistic / risk types of techniques, and the approach adopted should be supported by appropriate tools and data / information procurement.

At the detailed level under 'data and information processing', there are questions of what means can and should be used, ie. what is available, what is the ‘best’ of what is available, and is this what should be used or are further developments necessary? In addition to this, what constitutes the ‘best’ needs to be defined in the light of the overall philosophical framework; criteria need to be established.

It is also clear that the 'data and information procurement' aspects are inextricably linked with the processing and decision making areas. For example, in considering the questions raised about what data processing methods should be used, attention must turn to the data required. Can it be obtained or should it be obtained (i.e. how vital is it for effective use in the ideal process); with what certainty is the data known and how certain or precise does it need to be; how is the data manipulated or interpreted prior to use in processing and decision making.

The scope of work to address the above was divided into the following five work areas:

- approaches to span assessment
- uncertainty
- data

- surveys
- analytical tools

and the following aspects were considered:

- identifying the most appropriate overall philosophical approach for span assessment and ensuring that subsequent work is directed towards it
- ensuring that the decision-making process is supported by tools and information that incorporate and handle the uncertainty inherent in the problem
- identifying what assessment tools can and should be used, and what are the best features of those available
- determining what data needs to be obtained and with what degree of certainty
- benchmarking span analysis programs / systems
- determining what data can be obtained, to what degree of certainty they are known and how are they manipulated or interpreted
- formulating recommendations for "Best Practice" guidance.

2. APPROACHES TO SPAN ASSESSMENT

2.1 INTRODUCTION

A key element of a submarine pipeline integrity management system is a sub-system for the identification, assessment and, if necessary, correction of free spans that may occur as a result of scour or other sediment transport processes. Span assessment is an essential part of this sub-system and must include a procedure to inform the decision process on the need to intervene to reduce a span and / or prevent its further growth. The assessment process can range in content from a data review and the application of engineering judgement (which might be quite appropriate for pipelines with low failure consequences and / or where there is well known history of free span behaviour not prejudicial to safe operation of the system) to the rigorous application of advanced analytical techniques (which might be appropriate on high failure consequence pipelines and / or where the economic and / or technical constraints on an intervention are critical).

This section reviews and compares the benefits and dis-benefits of various procedures and analytical approaches that have been applied to pipeline free span assessment and makes recommendations for the adoption of a specific approach which is presently considered to represent a "Best Practice" in this arena.

2.2 PRINCIPAL CONSIDERATIONS

In determining the selection of an optimal approach to free span assessment, it is necessary to adopt a contingency approach that will be conditioned by system specific parameters. These will typically include the economic, safety and pollution consequences of a pipeline failure; the economic and technical feasibility of an intervention; the age and history of the pipeline system; the quality of the available data in terms of content, availability and accuracy; the applicability of analytical tools and any regulatory constraints.

It is typically found that the simpler approaches to free span assessment are inherently more conservative in determining acceptable span lengths and that the level of conservatism reduces as the level of sophistication in the span analysis increases. It is, however, important to note that in certain circumstances the simpler methods can lead to under-conservative (i.e. unsafe) results. Thus, the inappropriate application of the simpler methods may lead to either wasted expenditure on unnecessary interventions or losses from unpredicted system failure.

When using assessment methods at the more sophisticated end of the available assessment spectrum, it is necessary to ensure the quality of the data is compatible with the technique employed and that no important parameters are neglected in the determination of the acceptable span length.

Based on the perceived accuracy of the input parameters and the level of confidence in the analytic models there will be uncertainty in the results of the analysis. This uncertainty may be further compounded by the spacial and temporal variation that occurs as a span develops, migrates or self-corrects. It is therefore important to determine whether a deterministic or probabilistic approach is more appropriate in any specific system scenario. Risk / reliability based approaches to assessment can also be adopted as further discussed below.

Generally, there are three failure modes that have to be considered when assessing a maximum acceptable span length:

- Pipe failure under static loading
- Pipe failure under instantaneous dynamic loading, and
- Pipe failure under long term dynamic loading (fatigue).

For each of the above failure modes it is further necessary to determine appropriate acceptance criteria.

In particular conditions it may be necessary for further failure modes to be considered. For instance, if a pipeline has a propensity for its weight coating to detach, tight limitations on dynamic response may be required to prevent further weight coat loss and the stability of the pipeline being thus impaired.

The above failure modes and associated loading combinations and acceptance criteria are also further discussed below.

2.3 AVAILABLE APPROACHES

2.3.1 The Basic Approach

Other than the direct application of engineering judgement to the bare inspection data, the most basic approach taken to determining a maximum acceptable span length is the use of a simple deterministic, stress based criteria to assess the limiting span length under static conditions coupled with ensuring avoidance of the onset of vortex shedding resonance by the use of a reduced velocity approach.

A typical basic static analysis approach is to use simple linear elastic methods of analysis and limit the maximum equivalent stress (arising from pressure, temperature and bending) to a proportion (as dictated by pipeline codes) of the specified minimum yield strength (SMYS) of the pipe material.

The limiting span length due to static stress L_{ss} can be computed from:

$$L_{ss} = SF_{ss} \sqrt{\left[\frac{2Ip\sigma_b}{q_{max} D}\right]} \qquad (2.1)$$

where I is the pipe moment of inertia,

p is a factor relating to the maximum bending moment in the span,

F_b is the maximum allowable bending stress in the span,

q_{max} is the uniformly distributed load per unit length of the span,

D is the pipe outside diameter.

and SF_{ss} is a safety factor limiting the span length to 90% of the estimated critical length, ie. $SF_{ss} = 0.9$.

The maximum allowable bending stress in the span is a function of the hoop stress developed by internal and external pressures, and the longitudinal thermal and Poisson effect stresses. The combination of these hoop and longitudinal stresses is limited to 96% of SMYS (F_y).

The factor p is a function of the end conditions at the shoulders of the span and the effective axial force present. This term typically varies between 4 and 35. For the preliminary assessment, a value of p = 8 has been recommended as representing an end condition between fully built-in and simply supported, together with an axial force of about 50% of the Euler buckling load; this value being considered 'generally' conservative. When the necessary data is available a more sophisticated approach makes reference to a graph relating p to the dimensionless parameters:

$$\$_e = T_e L^2 / EI \text{ and } (= E_f L^4 / EI$$

where T_e is the effective axial tension

E_f is the soil modulus

and E is the pipeline Young's modulus

This method assumes that the span length, L, is known from inspection data and soil modulus E_f is either estimated or taken to be $2MN/m^2$. The uniformly distributed load q_{max} is a function of the submerged weight of the pipe and the horizontal loading on the span, due to current and waves. It should be noted that, with regard to horizontal loading typically:

- The wave and current velocities are to be derived from the 50 year return period data;
- The hydrodynamic drag coefficient is to be taken as 0.7 and 1.05 for smooth and rough pipe, respectively;
- In combining the current and wave velocities, the critical wave phase angle has been assumed to be zero.

Further refinement can be obtained by using span specific inspection data.

A 'safety factor' can be applied to the calculated allowable span to provide a margin against span growth prior to the next planned inspection. A value of 0.9 has been adopted.

The simple approaches which limit the maximum equivalent stress to a proportion of the minimum yield stress of the pipe material are inherently more conservative than limit state type analysis which uses the material stress / strain properties more efficiently. The approach uses unsophisticated structural mechanics and some parameters such as soil / structure interaction, axial force and P-* effects are not treated explicitly. The method is based on small deflection assumptions and does not consider the effects of membrane action.

2.3.2 Screening Approaches

Further sophistication can be achieved by using free span assessment procedures embodying a screening approach where spans are classified as acceptable or otherwise according to some initial criteria. Spans failing the initial criteria are then either subject to intervention or subjected to a series of more rigorous analyses and / or more detailed inspections to provide further input to the intervention decision making process.

Some screening procedures classify spans in terms of the need for future inspection or remedial works, for instance:

Acceptable Spans

The span may be left indefinitely without the need for correction.

Reviewable Spans

The span should be marked and its history monitored during yearly inspections. If it exists for more than three consecutive years it should be recategorised as rectifiable and corrected during the next IRM programme.

Rectifiable Span (next IRM)

The span may be lef t until the next scheduled IRM Programme and then corrected.

Rectifiable Span (immediately)

The span must be corrected immediately.

Each span category is based on a different set of acceptance criteria for four loading conditions:

i) static
ii) quasistatic
iii) dynamic
iv) fatigue.

The loading conditions are a combination of functional, environmental and vibrational elements as specified below.

Combination	**Functional**	**Environmental**	**Vibration**	**Checked against excessive**
Static	T	X	X	Static stress
Quasistatic	T	T	X	Static stress
Dynamic	T	T	T	Dynamic stress
Fatigue	T	T	T	Fatigue damage

These three elements are defined by the following sub-elements:

- Functional, comprising:
  - self-weight of pipeline and contents,
  - thermal loading, internal pressure loading,
  - transient operational effects,
  - hydrostatic pressure loading,
  - residual installation loads.

- Environmental, comprising:
  - current loading,
  - wave loading.

- Vibration, comprising:
  - additional in-line Morison forces allowing for span response amplification

due to resonance phenomena,

- effects due to periodic flow acceleration relating to the pipe/seabed proximity,
- effects due to the periodic shedding of vortices.

The acceptance criteria for each of the four loading conditions is related to a proportion of specified minimum yield stress (SMYS) or Miner's damage ratio O. The relationship between span category, load condition and acceptance criteria is summarised in Table 2.1.

As would be expected, it is the time dependent dynamic / fatigue factors that most affect the classification of category. Considering the static and quasistatic conditions above, the categorisations will be at one of three levels: 'Acceptable', 'Reviewable' (if quasistatic span length is less than the static span length) or 'Rectify Immediately'. Therefore, the advantages of this approach are largely lost if the assessment is limited to static strength behaviour only.

2.3.3 The Tiered Approach

A generic system has been developed that is considered to represent a 'Best Practice' for the determination of the acceptability of pipeline defects. This procedure is shown graphically in Figure 2.1 which illustrates that the procedure involves *information transfer* to and from a *process*, with a *result* ensuing. Inspection provides information to the assessment procedure; this is amalgamated with the other data and provides input, along with the load combinations and analytical criteria, into the analytical methods. Specific application of the generic procedure to minimise the need for remedial intervention for free-spans is depicted in Figure 2.2. Each failure mode is subjected to a tiered screening approach that employs increasing levels of analytical complexity, for each potential failure mode as shown in Figures 2.3, 2.4 and 2.5. The results of the analytical methods, in conjunction with the acceptance criteria, are then used to decide the acceptability or otherwise, of a span.

