GUIDELINES FOR TRENCHING
DESIGN OF SUBMARINE PIPELINES

Prepared by Trevor Jee Associates
for the Health and Safety Executive

Offshore Technology Report
Health and Safety Executive
GUIDELINES FOR TRENCHING
DESIGN OF SUBMARINE
PIPES

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HSE BOOKS

Health and Safety Executive - Offshore Technology Report
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Results, including detailed evaluation and, where relevant, recommendations stemming from their research projects are published in the OTH series of reports.

Background information and data arising from these research projects are published in the OTI series of reports.
1. SUMMARY

Trenching of subsea pipelines is employed to improve on-bottom stability and to provide protection against trawling activities. In the water depths typical of the central and northern North Sea trenching is rarely required for stability reasons but, with there being extensive fishing activity, trenching is used to provide protection. The loads that can be applied by fishing gear onuntrenched pipelines can be substantial.

Traditionally all pipelines less than 16" diameter have been trenched in the North Sea. This document presents new guidelines, developed by the Trenching Guidelines Joint Industry Project (JIP), to assist in evaluating the consequences of leaving pipelines exposed to trawl loads and to provide a rationale for leaving smaller linesuntrenched if it is safe and cost effective to do so.

The Trenching Guidelines JIP was set up and managed by Trevor Jee Associates with industry wide support from operators, design houses and the HSE.

These guidelines provide methods, models and criteria by which subsea pipelines may be designed for interaction with trawl gear. These guidelines are applicable to
• rigid steel subsea pipelines
• unbonded flexible pipelines, and
• piggy-backed pipelines.

A full summary of the work done in the JIP and the development of the guidelines is included as Appendix G of this document.
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3. GENERAL

3.1 BACKGROUND

Trenching of subsea pipelines is employed to improve on-bottom stability and to provide protection against trawling activities. In the water depths typical of the central and northern North Sea trenching is rarely required for stability reasons but, with there being extensive fishing activity, trenching is used to provide protection. The loads that can be applied by fishing gear on untreated pipelines can be substantial.

Traditionally, the ability of a pipeline to withstand loads from fishing gear has been judged solely on the basis of the pipeline diameter. As a consequence of extensive research carried out between 1974 and 1980 it was concluded that subsea pipelines of 16” diameter and greater could withstand fishing loads and therefore did not require protection by trenching. This 16" rule became the general practice which is now verified by many years of operational experience.

With a growing trend towards deep water developments, high temperature high pressure reserves, and increasing numbers of small diameter flowlines for subsea and step-out developments, the necessity to protect smaller diameter pipelines needed to be reconsidered and consequently the Trenching Guidelines joint industry project (JIP) was set-up. These guidelines have been developed by this JIP and are based on the findings of the studies performed.

A full summary report of the JIP and the development of these guidelines is included as Appendix G of this document.

3.2 TRENCHING GUIDELINES JIP

The Trenching Guidelines JIP was set-up by Trevor Jee Associates with the assistance of Shell U.K. Exploration and Production Ltd. The project attracted industry wide support; the sponsors are listed in Table 1.

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<th>Trenching Guidelines JIP Sponsors</th>
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Technical support was provided to the project by the companies listed in Table 2.
### Table 2
Trenching Guidelines JIP Technical Contributors

<table>
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<tr>
<th>Trevor Jee Associates</th>
<th>DNV</th>
<th>Brown &amp; Root</th>
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<td>Seafish Industry Authority</td>
<td>Andrew Palmer &amp; Associates</td>
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#### 3.3 SCOPE OF APPLICATION

These guidelines provide methods and criteria by which subsea pipelines may be designed for interaction with trawl gear. These guidelines are applicable to:
- rigid steel subsea pipelines
- unbonded flexible pipelines, and
- piggy-backed pipelines.

Whilst the supporting data supplied within this document are derived from North Sea sources, the methodology and criteria can be applied to any location.

The guidelines do not cover:
- cables
- bonded flexibles, or
- other sources of third party interaction, such as anchoring and dropped object.

In addition, other design considerations associated with the trenching/burial status of pipelines, such as stability, thermal performance and upheaval buckling, are not detailed here, but do need to be addressed by the designer.

Whilst not addressed within the scope of these guidelines, the designer does also need to consider the implications of the pipeline design and the trenching/burial status of the pipeline on the safety of fishermen and other users of the sea.

#### 3.4 APPROACH

##### 3.4.1 Models versus formulae

Application would be most simple if the guideline were based on a set of formulae and graphs. However, both the motion of the trawl gear and the response of the pipe are complex. They rely on many input variables. To simplify to the point of being able to produce a graph means to make conservative assumptions. These guidelines therefore specify the models to use, and allow designers to derive the loads for their individual cases.