The tiered screening process involves implementing successively less conservative and more sophisticated analytical and modelling techniques. In this way pipeline spans that pass conservative tests, which are designed to be easily and rapidly applied to bulk-processing of large numbers of spans, are screened out at an early stage, leaving fewer spans to be analysed using the more complex techniques of the higher tiers. The basic structure of each tier is similar insofar as it involves the interaction between *data*, *load combinations*, *analytical criteria*, an *analytical method* and an *acceptance criterion*, before a decision is made whether to accept a span. If a span is found to be acceptable, it is passed to the next failure mode assessment (static strength to dynamic strength, dynamic strength to fatigue), or if it is deemed to be not acceptable it is passed to a higher tier level. If a span is determined to be not acceptable at the Tier 3 level, then it is classified as significant and must be rectified. If and only if the span has been determined to be acceptable for all three failure modes is it classified as superficial.

The precise interactions between the data, load combinations, analytical criteria, analytical methods and acceptance criteria may differ between the tiers. This is because the different analytical methods employed may, in each case, require distinct inputs and produce distinct outputs and, consequently, the process will require different modes of handling. The tiered approach is intended to be flexible and the manner in which it is to be applied is largely at the discretion of the individual applying the procedure.

To date, specific deterministic processes, including load combinations and acceptance criteria, for assessing static span strength at Tier Levels 1, 2 & 3 and dynamic acceptability at Tier Level 1 are available and are presented in Appendices A, B, C,& D respectively.

Work undertaken on the tiered approach to dynamic and fatigue assessment is detailed in Appendix E.

An evaluation analysis of various acceptance criteria, particularly in relation to static strength is reported in Appendix F.

Span Category	Load Condition	Environmental Return Period	Acceptance Criteria
Category I	Static	N/A	# 72% SMYS
(Acceptable)	Quasistatic	-	-
	Dynamic	50 yr max wave & 10 yr current	# 96% SMYS
	Fatigue	1 yr wave & 1 yr current	O # 0.0025
Category II	Static	N/A	# 72% SMYS
(Reviewable)	Quasistatic	50 yr max wave & 10 yr current	# 96% SMYS
	Dynamic	3 yr max wave & 3 yr current	# 96% SMYS
	Fatigue	1 yr wave & 1 yr current	O # 0.01
Category III	Static	N/A	# 72% SMYS
(Rectifiable	Quasistatic	-	-
next IRM)	Dynamic	-	-
	Fatigue	1 yr wave & 1 yr current	O # 0.04
Category IV	Static	N/A	> 72% SMYS
(Rectifiable	Quasistatic	-	-
immediately)	Dynamic	-	-
	Fatigue	1 yr wave & 1 yr current	O $ 0.04

Table 2.1 Relationship between Span Category, Load Condition and Acceptance Criteria

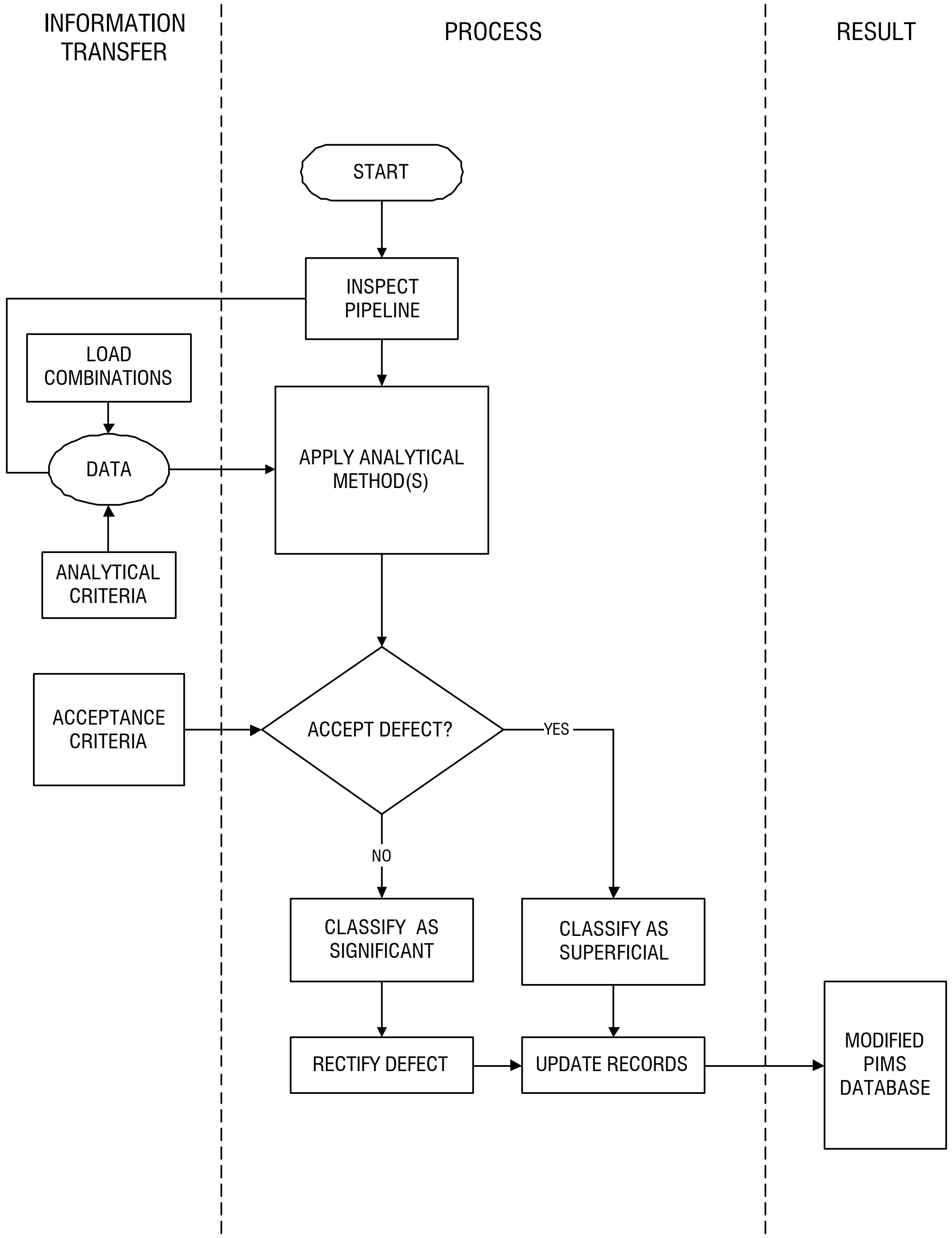


Figure 2.1 Generic Defect Assessment Procedure
(PIMS = Pipeline Inspection Management System)