##### 3.4.2 Coping with change

Trawl gear and fishing practices are changing and will continue to do so. Therefore these guidelines need to cope with a changing design load. They do so firstly by having models rather than fixed design curves, and secondly by requiring the Operator to monitor the design loads over the life of the pipeline.
3.5 TRAWL INTERACTION WITH PIPELINES

3.5.1 Fishing gear
There are two main types of demersal trawling practised in the North Sea, namely, beam trawling and otter trawling. These fishing practices are explained and illustrated in Appendix A. Briefly:

- Beam trawling is employed for the capture of flat fish and uses a steel beam to hold the net open. The beam is held off the seabed at each end by a skid-like shoe assembly.
- Otter trawling is employed for the capture of round fish and the net is held open by two otter doors which use a combination hydrodynamic force and friction with the seabed to create a spreading force on the mouth of the net. Otter trawling may also employ a central clump weight if two nets are being towed by a single vessel, i.e. twin-rig otter trawling.

3.5.2 Loads
When crossing a pipeline the loading exerted by trawl gear on the pipeline is considered in two phases:

- an initial impact loading as the gear first contacts the pipeline
- a pullover force as the trawl door or beam is pulled over the top of the pipeline. The pipeline response may be amplified by locked-in thermal loads.

In some circumstances, a further type of loading could result if the gear were to snag or hook on the pipeline rather than cross it. In this condition a significant sustained loading could be applied as the vessel attempted to haul its gear free of the pipeline. This loading could greatly exceed the pullover load expected during a normal crossing of the pipeline.

3.5.3 Consequences
The potential consequences of the above loadings on small diameter pipelines would be:

- **Impact** The initial hammer blow could cause a dent in the pipe wall. In the extreme case, this could impede the passage of pigs, or cause a stress concentration leading to a fatigue failure due to operational cycles.
- **Pullover** Forces as the trawl board or beam is pulled over the top of the pipe could lead to displacement of the line, and bending at the point of contact. This could result in yielding of the pipeline and, in the extreme case, could lead to a local buckle.
- **Hooking** Hooking of a trawl door or beam under a pipeline could initially result in the large lateral deflection of the pipeline. If caught to rest by the hooking, the fishing vessel could fall back and exert a large vertical load on the pipeline whilst attempting to haul the gear free. Both of these occurrences could lead to yielding of the pipeline in bending and ultimately to local buckling.

3.6 DESIGN METHODOLOGY

3.6.1 General
The general methodology is shown in Figure 1.
The first step is establishing the data about the pipeline, its environment and the fishing gear. The data requirements are described in detail later in this document. It is recommended that fishing gear data are obtained through a study of fishing activity specific to the pipeline location. The Go/No-go filter screens out the cases where the result is known without further analysis. For the remaining cases, three analyses are then done:

- To assess the pullover force-time-history and the resultant pipe bending
- To assess the impact energy and the resultant dent in the pipe.
To assess the loads and consequent bending due to hooking of trawl gear.

Engineering models and methodologies are defined for each of these three analyses. The results of each of the above are compared with acceptance criteria. This provides a deterministic assessment of the acceptability of the analysed case.

There are however cases where one can accept that there is a finite risk of damage to the pipeline. This risk can be quantified by using Monte Carlo analysis to give an expected cost of repair. The trench decision may then be based on a comparison of the whole life costs of the trenched versus non-trenched options.

### 3.6.2 Three level assessment

Inherent in the methodology are three levels of assessment. The levels are:

- **Simple first pass filter** This gives a coarse filter which identifies extreme cases that do, or do not require protection.
- **Deterministic assessment** The deterministic assessment conducts a detailed analysis for the combination of parameters giving the worst case condition. If the pipeline can be shown to withstand this load case it will withstand all others.
- **Risk/cost assessment** If the pipeline design fails the deterministic analysis, it is shown to fail under worst case loadings, the risk/cost assessment can be applied to determine the probability of failure and the lifetime costs associated with that failure. This gives a means by which the costs of providing protection can be assessed against the increased risk and associated costs of not providing protection.

### 3.6.3 Monitoring

Fishing gear and practices are continually changing, and cannot be reliably predicted in the long term. It follows that the loads on an untrenched pipeline will change. It is therefore necessary to monitor the fishing activities throughout the design life of the pipeline to ensure that loads do not exceed safe levels.
4. FIRST PASS FILTER

This filter determines which cases will pass, and which are likely to fail, based on the current (1998) North Sea fishing gear. If your circumstances are significantly different such that this filter cannot apply, then continue to the next section.

4.1 GO

A rigid pipeline may be left unternched if the following three conditions are met:

1. It is
   - either coated with concrete weight coat
   - or coated with an insulation coating (≥20mm thick for otter boards and clumps, ie impact energy up to 14kN, ≥45mm for beam trawls, ie impact energy up to 38kN)
   - or is within a pipe-in-pipe system
   - or is inside a bundle carrier pipe.

2. It is
   - either ≥16" nominal steel diameter
   - or is 10-14" nominal steel diameter in an area where it will not span nor will be subject to beam trawls.

3. It is operating at a temperature increase less than 40°C.

Flexibles and all other rigid cases require further evaluation.

4.2 NO-GO

It is unlikely that unarmoured flexibles, and 2-3" piggyback lines spanning clear above a larger line will meet the acceptance criteria for a deterministic analysis. However, the risk analysis approach could still be applied.
5. DESIGN DATA

5.1 GENERAL

The following basic data categories need to be considered in the trenching design of submarine pipelines:

- pipe parameters
- pipeline operating strategy
- environment and seabed topography
- fishing activities
- costs

The level of data required depends on the extent of analysis to be performed, ie whether a deterministic analysis or a risk/cost assessment. The required data is listed below.

5.2 PIPE PARAMETERS

Pipe parameters are used to define:

- the physical and mechanical characteristics of the pipeline so that its resistance to damage can be determined,
- the pipeline route and length so that the extent of interaction with fishing activities can be predicted,
- the quantities of materials required so that costs can be determined.

The pipe parameters must be specific for the trenching status being analysed and must satisfy the other design considerations associated with trenching status. Associated design considerations would include stability, thermal performance, end expansion and upheaval. For example, if analysing a non-trenched pipeline case, the pipeline design considered must have sufficient stability to be non-trenched.

The following data are required:

- pipe diameter
- wall thickness
- corrosion allowance
- material yield strength
- material toughness
- coating type
- coating thickness
- coating material properties
- pipeline length (risk/cost assessment only)
- pipeline heading (risk/cost assessment only)

5.3 ENVIRONMENTAL CONSIDERATIONS

The susceptibility of a pipeline to damage may be reduced by embedment of the pipeline into the seabed or by self-burial over a period of time. Likewise, the risk of damage may be increased by rock outcrops, pockmarks, scour or sandwave movement resulting in freespans in the pipeline.
The following data are required:
- soil properties
- historical data on self burial (risk/cost assessment only)
- historical data on scour (risk/cost assessment only)
- seabed topography

5.4 FISHING ACTIVITIES

In the open sea, third-party interactions with pipelines are primarily due to fishing activities. The following data on fishing activities in the area of the pipeline are required.

- fishing gear mass distribution
- fishing gear velocity distribution
- fishing intensity
- trawl directionality distribution (risk/cost assessment only)
- warp pull capacity and winch load limiters/brake settings
- expected developments in trawl gear or practices in the area.

Fishing data are often not readily available during the early stages of a feasibility study or conceptual design. Appendix A therefore contains typical fishing gear data (appropriate to mid 1990s) compiled for the UK sector of the North Sea. Whilst these data are adequate for initial feasibility studies, it is recommended that a detailed fishing activity study is performed, drawing on both official statistics and surveys of fishermen, if a non-trenched design option is being pursued.

It is recommended that fishing activity be monitored during drilling to provide a picture of activity in the area. Furthermore it is important to ensure that assumptions about fishing activity made in the design remain valid. Fishing activity should therefore be monitored during the field life and any changes assessed for their affect on the pipeline.

5.5 OPERATING STRATEGY

The operating, maintenance and contingency strategies will differ in some respects between trenched, buried and non-trenched pipelines. To establish lifetime costs for a pipeline system and to determine the cost effectiveness of a non-trenched pipeline as compared to a trenched or buried pipeline it is necessary to define the differing strategies.

Data to be considered in the development of lifetime costs include:
- pipeline survey requirements, ie, survey type and frequency (risk/cost assessment only)
- intelligent pigging (risk/cost assessment only)
- anticipated remedial works, eg spanning rectification (risk/cost assessment only)
- repair strategies, eg, for dents, buckles, loss of anodes, coating damage, etc (risk/cost assessment only)

5.6 COST DATA

To assess the cost effectiveness of non-trenching, costs are attached to the risks of damage and overall lifetime costs are developed for the pipeline system. Data required may include costs for the following:
• engineering and project management (risk/cost assessment only)
• materials (risk/cost assessment only)
• construction and commissioning activities (pipelay, trenching, rockdump, etc) (risk/cost assessment only)
• inspection and survey (in operation) (risk/cost assessment only)
• span rectification (risk/cost assessment only)
• contingency repairs (risk/cost assessment only)
• deferred production (risk/cost assessment only)
• oil spillage clean-up and compensation (risk/cost assessment only)
6. IMPACT

This section gives the method for assessing the impact resistance of the pipeline. The sequence is as follows:

- Consider first flexible pipelines. The rest of the section then relates to rigid lines
- Eliminate cases where the pipeline coating affords sufficient protection
- Assess the impact energy, denting energy, and dent size using formulae given, and cross check against physical test results
- If necessary go to a more detailed simulation to establish the denting energy, or carry out physical tests.