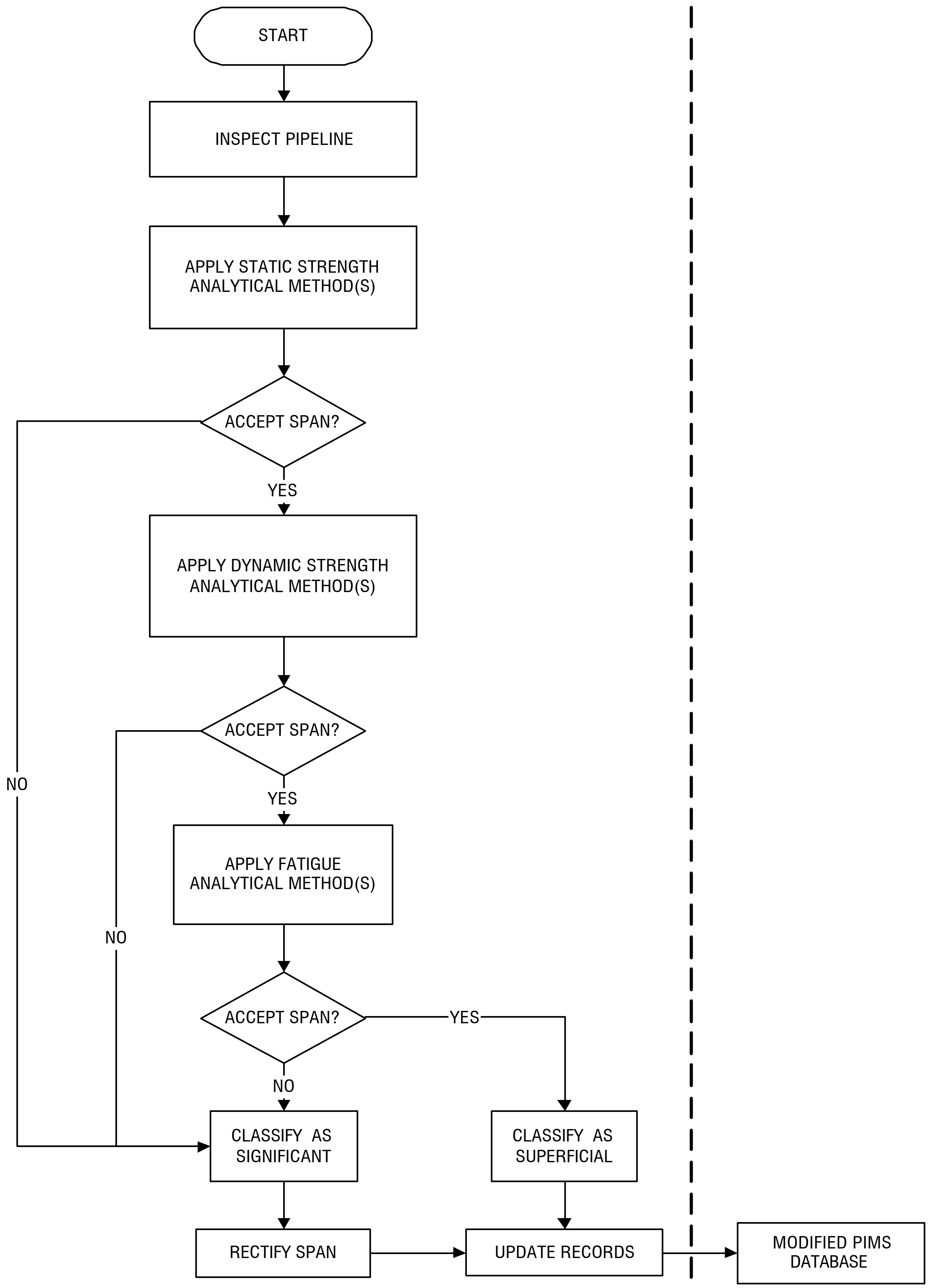


Figure 2.2 Overall Pipeline Span Defect Assessment Procedure

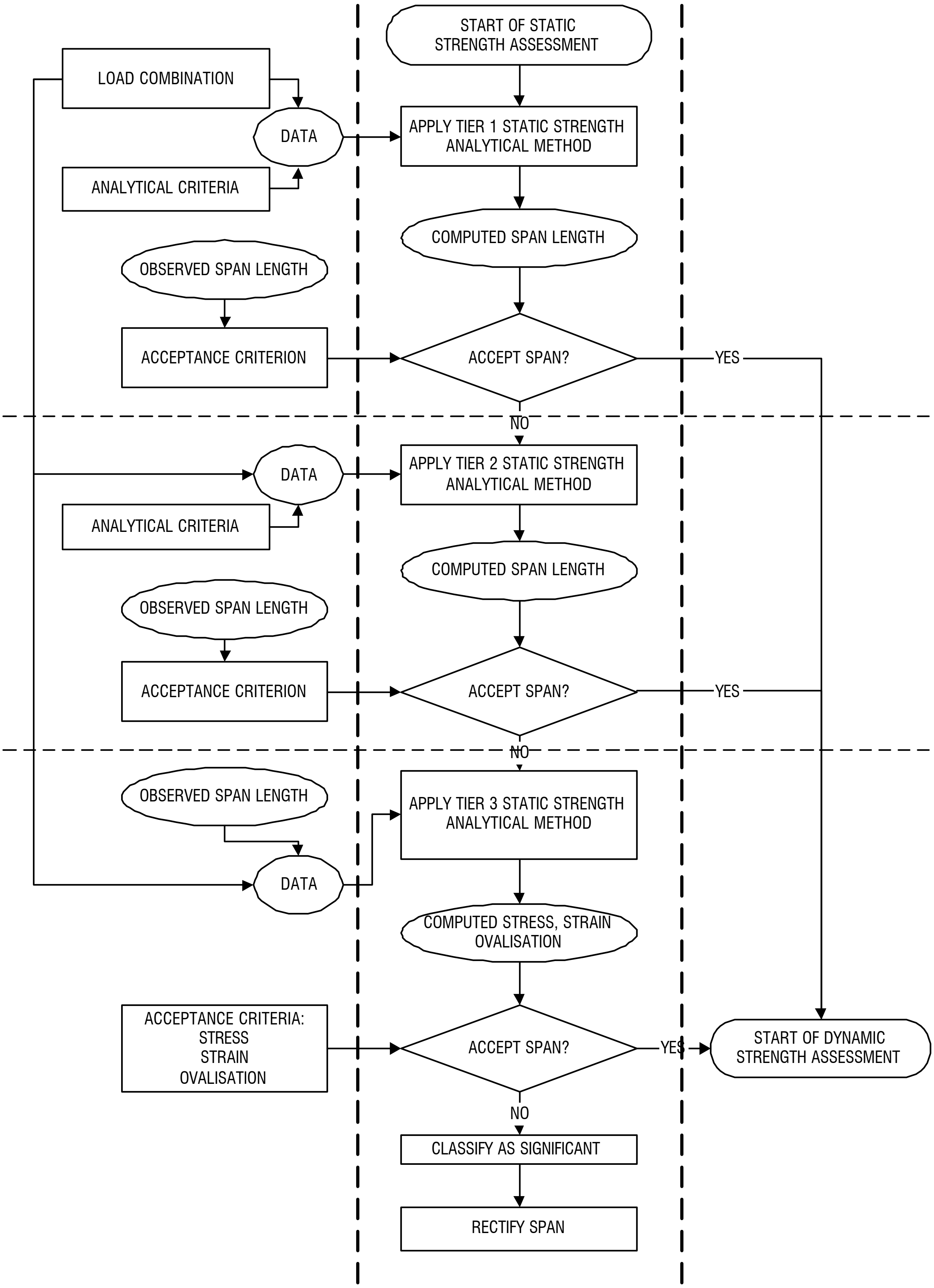


Figure 2.3 Tiered Pipeline Span Defect Assessment Procedure: Static Strength

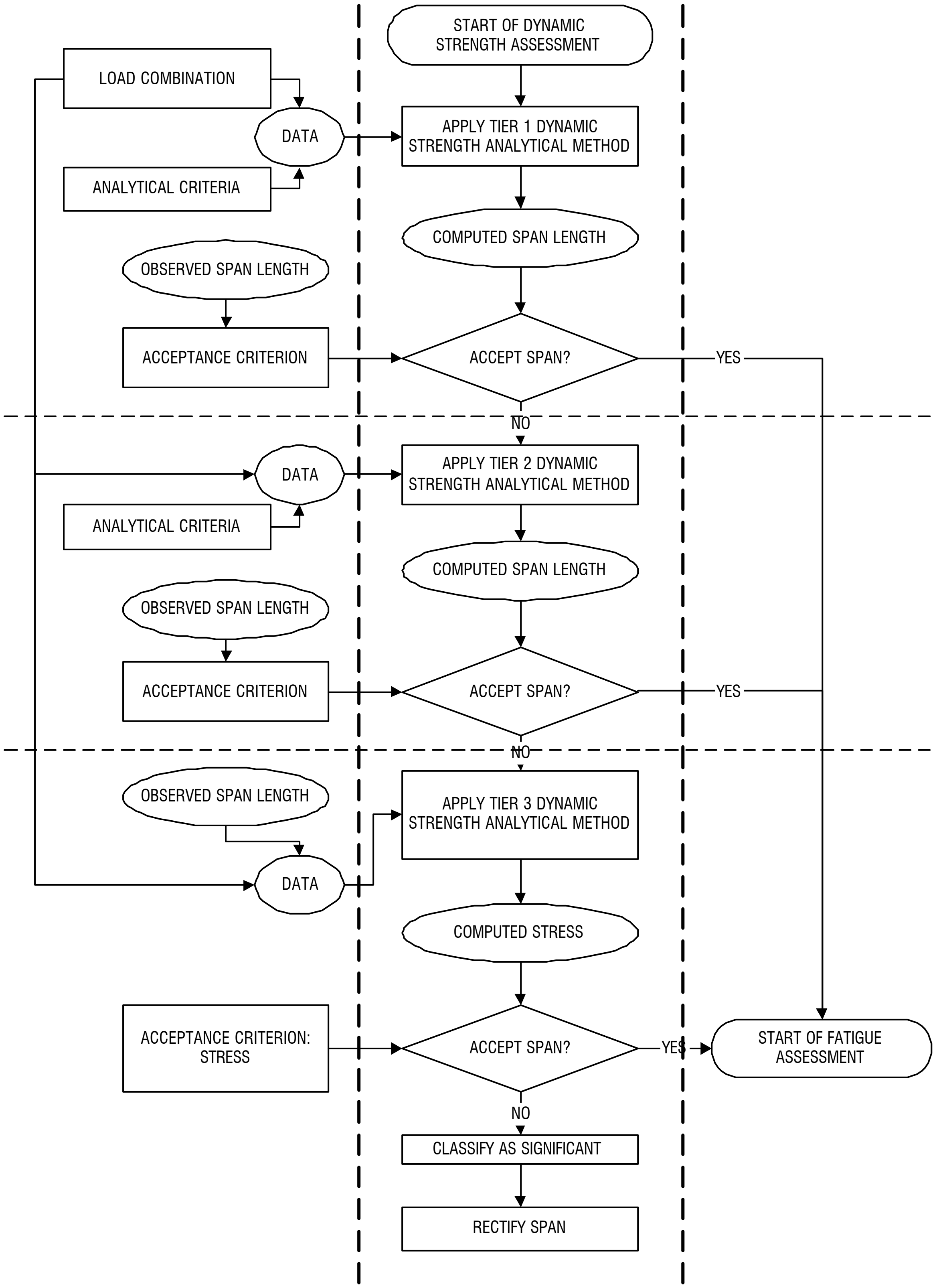


Figure 2.4 Tiered Pipeline Span Defect Assessment Procedure: Dynamic Strength

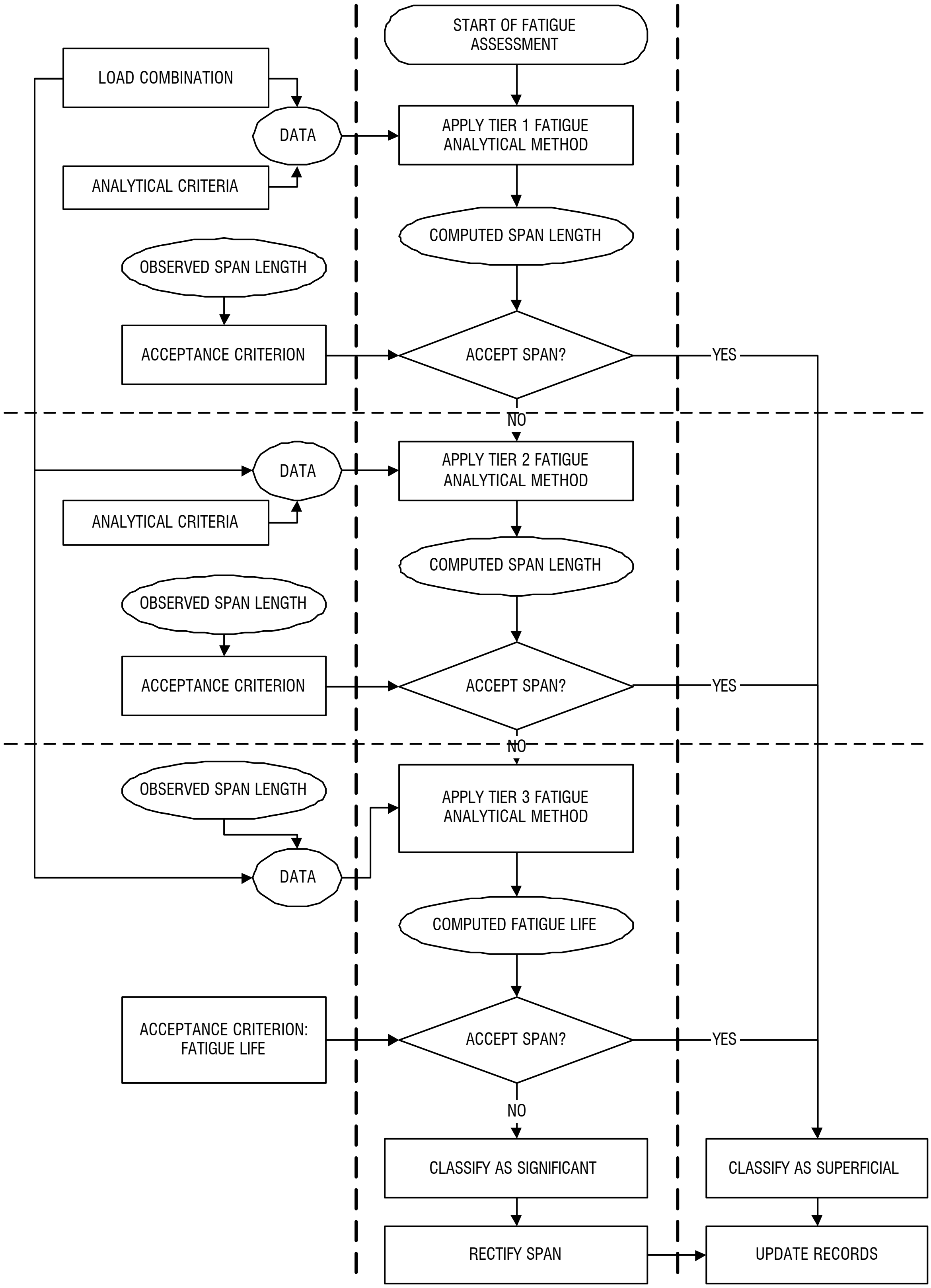


Figure 2.5 Tiered Pipeline Span Defect Assessment Procedure: Fatigue

3. UNCERTAINTY FRAMEWORK

3.1 PREAMBLE

As noted above the assessment of submarine free spans is complicated by the various uncertainties that are inherent in the problem. The interaction of these uncertainties from both the observation of the span and the computation of its acceptability (or otherwise) is illustrated in Figure 3.1. The uncertainties can be classified into three key areas viz:

- Statistical uncertainty associated with the both 'fixed' data (e.g. pipeline material properties, residual lay tension, soil properties etc.) and 'variable' data (e.g. span location, span length, span / sea-bed gap, trench characteristics, wave / current parameters, temperature, pressure, etc.)

- Model uncertainty associated with hydrodynamic loading, structural response and dynamic analysis etc.

- Temporal and spatial uncertainty associated both with a span's development history and with its predicted future behaviour.

Because of these uncertainties there is a need to optimize the balance between the level of sophistication of the analytical tools employed and the quality of the input data available. This balance must include consideration of the cost benefit aspects to determine the best 'value added' options between, for example, further refined data collection; more rigorous analysis; and expenditure on remedial measures. A risk based approach supported by reliability analysis is considered a 'Best Practice' approach to addressing this problem which also requires significant experience and engineering judgement to determine a best strategy. Again, as noted earlier, a risk based approach is also consistent with international regulatory trends.

Key areas of uncertainty include:

Statistical:

- Span location: Survey datum and accuracy

- Span length: Survey accuracy (depending on the survey method employed, there can be instances of touch down that are not identified by the survey), span interpretation

- Span end conditions: Extent of burial
(see Figure 3.2)

- Pipeline / sea-bed gap: Survey accuracy (the extent of the gap can be difficult to obtain)
(See also Figure 3.2)

- Trench characteristics: Survey accuracy (whether the pipeline is in a trench and, if so, the trench configuration)
(see Figure 3.3)

- Geotechnical: Sub-grade reaction, friction and damping characteristics (often not available and are subject the inherent spatial variability)

- Environmental: Directional wave / current characteristics and combined probabilities, scatter diagram data

- Material / weld properties: Yield, ultimate strength, fatigue, toughness, defects etc.

- Coating: Weight, condition

- Corrosion: Nature /extent of metal loss, CP system effectiveness

- Existing stress state: Residual lay tension, creep, span history, degree of axial constraint (see Figure 3.4)

Model:

- Hydrodynamics: Kinetics and kinematics (combined wave / current), gap effects

- Fluid loading: Drag / lift coefficients; transfer function

- 'Static' response: Loading model, analytical model (see Figure 3.5)

- Fatigue: Loading model, dynamic response model, SCFs and damage model

- Stress / strain predictions: Material behaviour model

Temporal / Spatial:

- Span history: Survey frequency, survey accuracy, inter-survey behaviour (See Figure 3.6)

- Span future behaviour: Predictive model and data

Some preliminary work has been undertaken to identify the relative significance and importance of some of these key parameters and is reported in BOMEL, 1995, the full text of which is included in Appendix H. A series of analyses were performed using a sensitivity methodology that utilised Monte Carlo simulation. The technique corresponds to a Level Three reliability method; although a reliability analysis per se was not performed, the approach embedded the application of reliability techniques to assess the sensitivity of a deterministically-based assessment procedure. The work concluded that:

- It is evident that there are three possible routes to reducing the conservatism inherent in the span assessment procedure:
  - maintain the usage of the current techniques, and rely on the procurement of 'better' data;
  - adopt more complex analytical span assessment tools that better represent the mechanical behaviour of spans;
  - incorporate less onerous acceptance criteria.

- The analyses highlighted the dangers of classifying a span as being governed by a particular criterion based on a single deterministic calculation. Introduction of variability in the input parameters may influence which criterion governs, which should be based on a balance of probabilities. Changes in the variation assigned to input parameters may result in a parameter assuming an importance greater than that indicated by a deterministic calculation.

- Two groups of parameters pertaining to modelling of the span response, and hydrodynamic loading were found to impose the greatest influence on limiting spans. These groups contained:
  - bending moment factor p and natural frequency parameter f;
  - current velocity V_c, maximum wave induced velocity V_w and significant wave induced velocity V_{wsig}.

- The parameters in the first group were the most influential and enhanced limiting span lengths may result from improved data on these. However, they will be strongly dependent on span end support conditions and effective axial force in the pipeline, and hence a different structural model would be necessary to determine the relative influences of these.

- It is apparent that for beneficial changes to occur as a result of improved data, improvements may be necessary to all key input parameters as significant enhancement of a single parameter may not necessarily lead to a commensurate enhancement of limiting span length.

- Early indications, however, are that significantly improved limiting span lengths would not accrue from improved data and that the greatest sources of conservatism are most likely the analytical methods and restrictions/criteria imposed by codes and guidelines.

3.2 RISK AND RELIABILITY FUNDAMENTALS

A variety of qualitative and quantitative risk-based approaches to the strategic integrity management of engineered systems have been proposed and used widely in a number of industries, including the offshore industry. In offshore structural engineering, risk and reliability techniques have been used for more than a decade to prioritise the inspection of the welded connections of steel jackets. A number of schemes have also been proposed for the assessment of land-based and sub-sea pipelines.

Two commonly used methodologies are *qualitative indexing* and *quantitative risk assessment*; approaches based on a combination of the two have also been suggested.

3.2.1 Qualitative Indexing Systems

Qualitative risk indexing approaches are based on assigning subjective scores to the different factors that are thought to influence the probabilities and consequences of failure. The scores are then combined using simple formulae to give an index representing the level of risk. The resulting indices for different components (or pipe zones, or failure modes, or hazards) can then be ranked to determine components with the highest risk.

Clearly the main advantage of this approach is that it is very simple to apply.

However, there are a number of disadvantages with this approach:

- the index does not give any indication of whether the risk associated with a particular segment is unacceptable;

- no guidance is provided as to whether any risk reduction action is necessary;
- it is very difficult to calibrate the scoring and indexing system for pipelines, and to validate the results.

An example of an Indexing system is that developed for the MTD (MTD, 1989) to prioritise the inspection requirements for detecting and monitoring fatigue cracking of components in jacket structures. The approach is based on deriving a numerical criticality rating for each component.

The criticality rating Z_j for any component *j* in a given year *n* is based on a function of:

- consequence of failure,
- mode of failure,
- likelihood of failure,
- cost and reliability of inspection,
- inspection history data.

The MTD's criticality rating function is given by:

$$Z_j = (X_j \times Y_j) + W_j \tag{3.1}$$

where X_j is the weighting for the consequence of failure
Y_j is the weighting for the likelihood of failure
W_j is the weighting reflecting the inspection history of the component

The weighting for the consequence of failure, X_j, is evaluated as the sum of nine individual weightings for items such as redundancy or importance of chord and brace, immediate risk to life, risk to environment, risk of lost production, cost of repair, confidence in assessment, etc. Weightings for each of the individual items are judged subjectively as *high*, *medium*, or *low*, and assigned numerical values; values are suggested for each category and item which range from 1 to 100, and the suggested weightings are such that an average score is 80.

The weighting for the likelihood of failure, Y_j, is evaluated as the sum of eight individual weightings for items such as susceptibility to damage, whether a defect is known to exist, corrosion condition, fabrication quality, confidence in assessment, etc. Again each item is judged as *high*, *medium* or *low*, and assigned numerical values; values are suggested ranging from 1 to 100, and the average suggested score is 80.

The rating is also influenced by the time elapsed since the last inspection. Weightings for the inspection history, W_i, are suggested ranging from 0, if the component was inspected last year, to 6400, if the previous inspection was more than 5 years ago. The values suggested are preliminary, and the MTD report cautions that the procedure needs further systematic review, and formal calibration or bench-marking studies need to be undertaken.

As discussed by Descamps et al 1996, when the methodology was applied to a real northern North Sea structure, it was found that too much weight was applied to the consequences of failure compared to the likelihood of failure. As a result only elements classified as *primary* were repeatedly recommended for inspection throughout the lifetime of the structure. Descamps et al. have revised the MTD methodology in an attempt to balance the effects.

Henderson, P. A.,1996, and Kaye, D.,1996, discuss a qualitative risk assessment procedure for pipelines using a “Boston square”. Kaye’s matrix is shown in Table 3.1; Henderson considers five categories for probability and consequence. The matrix defines a *ranking number* which defines the risk of the failure mechanism, where the lowest number is the least severe and the highest is the most important.

However, Kaye notes that *risk ranking alone does not give any guidance on how risk may be controlled, and does not show how inspection may help to manage these risks*. In an attempt to manage the risks, they both consider the value of the inspection and introduce a third dimension to transform the Boston square into a “Boston cube”. Thus, *inspection criticality* is defined as the product of *failure probability*, *failure consequence* and *inspection value*.

Having identified the high risk scenarios for each mode and mechanism on every section of the pipeline the value of inspection is assessed. Henderson gives the following examples of *inspection value*:

- High value — internal corrosion, which can be monitored closely by inspection and measures taken to remedy the rate of decay;

- Low value — trawl board impact, which cannot be monitored by inspection as the event can occur immediately after inspection.

Kaye gives details of a case study of the use of a Boston cube for a modern, large diameter export trunkline in the North Sea, and the results are summarised in Table 3.2. For this example, spanning was found to have the highest inspection criticality with a value of 12.