6.1 FLEXIBLE PIPELINES

Flexible pipelines have low resistance to impact damage. Their limit on denting energy is generally in the 1-10 kJ range. Beyond this, they are prone to cracking of the steel windings which could ultimately lead to rupture. Therefore, in general it will be necessary to protect flexible pipelines from impact.

There are two routes to further define impact response:

- Request from the supplier the maximum denting energy that the flexible can withstand, or
- Perform impact tests on the specific flexible product to determine the impact resistance. A specification for impact testing is given in Appendix F.

Reference should be made to API 17J ‘Specification for unbonded flexible pipe’ and API 17B ‘Recommended practice for flexible pipe’ for guidance on impact design requirements, specification and testing of flexible pipe.

6.2 COATED RIGID PIPELINES

The following coatings are deemed to protect the pipe against impact without further analysis:

- Concrete coatings with concrete or mastic field joints will protect the pipe steel against denting from both otter and beam trawls.
- Pipe-in-pipe and bundles protect the flowline against denting from both otter and beam trawls.
- Insulation coatings of thickness greater than 20mm will protect the pipe against denting by otter board or clump weight impacts (impact energy up to 14kN), and thicknesses greater than 45mm will protect the pipe against beam trawls (impact energy up to 38kN). Damage to the coating itself may result and therefore continued thermal or corrosion protection needs to be designed or tested for.

Other coating systems or impact cases need to be analysed or tested as detailed below. Thin coatings (eg 0.5mm fusion bonded epoxy, 3mm PE, 2mm PP) offer little impact energy absorption, so the dent depth should be assessed as if the pipe were uncoated. Where pipeline coating and field joint system differ, both coating systems shall be analysed or tested.

6.3 PREDICTION OF DENT SIZE

The route is to find the impact energy, derive the denting energy, and hence find the dent size.
6.3.1 Impact energy

The impact energy equals the change in the kinetic energy of the trawl gear. This is found as an output from the pullover simulation model\(^1\) developed for the JIP. In the model, the following conditions are observed:

- The change in kinetic energy is given by:

\[ \Delta E = \frac{1}{2} m_{d(ow)} u_1^2 - \left[ \frac{1}{2} m_s (u_2^2 + v_2^2) + \frac{1}{2} I_s \omega^2 \right] \]

where

- \(m_{d(ow)}\) is the mass of the steel in the otter door, beam or clump weight, plus the associated hydrodynamic added mass (examples of which are given in Appendix A)
- \(u_1\) is the initial velocity
- \(u_2, v_2,\) and \(\omega\) are the final velocities
- \(m_s\) and \(I_s\) refer just the steel mass of the gear, conservatively neglecting added mass after the collision.

- No energy is transferred from the associated net, briddles, lines or warps.
- The velocities of the gear after impact are based on conservation of momentum, so depend on the geometry and configuration of the trawl gear and of the pipeline, particularly on the degree of pipeline embedment or spanning, and on the leading radius of the trawl gear.

Impact energy may alternatively be estimated by one of the following methods:

- assume that the impact energy is equivalent to the total kinetic energy of the trawl door, beam or clump (potentially very conservative)
- perform simulation of the impact event using other methods, such as dynamic finite element analysis
- conduct model or full scale tests.

The total impact energy for a beam will be spread between two impact locations. For beams, it is recommended that the maximum energy associated with a single impact location is taken as being 0.66 times the total impact energy.

6.3.2 Denting energy

The impact energy is absorbed in a number of ways, through deformation of the coating, the pipe wall, global deformation of the pipeline and seabed, and deformation of the trawl gear. The denting energy is that portion of the energy that is absorbed by the local deformation of the pipe wall.

The approach is as follows:

- Assume conservatively that it is equal to 50% of the impact energy, find the resultant dent size from the next section, and check whether it meets the acceptance criteria.
- If the above approach fails, the route forward is from the following:
  - by comparison with the test results given in Appendix B
  - conducting impact tests on sections of coated pipe as per the specification in Appendix F
  - determining the denting energy by detailed simulation as described below.

\(^1\) This simulation model is available to JIP sponsors only. Commercially available simulation software is being developed by Trevor Joa Associates.
6.3.3 Denting model
The dent depth $d_i$ is found from the Ellinas-Walker formula:

$$d_i = \frac{1}{4} D_m \left( \frac{E}{25 \sigma_y t^2} \right)$$

where $E$ is the denting energy, $t$ the wall thickness, $D_m$ the mean diameter, and $\sigma_y$ is the specified minimum yield stress. This formula gives the dent depth in unpressurised pipe, and this is the value used in the acceptance criteria.

6.4 DETAILED SIMULATION FOR DENTING ENERGY

In order to predict the proportion of impact energy going into denting of the pipe steel, a detailed simulation of the impact process, including all local and global pipe effects, can be performed using dynamic non-linear finite element analysis. This analysis should include the following system effects:
- beam model of pipeline
- mass of pipe, coatings and contents,
- buoyancy (based on outermost diameter of pipe and coatings),
- axial and lateral seabed friction,
- added mass and hydrodynamic drag,
- effective non-linear spring stiffness of the pipe wall at the impact location which from Ellinas-Walker is:

$$F(d) = 37.5 \sigma_y t^2 \sqrt{\frac{d}{D_m}}$$

where $F(d)$ is the force for a given dent depth $d$.

- effective spring stiffness of the coating applied in series with the pipe wall stiffness
- dynamic impact at the appropriate velocity, including for added mass
- the stiffness of the trawl gear may either be included or be conservatively ignored.

![Diagram](Image)

**Figure 2**
Schematic of detailed simulation model
7. PULLOVER

This section defines how to carry out a pullover analysis for a pipeline. The sequence for rigid lines is as follows:
- determine the time varying load on the pipeline as the trawl gear is pulled over the pipeline
- determine the initial stress/strain condition of the pipeline accounting for the effects of thermal and pressure loadings, end restraints and lateral snaking/buckling of the line
- determine the response of the pipeline to the force-time history
- account for the interaction between the motion of the trawl gear over the pipeline and resultant flexing of the pipeline and iterate to a solution.

7.1 PULLOVER LOADS

7.1.1 JIP model
The force-time history is found from the 2-dimensional trawl gear pullover simulation model developed for the JIP.

This model determines the motion of the trawl gear over the pipeline and the resultant loads on the pipeline during the pullover. It uses a time-step finite difference routine to solve the momentum and force balance equations as the trawl door or beam first impacts the pipe and subsequently slides and rotates over the top. It takes account of the following in two dimensions:
- friction between the pipe and trawl gear
- embedment depth or span height of the pipe
- geometry of the trawl board leading edge, particularly the radius of the bottom corner
- warp attachment point and angle
- ship motion and warp catenary stiffness to determine how the warp load varies as the trawl gear is halted.

7.1.2 Output
The outputs of the JIP model are the horizontal and vertically downward forces on the pipeline versus time. These are used to find the pipeline response below.

An example of output produced by this simulation model is illustrated in Figure 3 and shows the gear imparting both horizontal and vertical (downward) loads as it is pulled over the pipeline. It is important to take the vertical forces into account in that they act to decrease the pipe deflections and stresses. The vertical component of force may be significant with small diameter pipelines.
7.1.3 Flexing Interaction

One effect which particularly influences the loading for smaller diameter (≤16") pipelines is the interaction of the pipeline and trawl gear motions. The flexing of the pipeline during the pullover will have the effect of decreasing the peak pullover load whilst increasing the duration. For small diameter pipelines this effect must be considered when determining the pullover force-time history.

The Trenching Guidelines JIP simulation model allows for pipeline movement to be incorporated in the simulation. The interaction between trawl gear motion and pipeline motion can therefore be solved by an iteration of developed force-time history (from pullover model) and resultant pipeline response (from pipeline response model).

7.1.4 Refinements

Since the JIP model is a 2D equivalent of a 3D motion, the loads are conservative. Should it be necessary to refine the results, the following methods are available:

- finite element simulation of trawl gear pullover incorporating the features above
- model tests of pullover
- full scale tests of pullover

7.2 PIPELINE RESPONSE

The pipeline response is found by dynamic, non-linear finite element analysis. In practical terms this means adapting the example input decks (see Appendix E FE analysis input decks) and
running them on the ABAQUS finite element program\(^2\). The output is peak bending strain at the point of impact.

The following effects are included within the model, and need to be included in any models for alternative FE codes:
- mass of coatings and contents
- buoyancy (based on outermost diameter of pipe and coatings)
- axial and lateral seabed friction
- internal pressure and temperature, including pressure stiffening due to the internal fluid column
- added mass and hydrodynamic drag
- horizontal and vertical components of the pullover force-time history

Certain points need to be addressed to ensure that the model is realistic. These are:
- Choosing end constraints
- Allowing for lateral buckling
- Applying multiple impacts
- Choosing the output strain

### 7.2.1 End constraints

For a long pipeline, the length of pipeline modelled should be sufficient to ensure that end effects do not have an influence on the response. i.e. the end may be anchored, but should be far enough away (say 2-3 km) for there to be no forces on the anchor due to the pullover, and to be outside the active length which is feeding in to the lateral buckle.