3.2.2 Quantitative Risk Systems

Quantitative risk systems are based on estimating the level of risk by direct assessment of the probability and consequences of failure. Depending on the sophistication of the approach, the probability of failure may be estimated using historical failure rate data (actuarial approach) or advanced structural reliability methods (notional approach).

Most of the quantitative risk systems are based on *Bayesian Decision Theory* (see for example Benjamin, J. R. and Cornell C. A., 1970). This theory has been applied to a number of areas, and is concerned with decision making which depends on factors that are not known with certainty; it offers a convenient framework for the inclusion of subjective information. The decision problem is often illustrated using a 'Decision Tree', and an example is shown in Figure 3.7.

The terminology of decision theory is rather general; in the context of the present analysis the terms can be defined as:

an *experiment*	corresponds to an inspection option (method/time)
an experiment *outcome*	corresponds to an inspection measurement or result
an *action*	corresponds to a repair or maintenance option
an *outcome of nature*	corresponds to no failure, or loss of containment or serviceability
a *utility*	corresponds to expected cost

From basic Bayesian decision theory, the problem of the decision maker is to choose an *experiment E* (an inspection option) yielding a random or uncertain *outcome Z* (inspection result) that can be used by the decision maker to choose an *action A* (repair option). When the decision maker has taken an action (to repair or not) this will result in a random *outcome of nature 1* (failure or not). The chosen inspection method and repair option together with the outcome determines a *utility value U* (expected cost).

The part of the analysis starting once the results of an experiment (inspection) are known, and involving the choice of an action and its random outcome, is known as a *posterior* analysis; the statistics of the utility (expected costs) can be estimated using known statistics (about the existing state of the pipeline). Whereas the complete analysis, where the choice and results of an inspection are still unknown, is known as a *preposterior* analysis.

The theory associated with defining the conditional, marginal, prior and posterior probabilities is well defined in a number of texts.

The application of advanced reliability-based techniques to offshore systems, specifically structures, is primarily due to work by Madsen and his co-workers using the PROBAN suite of software (Madsen et al 1987 and Madsen, H.O., and Sorensen, J. D.,1990). Most of the quantified risk applications to offshore structures have been based on this work.

The main impetus for Madsen et al's research came from concerns over the catastrophic consequences of fatigue following a number of major incidents; and the need to address the increasing expense and dangers of inspecting the joints of offshore jackets, particularly as structures moved into deeper waters. Madsen et al have developed a theoretical framework which has brought together probabilistic analysis, fracture mechanics, fatigue crack growth theory, probability of detection (POD) curves, and reliability updating for inspection and repair, etc..

Reliability-based methodology has also been incorporated into procedures for 'optimising' the design, inspection and repair of fatigue sensitive elements (Madsen, H.O., and Sorensen, J. D.,1990 and Faber et al, 1994). The basis of the procedures is that the optimal inspection and maintenance plan is one which yields the minimum expected total costs for maintaining the system throughout its anticipated life (design decisions may also be 'optimised' by including the initial costs). The optimisation can be summarised mathematically as:

$$\begin{aligned} &\textit{minimise} \quad E[C_t] = E[C_f] + E[C_i] + E[C_r] \\ &\textit{subject to} \quad P_f \leq P_f^T \end{aligned} \tag{3.2}$$

where $E[C_f]$ is the expected cost associated with failure,
$E[C_i]$ is the expected cost of inspection,
$E[C_r]$ is the expected cost associated with maintenance or repair,
P_f is the probability of failure, and P_f^T is the target.

Using a very similar methodology a software system for Inspection and Maintenance planning of fixed offshore structures using Reliability based methods (IMREL) under an EC funded THERMIE project known as Reliability based Inspection Scheduling (RISC) see Faber et al, 1994; Dharmavasan et al, 1994; Peers et al,1994; and Goyet et al,1994. The basic methodology has been linked with a knowledge-based system (Peers et al,1994), and some case studies are presented in Goyet et al,1994.

A hybrid approach is suggested by Descamps et al.,1996 who propose a *targeted inspection planning methodology* which is based on a *semi-probabilistic approach*, followed by a *probabilistic approach*. The semi-probabilistic approach is based on a quantitative risk-based ranking (indexing) system, and its aim is to identify critical members. Together with engineering judgement an inspection programme can be developed which maintains the level of confidence in the integrity of the structure. Alternatively the member criticality information can be used with a probabilistic approach which is based on detailed risk analysis; its objective is to determine the overall financial risk associated with failure sequences starting with the failure of each identified critical component. Risk is taken as the measure of inspection priority, and is expressed as the probability of failure multiplied by the estimated consequential costs of failure. Thus, for a simplified failure sequence consisting of member failure (event E_0), and structural collapse (event E_1) under extreme environmental loading following failure of member 0, the expected costs associated with member failure are given by:

$$Expected\ Cost(member\ failure) = P[E_0] \times P[E_1 | E_0] \times Cost(structural\ collapse) \quad (3.3)$$

where $P[E_0]$ is the probability or likelihood of member failure due to progressive deterioration (ie. fatigue or corrosion), or accidental damage (ie. ship impact, dropped object etc) determined from Fault Tree Analysis,

$P[E_1 | E_0]$ is the probability of structural collapse given the initial member failure E_0, and is evaluated from structural reliability analysis,

and $Cost(structural\ collapse)$ is assessed from Cost Analysis.

Onoufriou et al, 1994 present the application of reliability based optimised inspection planning (OIP) techniques to a number of North Sea jackets. The paper states that the analysis, which was undertaken using the PROBAN and PROFAST programs, achieved *significant safety and cost benefits* for both new and existing platforms.

Monte Carlo simulation can also be used to update reliability estimates to account for inspection information (by sampling from modified distributions) as discussed by Oakley et al,1994. Their approach, together with a very simplified method for estimating system reliability, has been applied to North Sea platforms. The paper concludes that critical joints were identified for inspection and a higher reliability was available per unit cost.

A number of quantitative risk-based approaches have been proposed for pipelines. However, one of the main limitations of the published quantitative risk approaches for pipelines is that they typically base the failure probability estimates on historical failure rates.

Nessim, M. M. and Stephens, M.J. 1995 illustrates a framework for “risk-based optimisation of pipeline integrity maintenance”. Their approach is based on *system prioritisation* to rank pipeline segments with respect to the need for integrity maintenance; and *decision analysis* to assess available maintenance alternatives and determine the optimal choice for each targeted segment. They suggest that failure rates are estimated from publicly available data, company specific information and subjective judgement, but point out that for the process to be meaningful the estimates must reflect the specific attributes of the line segment under investigation.

A number of quantitative risk approaches have also been proposed to assess specific risks in pipelines; these include corrosion and geotechnical hazards.
Reliability analysis has also been applied to estimate failure probabilities for a number of other pipeline failure modes, including:

- upheaval buckling (Mork et al, 1995a)
- cross-flow vortex shedding (Mork et al, 1995b)
- pipeline spans (Roland et al,1995)
- dropped objects (Katteland, L. H. and Oygarden, B., 1995)

This list is by no means exhaustive.

A major joint industry project, the SUPERB project for Submarine Pipeline Reliability Based Design (see Sotberg et al, 1996) was initiated in 1991 to develop and apply risk and reliability procedures to pipeline design. The project has developed limit states, target reliabilities, and calibrated safety factors for a number of design-based applications.

A recommended 'best practice' approach to a risk / reliability based system for the integrity management of pipelines, and in particular inspection scheduling, is detailed in Appendix G.

3.3 SPATIAL AND TEMPORAL VARIABILITY

Recent work (Mork et al.,1999 & Fyrileiv et al., 2000) has addressed the issue of the spatial and temporal variability of pipeline free spans using a reliability approach and probabilistic input. Whereas there are established procedures to assess the ultimate and fatigue limit states for stationary spans (which are generally 'designed-for' spans), this is not the case for spans that develop, migrate and, perhaps, self correct with time (which are generally unplanned-for defect spans). For instance, for non-stationary spans (that might occasionally become 'long') a fatigue calculation based on the extreme length (and therefore, probably, extreme dynamic response) may be over-conservative and lead to unnecessary intervention expenditure. Similarly, conclusions reached about acceptable spans in pipelines assumed to be constantly in operation may be inappropriate for pipeline free spans where the system is shut down for significant periods and where, therefore, the variation of axial loads in the pipeline result in a change to natural frequency and thus dynamic response. The above referenced work reports on the use of survey data to estimate both past and future span behaviour and to thereby address the effects of short term span length and varying operational conditions on the ultimate and fatigue limit states of the pipeline. The authors conclude that, for the specific pipeline investigated, failure to allow for spatial and temporal variation of parameters such as span length, leads to unnessarily conservative estimates of critical span length.

Using such a sophisticated analytical approach is, of course, highly dependent on having high quality continuous data sets of the relevant parameters and is very system specific.

Probability	Consequence		
High	3	6	9
Medium	2	4	6
Low	1	2	3
	Low	Medium	High

Table 3.1 Example of "Boston Square"

Failure mechanism	Probability (P_f)	Consequence (C)	Risk (= $P_f \times C$)	Inspection value (Iv)	Inspection criticality (= $P_f \times C \times Iv$)
Spanning	2	2	4	3	12
Instability	2	1	2	1	4
Thermal buckling	1	1	1	2	2
Impact	1	1	1	1	1
External corrosion/CP system	1	2	2	3	6