If the pipeline is sufficiently short (say less than 5 km), the full length should be modelled and representative end constraints included.

### 7.2.2 Lateral buckling

The recommended approach for the finite element modelling of pipelines operating at elevated temperatures is to introduce a small deflection (an initiator) into an otherwise straight pipeline and then raise the temperature and pressure to operational conditions. As the temperature and pressure are raised lateral buckling occurs. The pullover load is then applied at the peak of the buckle in order to find the total strain.

The modelling should use a single initiator of versed-sine profile with amplitude 0.5m and wavelength 150 diameters. The results are, however, insensitive to the exact size and shape of the initiator.

### 7.2.3 Multiple crossings

The analysis should consider multiple crossings at the same point, and find each time the peak bending strain. From this should be determined:
- either the resultant limiting strain due to any number of crossings, i.e. further crossings give no increase in the peak strain
- or, using risk analysis, the strain from the maximum number of impacts expected at that point.

\(^2\) ABAQUS may be licenced from HKS, Suite G16B, The Genesis Centre, Science Park South, Birchwood, Warrington, Cheshire WA3 7BH, tel +44 (0) 1925 810166, fax +44, (0) 1925 810178, e-mail hotline@hks.co.uk
7.2.4 Strain results
As a result of the pullover, the bending strain typically peaks and then relaxes as the pipe springs back. The output result for comparison with the acceptance criterion is the peak strain rather than the final value.

7.3 FLEXIBLES

The approach to pullover analysis for flexibles is as follows:
- Derive the pullover loads as above
- Ask the supplier to determine response of the flexible to this load, following the same principles of analysis to identify bending radius at the pullover point, tension at the pullover point, and tension/bending at the nearest end fitting.
- Ask the supplier to define acceptance criteria, including at least the following:
  - minimum bend radius at operating conditions
  - maximum tension in the pipe at the minimum bending radius
  - maximum tension in the pipe at the nearest fitting, combined with any bending that the pullover may induce there

There is one further concern to consider: slicing into the outer sheath of the flexible. As the trawl gear passes over the top of the pipe, it could rotate and slide over on an exposed edge, cutting into the sheath. If this allows undetected water ingress, the armour may eventually corrode and fail.
8. HOOKING

This section defines how to evaluate the effects of hooking in terms of:
• bending in pipe due to the initial snagging load, and
• bending resulting from lifting the pipe by a sufficient height to release the trawl gear

8.1 FLEXIBLES

Due to the proprietary nature of flexibles, it is recommended that the supplier should determine the response to hooking loads.

8.2 HOOKING: INITIAL SNAGGING

8.2.1 Circumstance
Snagging is when the gear comes fast on a pipeline and brings the vessel to a halt. This is rare, but can happen for any type of gear.

8.2.2 Load
The snagging load is found as:

\[ F_{\text{snag}} = \nu \sqrt{\frac{E_w A_w M_v}{l_w}} \]

where \( F_{\text{snag}} \) is the peak snagging load, \( \nu \) is the trawl velocity, \( E_w \) is the elastic modulus of the warp, \( A_w \) is the cross sectional area of the warp, \( M_v \) is the mass of the vessel (including added mass) and \( l_w \) is the warp length.

The snagging load will be limited by the capacity of the trawl warps or, where fitted, the brake limiter setting on the trawl winches. It should be remembered that actual breaking strength for warps may exceed the specified minimum breaking strength. Also, with beam trawls warps are generally double or triple rigged. Typical warp parameters and where appropriate, load limiter settings, are provided in Appendix A.

8.2.3 Strain
For rigid pipelines, to find the strain in the pipeline due to snagging, a static finite element analysis is performed for this load applied to the pipeline with the load oriented at an angle \( \theta \) above horizontal defined by:

\[ \theta = \arcsin \left( \frac{d}{l_w} \right) \]

where \( d \) is the water depth and \( l_w \) is the warp length. The other input parameters are similar to the pullover model. An example of the finite element input deck is given in Appendix E.

A simple, but conservative approach is to apply the full load and check the strain against acceptance criteria. If this fails, do as follows:
• Ramp the applied load (applied at angle \( \theta \)) to determine the load and lateral displacement at which the pipeline begins to lift off the seabed.
• At this load, it may be assumed that the otter door will begin to rotate and the edge of the door will pivot about the point of contact with the seabed.
• A further lateral displacement of the greater of half the door length or half the door height should be applied to determine peak displacement and strain.

### 8.3 Hooking: Gear Retrieval

#### 8.3.1 Circumstance

In the event of hooking of gear, and not being able to free it by pulling forwards backwards or sideways, the fishing vessel will haul vertically at the hooking location until the warps break.

With beams the gear would release as soon as the pipeline begins to raise. This case does not, therefore, need to be assessed for beams. The clump weight designs currently seen will behave similarly to beams. Clump weight designs are, however, still developing and the ability to release from beneath pipelines therefore needs to be considered by the designer for the specific equipment anticipated in the area of the pipeline.

#### 8.3.2 Strains

The bending strains are found by static finite element analysis, for raising the pipeline to the height required for the gear to release. An example input deck is given in Appendix E. FE analysis input decks. Once again, the input parameters are similar to the pullover case. The following criteria apply:
• With otter doors, the maximum distance that the pipeline is raised before the door releases is the greater of half the door length or half the door height, as illustrated in Figure 4.
• The load is limited to the breaking strength of the trawl warps. Typical warp parameters are provided in Appendix A.

![Figure 4](image)

**Figure 4**

Pipe Movement after Hooking
9. ACCEPTANCE CRITERIA

These are the acceptance criteria for the various load cases.

9.1 DENTING

The dent depth in pipelines with zero internal pressure shall be no more than:

- 4% for pipe of D/t less than 18
- 2% for pipe in the range 18<D/t<30

To go beyond these dent depths or D/t ratios, the design shall demonstrate:

- that the pipeline has adequate fatigue life, taking account of the stress concentration caused by the dent, and the pressure and temperature stress fluctuations due to operation of the pipeline. The recommended method for calculation of fatigue life is presented in Appendix C
- and that all the types of pigs required during the design life will pass the dent

Gouging of the pipe wall must be prevented by use of a coating of sufficient properties and thickness to prevent metal-to-metal contact during the impact process.

In deep water applications, the hydrostatic collapse of the dented pipe should be considered by treating the dent as an ovalisation of the pipe.

9.2 PULLOVER AND LATERAL BUCKLING

- The strains in the pipe due to the combination of lateral buckling and pullover shall satisfy the following:

\[
\frac{1.3\varepsilon_b}{\varepsilon_{be}} + \frac{P}{P_o} + \left(\frac{F_x}{F_{x0}}\right)^n \leq 1 \text{ where}
\]

\[
\varepsilon_b = \text{bending strain}
\]

\[
\varepsilon_{be} = \text{critical bending strain} = 15\left(\frac{t}{D}\right)^2
\]

\[
P = \text{external overpressure}
\]

\[
P_o = \text{characteristic pressure to cause hydrostatic collapse given by :}
\]

\[
\left(\frac{P}{P_o}\right)_1\left(\frac{P_o}{P_y}\right)^2 - 1 = 2\frac{P_o}{P_y}\left(\sigma_0\cdot \frac{D}{t}\right)
\]

\[
P_o = \frac{2E}{(1-v^2)}\left(\frac{t}{D}\right)^3
\]

\[
P_y = 2\cdot \sigma_y \cdot \frac{t}{D}
\]
\( F_c = \text{local axial compressive force} \) (\( = 0 \text{ if tensile} \))

\( F_{xc} = \text{critical axial compressive force} = \pi \cdot (D - t) \cdot t \cdot \sigma_y \)

\( n = 1 + 300 \cdot \frac{t}{D} \)

\( D = \text{outside diameter} \)

\( t = \text{nominal wall thickness} \)

\( E = \text{Elastic modulus} \)

\( \nu = \text{Poisson's ratio} \)

\( \sigma_y = \text{yield stress} \)

\( f_0 = \text{the initial ovalisation of the pipe cross section} \)

The axial compression \( F_c \) is local to the point of bending following the pullover.

- Cumulative strains resulting from any subsequent impacts of the gear at the same point shall also satisfy the above criteria.

### 9.3 HOOKING

- The strains in the pipe due to the combination of lateral buckling and hooking shall satisfy the following:

\[
\frac{\varepsilon_b}{\varepsilon_{bc}} + \frac{P}{P_c} + \left( \frac{F_x}{F_{xc}} \right)^n \leq 1
\]

- Multiple hookings at the same location need not be considered.
10. QUANTITATIVE RISK ASSESSMENT

10.1 APPLICATION

Where the deterministic analysis, considering a worst case combination of parameters, shows that damage to a pipeline may be sustained from trawl gear interaction, risk analysis techniques can be applied to determine the probability of damage and to determine the subsequent lifetime costs of the pipeline. It may then still be possible to justify non-trenching of the pipeline if the risk of damage is sufficiently low and subsequent lifetime costs are less than for the trenched pipeline option.

10.2 FREQUENCY OF FAILURE

The parameters that dominate the variability of pipeline response to the three load condition, ie impact, pullover and hooking, are:

- trawl gear type
- trawl gear size
- angle of approach of trawl gear
- spanning/embedment of pipeline.