Table 3.2 Example of use of Boston Cube

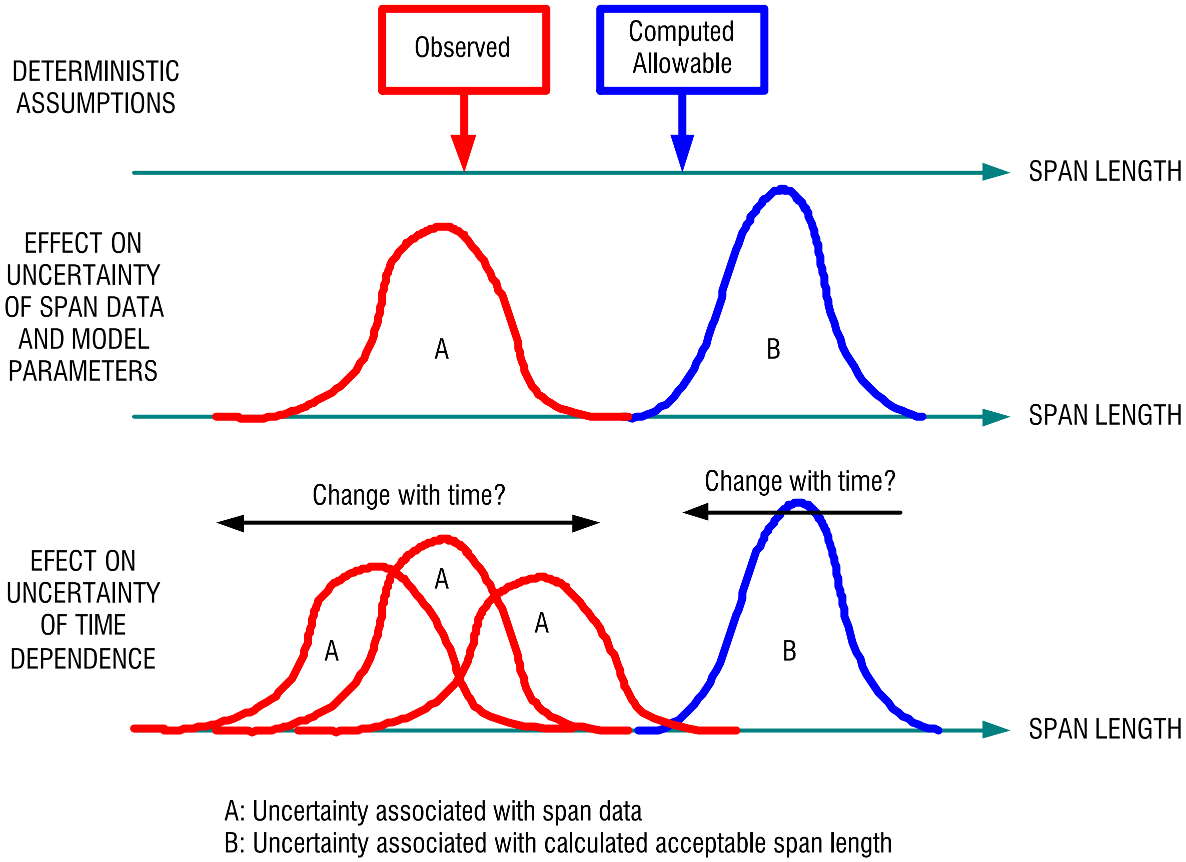


Figure 3.1 Illustration of Effect of Uncertainty in Span Data and Computed Allowable Span Length and the Additional Uncertainty Associated with Time Dependency

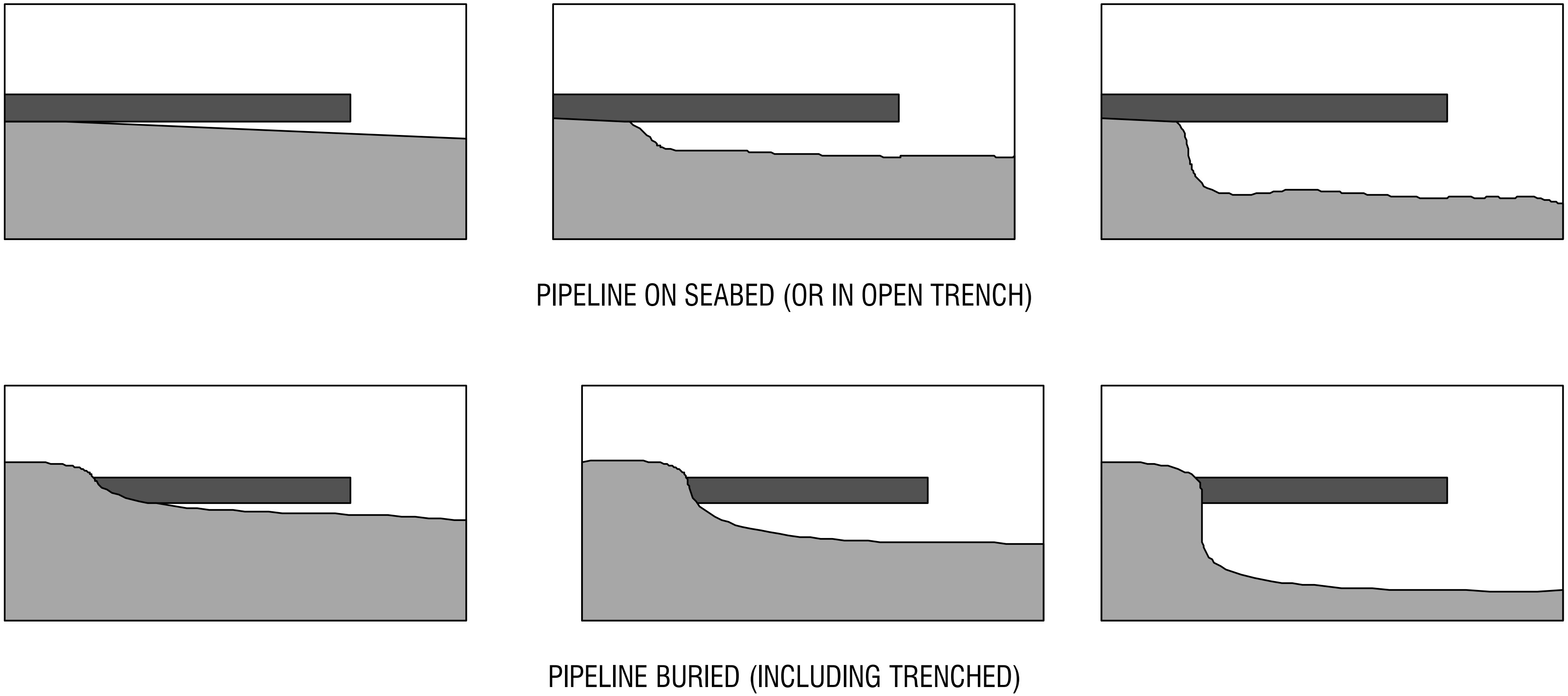
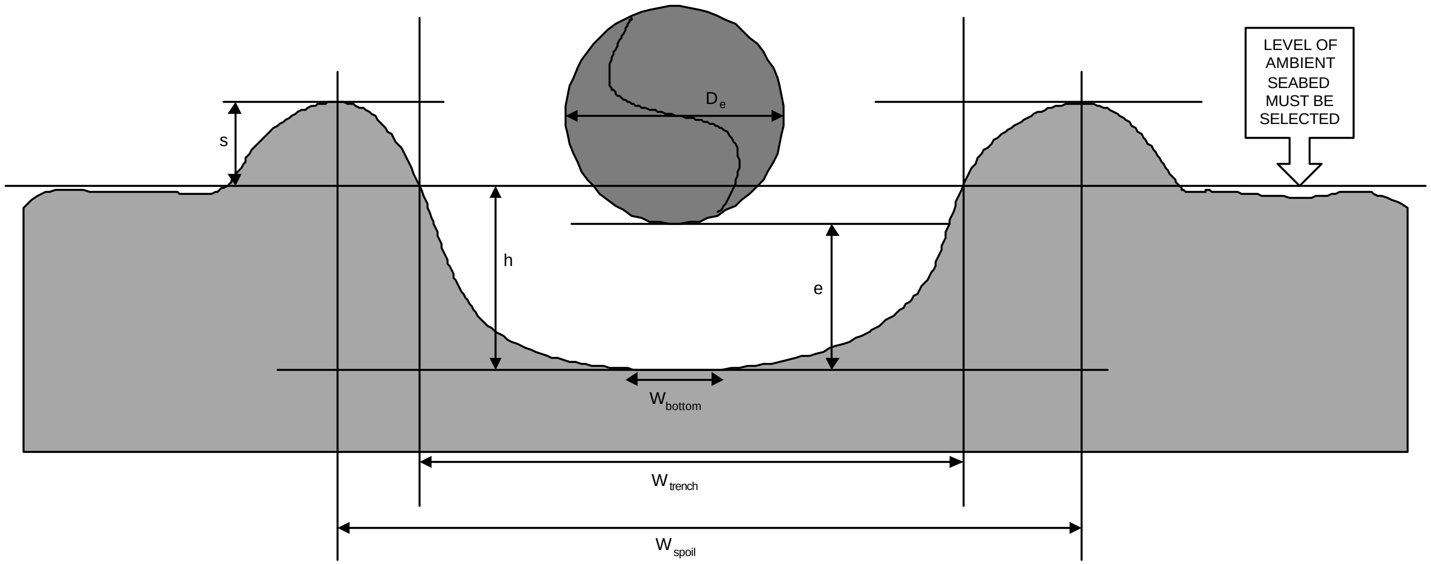


Figure 3.2 Possible End Conditions



h	depth of trench (below ambient seabed)
s	height of spoil (scour or trenching) (above ambient seabed)
W_{spoil}	trench width (top of spoil heaps)
W_{trench}	trench width (at ambient seabed level)
W_{bottom}	width of bottom of trench
D_e	pipeline external diameter
e	gap below pipeline

Figure 3.3 Trench Configuration Parameters

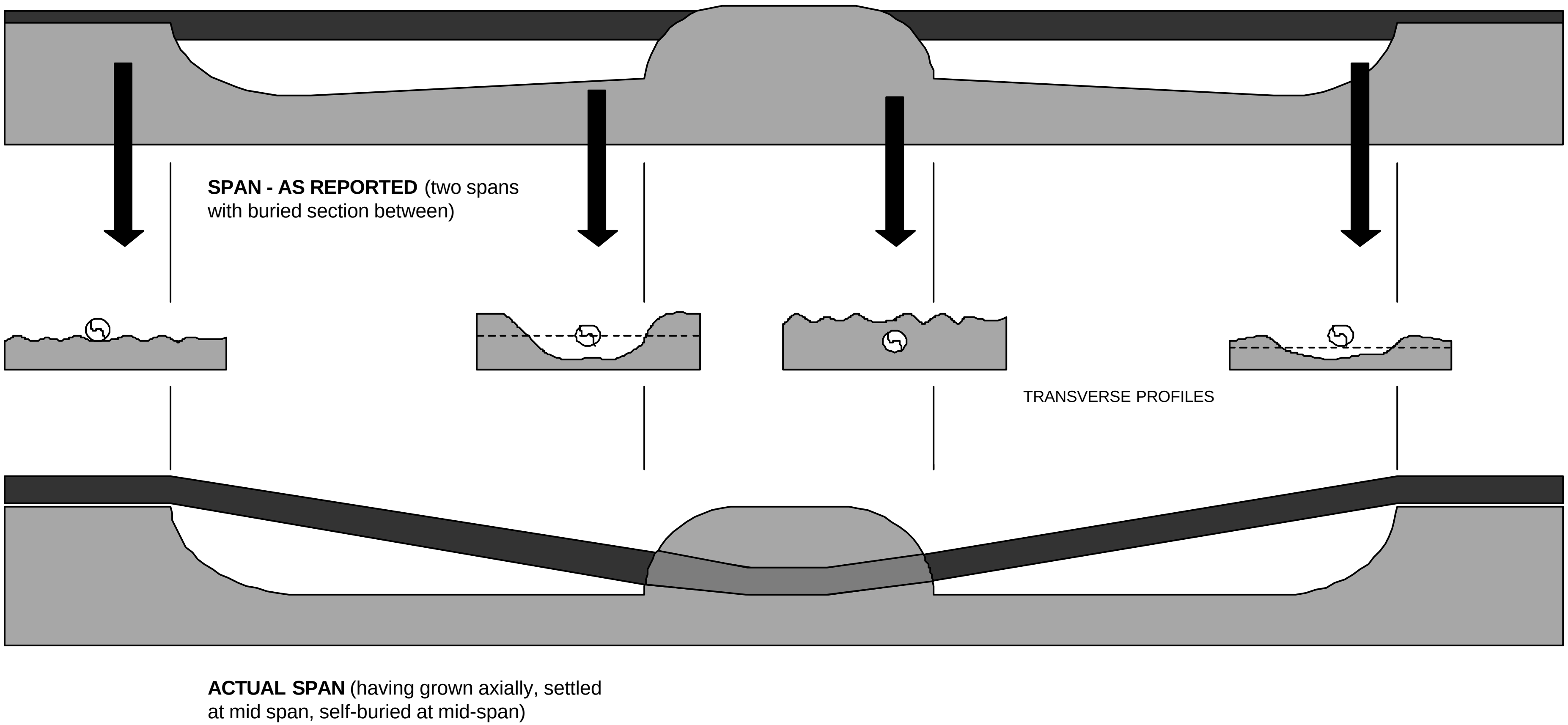


Figure 3.4 Possible Error in Interpretation of Survey Data (Function of Span History)

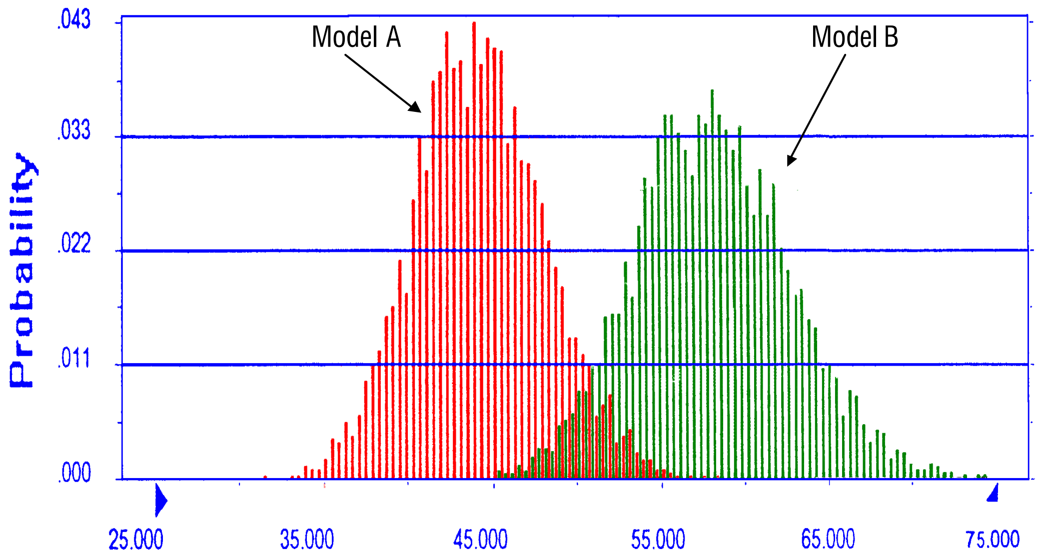


Figure 3.5 Affect of Model Assumption and Parameter Uncertainty on Calculated Acceptable Span Length

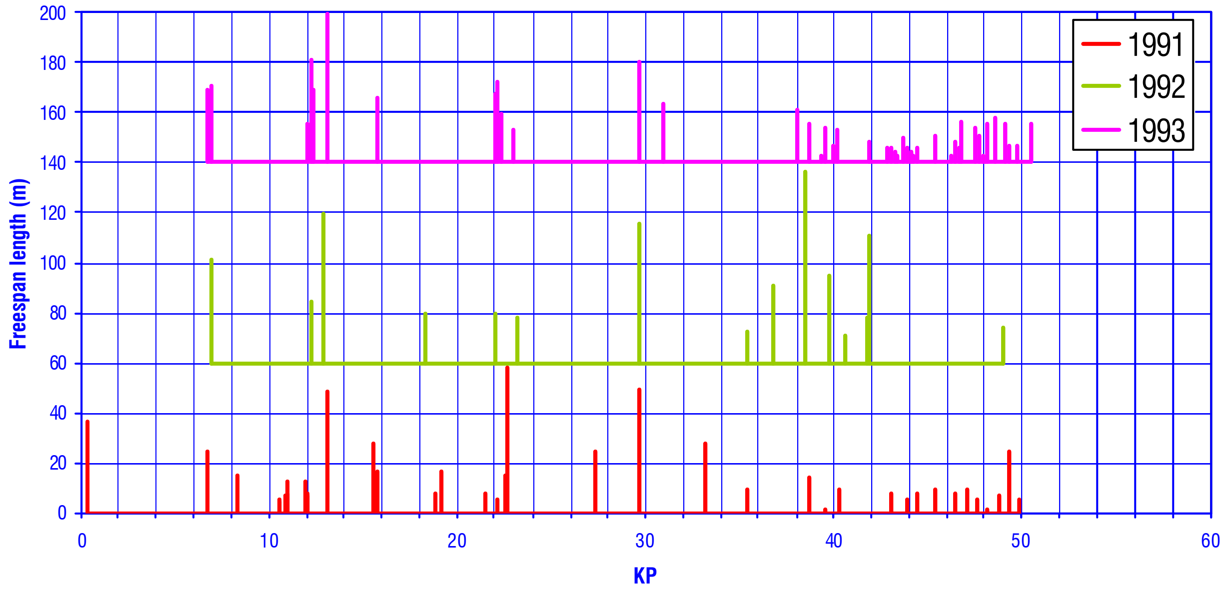


Figure 3.6 Typical Variation of Span Length and Location as Reported in Annual Surveys

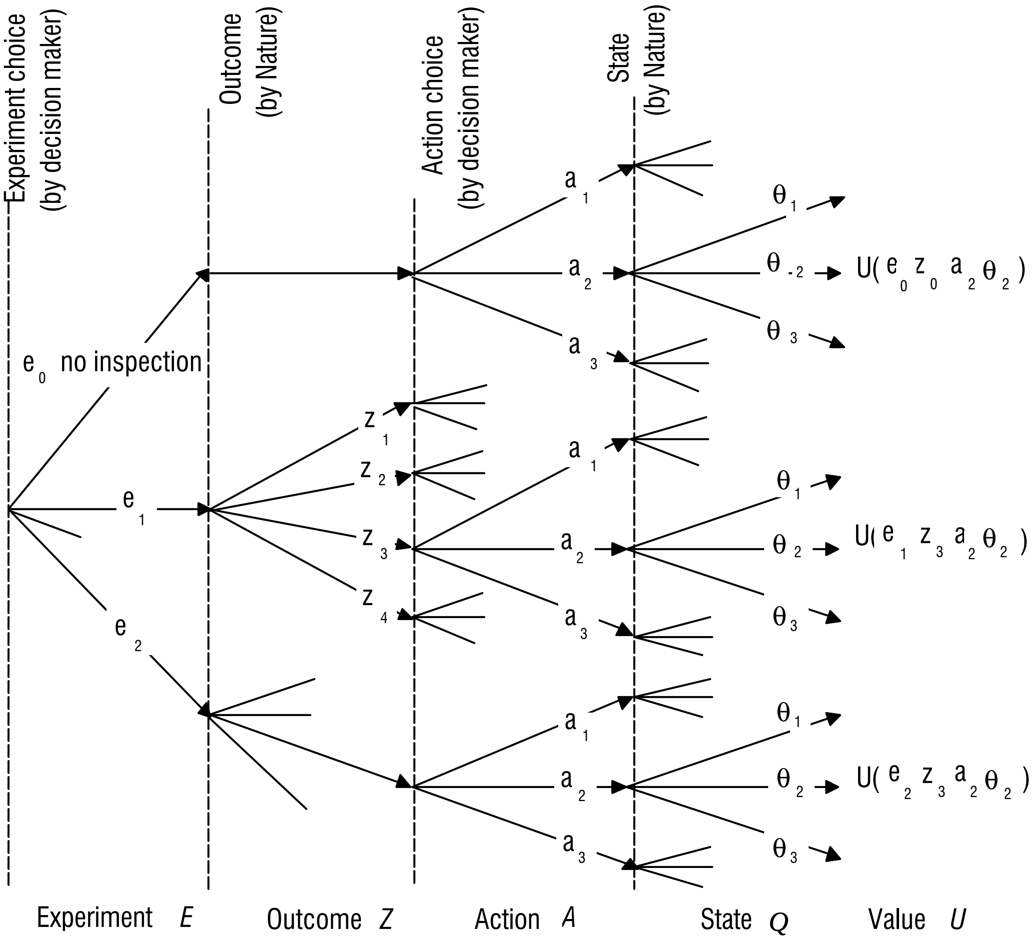


Figure 3.7 Illustrative Example of a Decision Tree

4. DATA FOR SPAN ASSESSMENT

4.1 PREAMBLE

The data required for assessment of a pipeline free-span and its required level of accuracy and / or uncertainty is highly dependent of the analytical approach that is to be utilised in evaluation of the span. Collection of free-span data is a very expensive activity and an appropriate balance is necessary between the data collection costs and the value it might add to the assessment process and thus the safe elimination of any remedial interventions. Sensitivity analysis in respect of acceptable span length, as a function of data uncertainty, is reported in BOMEL, 1995 (which is reproduced in Appendix H); the results strongly suggest that there was little sensitivity of acceptable span length to data uncertainty, except, perhaps, if significant improvement could be made to all the data inputs. It is necessary to ensure that high levels of data accuracy and therefore low levels of data uncertainty are not spuriously specified relative to the uncertainty in the overall assessment process.

4.2 DATA CLASSES

A detailed breakdown of the data into the three classes of: *pipeline*, *operational*, *environmental* and *inspection* is given in Table 4.1 for static analysis and Table 4.2 for dynamic analysis. Some data have to be processed by means of calculation into suitable input data for analysis.

The **pipeline data** include geometrical and material properties; these are used in the analytical model, the analytical criteria and the material characteristic. The axial restraint factor is used to approximate the degree of suppression of longitudinal strains in the pipe wall due to the interaction of the pipe with the seabed.

The **operational data** encompass installation (residual lay tension) and those related to the pipe contents: its density, pressure and temperature; these are used to derive some of the loadings applied to the span.

The **environmental data** include the parameters that relate to the fluid loading on the pipeline (for example, water depth and various wave and current data). They also contain parameters defining the mechanical interaction between the pipe and the seabed (for example, soil modulus and Poisson's ratio at the span shoulders); these particular parameters influence the support conditions at the shoulder of the pipeline.

4.3 DATA SOURCES

Appropriate sources of data must be used. If no data are available for residual lay tension or axial restraint factor, then these are to be estimated conservatively and included if they adversely affect the pipeline.

Data	Symbol
Pipeline Data	
Pipe outside diameter	D
Pipe nominal wall thickness	t
Corrosion coat thickness	t_e
Weight coat thickness	t_c
Steel density	ρ_s
Corrosion coat density	ρ_e
Weight coat density	ρ_c
Steel elastic modulus	E
Steel Poisson's ratio	ν
SMYS steel	σ_y
Steel thermal expansion coefficient	α
Axial restraint factor	λ_a
Pipeline heading	φ
Operational Data	
Residual lay tension	N
Internal pressure	p_i
Contents density	ρ_i
Contents temperature	θ_i
Design life of pipeline	T_p
Environmental Data	
Minimum water depth at LAT	h
Local seawater density	ρ_a
Local seawater temperature	θ_a
Current velocity data	-
Wave data	-
Hydrodynamic drag coefficient	C_d
Hydrodynamic added mass coefficient	C_a
Soil elastic modulus at span shoulders	E_f
Soil Poisson's ratio at span shoulders	ν_f
Longitudinal friction coefficient at span shoulders	μ_L
Transverse friction coefficient at span shoulders	μ_T
Inspection Data	
Kilometre point at start of span	KP_s
Kilometre point at end of span	KP_e
Freespan length	L_{obs}
Gap beneath span	G
Marine growth information	-

Table 4.1 Data Classes of Static Analysis

Pipeline data	
Pipe outside diameter	D
Pipe nominal wall thickness	t
Corrosion coat thickness	t_e
Weight coat thickness	t_c
Steel density	D_s
Corrosion coat density	D_e
Weight coat density	D_c
Steel elastic modulus	E
Steel Poisson's ratio	$<$
SMYS steel	F_y
Steel thermal expansion coefficient	"
Axial restraint factor	8
Operational data	
Residual lay tension	N
Internal pressure	p_i
Contents density	D_i
Contents temperature	2_i
Environmental data	
Minimum water depth at LAT	h
Local sea water density	D_w
Local sea water temperature	2_a
Hydrodynamic drag coefficient	C_d
Hydrodynamic added mass coefficient	C_m
Soil modulus at span shoulders	K_s
Current statistics	
Wave statistics	

Table 4.2 Data Classes for Dynamic Analysis

5. SURVEY METHODS

5.1 PREAMBLE

There are a number of inspection technologies and techniques that can be used to identify free-spans on submarine pipelines. These techniques normally require the mobilisation of a sophisticated and costly marine spread which is subject to operability constraints imposed by environmental conditions. It is therefore imperative that both the quality of data required in terms of type, accuracy and uncertainty and the survey frequencies are appropriately specified such that the associated costs are proportionate to the costs of analysis, intervention and / or the consequences of system failure. These considerations suggest that a "Best Practice" survey programme should be based on a risk /reliability based approach.

5.2 SURVEY TECHNIQUES

The lowest cost inspection technique for the detection of free-spans is normally the use of a towed fish with side-scan sonar capability. Reliability of span detection can be improved by making two passes, one on each side of the pipeline. The use of Remotely Operated Towed Vehicles (ROTVs), which can be "steered", can give enhanced data quality at a relatively small marginal cost. Side-scan techniques are, however, dependent on the competency of the survey party to interpret the records accurately; a subjective process open to human error. It is often beneficial, but costly, to visually confirm by camera mounted Remotely Operated Vehicle (ROV) any spans identified by side-scan, particularly to correctly identify touch down points. The side-scan technique does, however, have the advantage that long lengths of pipeline can be inspected in a relatively short time and that a relatively inexpensive mother ship can be used. Locational accuracy is limited by the offset of the fish to the vessel.

A more expensive option is to survey the pipeline by ROV with visual cameras and scanning sonar. This technique may be optimal if the survey is addressing other factors in addition to free-spans (e.g. weight coat condition, cathodic protection, anode depletion etc.). The process is relatively slow and therefore costly and requires an appropriate vessel to support the ROV activities. Interpretation of the visual findings is relatively easy and accurate and location can be quite precisely determined relative to datums. Good underwater visibility is, of course, necessary. The use of ROVs is also preferable when the pipeline is in a trench which can shadow towed fish side-scan. Trench profiles can also be determined by ROV mounted scanning sonar equipment.

Work is being undertaken to develop intelligent inertial pipeline 'pigs' to map the shape of a pipeline. Such data could be used to determine stress levels due to deformation. The use of radio-active sources to determine when a pipeline is in contact with the sea-bed is also being considered. Although development and hire of such tools will be expensive, they should provide high quality data and may prove to be economic by the significant savings that could be made by elimination of the marine spread.

Where probabilistic techniques are being used, and account taken of the temporal and spatial variability of spans as discussed in Section 3.3 above, it is particularly important to ensure consistency of both inspection methodology and survey datums so that trends in span length and location are accurately determined.

6. ASSESSMENT BENCHMARKING

A multitude of different methodologies and analytical tools have been developed by pipeline operators and service companies for both optimisation of survey activities and assessment of survey findings. Some of these are proprietary to the owners and others are commercially available. Some methodologies employ generic tools such as standard finite element packages.

The tools vary in sophistication and the influencing parameters included in the models they employ. The degrees of refinement available range from simple bending models to applications that take into account membrane action, levels of axial constraint, sub-grade reaction, and soil friction etc..

Selection of the most appropriate tool will be dependent on the amount and quality of the available input data, the cost of intervetnion to 'correct' the span and the perceived consequences of pipeline failures.

The quality, and therefore utility, of the output of these tools is often highly dependent on the experience and ability of the user to appropriately select values for the key parameters and to ensure the models realistically represent the actual conditions of the pipeline system. The work reported in BOMEL,1995 (repeated in Appendix H) does, however, suggest that in terms of minimising intervention costs there is generally more to be gained by using more sophisticated analytical techniques than in expenditure to obtain refined data.

To date there has not been a comprehensive study of the relative utility of available systems to assess their suitability for incorporation in assessment procedures. A study to benchmark both the results of using different tools to assess the same span and application of the same tool on the same span by different users would be feasible and provide useful data. The following packages are presently identified for possible inclusion in such a benchmarking study:

- ALKYON: "PIPESIN" / "PIPECAST"
- ANDREW PALMER: "PLUS ONE" / "SPAN"
- BOMEL: Proprietary software associated with 'tiered' approach to assessment / ABAQUS
- DHI: GSPAN
- FENRIS (SESAM)
- DNV / ABAQUS / In-house EXCEL Spreadsheet / FATFREE
- JPK: "SIMULATOR" / "SPANS"
- LR: Proprietary software

- PRC!: "FREESPAN" (originally developed by EXXON)
- RAMBOL: RHSpan / ANSYS ROSAP
- RCM: "OFFPIPE"
- SOUTHWEST APPLIED MECHANICS INC.: "SPAN"
- THALES: "SAGE PROFILE"
- ZENTECH: "PIPELINE"

Several organisations also use general purpose finite element packages such as ABAQUS and develop ad-hoc models of specific spans at various levels of sophistication.

7. DISCUSSION OF CURRENT PRACTICE

Although it is known that there is a wide variety of approaches being taken to the management of pipeline spans there is, at present, little to no information on the extent to which the various philosophies are used or on the relative cost / benefits so obtained.

Pipeline failures as a result of free-spanning are thought to be rare and it is possible that there have actually been no instances of this failure mode occurring. Nevertheless, there is a strong industry view that such failure potential is real and must be appropriately managed. There is, however, apparently a high variation in the level of concern and resource allocation devoted to the issue.

As discussed above, there is an apparent lack of consensus of the methodology to be used in respect of unplanned-for defect free-spans as opposed to those intentionally introduced in the design and construction process for which there are well established codes, guidance and procedures and where the associated analytical tools are developed and available.

Whereas adoption of a contingency approach to assessment of spans that develop in service is sensible, there would appear to be inadequate information available to assist in the decision process to determine which approach is most appropriate for any given pipeline system in terms of the risk it presents - that is the probability of a failure occurring and the potential associated consequences.

Because of the large number of variables in the assessment process it is considered that the use of a probabilistic / reliability type approach is optimal in many circumstances. However, the extent to which this approach is actually used is unknown.

Although it is evident that some pipeline operators keep comprehensive records of pipeline span management in terms of surveys, assessment and remedial works, there is no common database for the collection of such information and therefore combining the various data-sets to allow further statistical analysis is perceived to be difficult.

The use of a 'tiered' approach to assessment, as described above, to allow initial screening out of insignificant spans is thought to represent a 'Best Practice' in that it allows resources to be focussed to optimise cost / benefit on the overall hazard management process in respect of spans. When combined with a reliability approach the 'tiered' methodology is likely to represent a favourable scenario for development into an industry wide 'Best Practice' approach to span management.

8. WAY FORWARD

As the above Sections indicate, there has been a very significant amount of work undertaken in respect of pipeline free-spans. However, it is considered unfortunate that the development has generally been undertaken 'bottom-up' in response to various specific needs rather than as a structured 'top-down' strategic approach to the issues involved. It is therefore perceived that there is significant potential for further improvement that could be realised by adopting a systemic approach to the subject. Such an approach would present an opportunity to provide great benefit to all stakeholders in terms of reduced costs, and improved safety and environmental protection by developing universally acceptable 'Best Practice' guidance on the management of unplanned-for defect free-spans.

A staged approach to development of such guidance could be adopted.

Initial development work might consist of collection of data from pipeline operators to try and better understand the range and nature of current management practices in this area.

Following this a formal benchmarking exercise could be undertaken to assess the respective merits and demerits of the procedures and processes identified from the survey to identify best candidates for further development.

The 'tiered' approach, detailed for certain cases in the appendices, can be further developed and extended to from a complete set of assessment processes; further risk / reliability aspects could be included in the procedures.

The output from the above could then, ultimately, be consolidated into a high quality guidance document.

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