A risk assessment, therefore, need only consider distributions in these parameters. A range of analyses should be performed for each load condition so that the limiting conditions that give critical damage to the pipeline can be identified for each gear type.

By comparison of the parameters giving critical conditions to the parameter distributions, the probability of failure is determined. By multiplying the probability of failure by the number of crossing interactions a failure frequency is determined.

10.3 COST

The through-life costs may be assessed to determine whether the capital cost benefits of not trenching offset the potential increased operational costs.

The through lifetime costs may be calculated on a year-by-year basis and discounted back to nett present value to enable costs to be compared for trenched and non-trenched pipeline designs. All cost elements that may change due to trenching status need to be included in the estimate. Essentially it is necessary, therefore, to have designs for both trenched and non-trenched options. The following cost components may vary between the two pipeline design options:

- **Materials:** for example, additional wall thickness or weight coating may be required for stability of a non-trenched design or additional anodes may be required for a buried pipeline.
- **Construction:** in addition to the trenching costs themselves additional construction costs, such as rock-dumping for prevention of upheaval buckling of a trenched hot flowline, may be incurred.
- **Maintenance:** routine maintenance costs such as freespans rectification may be expected to differ for trenched and non-trenched designs.
• **Inspection/monitoring:** routine inspection schedules will differ depending on trenching or burial status. It is necessary to monitor fishing activities for non-trenched pipelines.

• **Decommissioning:** the costs associated with pipeline decommissioning may differ for trenched and non-trenched designs. Realistic costs for all decommissioning options should be included.

In addition to these costs, the risk costs associated with repair of damage inflicted by trawl gear will differ. This cost is calculated for each year as the sum of the risk of failure for each failure mode/criteria and the cost of repairing the pipeline. The costs will differ for the differing modes and criteria, and cost elements will not only include the repair costs themselves but could include loss of production, non-delivery penalty charges or, in the extreme case of loss of containment, environmental clean-up costs and knock-on costs (such as loss of motor fuels sales) resulting from the subsequent bad publicity.
11. APPENDIX A TYPICAL FISHING GEAR

There are two main types of demersal trawling practised in the North Sea, namely, beam trawling and otter trawling.

11.1 BEAM TRAWLING

Beam trawling is employed principally for the capture of flat fish such as plaice, lemon sole, Dover sole, halibut, turbot etc. The gear is designed to overcome the primary method of defence of these species which is to bury themselves into the seabed. The mouth of the net is held open by a large tubular beam running on heavy steel shoes whilst a series of chains dragged along the seabed disturbs the fish from the seabed and into the mouth of the net. The gear design is not suitable for the efficient capture of round fish such as cod or haddock, and the high capital and operating costs associated with beam trawling would not make catching the lower value round fish economically viable. In addition, EC quotas allocated to beam trawlers limit them largely to the capture of flat fish species. Beam trawling is, therefore, most prolific in the shallower sandy grounds containing flat fish concentrations.

Beam trawlers do not tend to 'hunt' for shoals of fish using sonar as do the round fish demersal or pelagic trawlers. The practice is generally to return to grounds that are known, through experience, to be productive at specific times of the year. The ground is then systematically covered as quickly as possible. The philosophy for beam trawling is that the greater the area of seabed covered in a trawl the larger the catch will be. This has resulted in the current situation of large beams and high trawl speeds. The desire for higher trawl speeds has also led to the requirement for heavier beams to prevent the gear lifting off the seabed. This, in turn, has driven the move towards larger, more powerful vessels.

The main beam trawler fleets operating in the North Sea are registered in Holland, Belgium or the UK. Small inshore beam trawlers are also used for catching shrimps in the shallow coastal waters of Belgium, Holland, Germany, Denmark and the UK.

11.2 BEAM TRAWL GEAR DESCRIPTION

Beam trawlers tow two beam trawls from outrigger booms, one each side of the vessel. The trawl consists of a tubular beam supported approximately 0.7-1.0m above the seabed by a heavy steel shoe at each end. The beam section is often increased over the mid-section to increase bending stiffness. The headline of the net is attached along the beam and the ends of the groundline are fastened to the base of each shoe. The bottom of the mouth of the net trails behind the beam and the top of the net so that fish lifted from the seabed as the trawl passes over are already trapped from above and cannot escape over the net. A number of heavy 'tickler' chains are strung between the two shoes as shown in Figure 5. These trail behind the beam but ahead of the net groundline and disturb the seabed surface lifting the fish up and into the mouth of the net.
When fishing for Dover Sole a heavy chain mat (approximately 200mm square mesh) is also strung from the beam.

11.3 BEAM TRAWL ACTIVITY

The Dutch fleet is by far the largest operating in the North Sea, both in terms of numbers of vessels and vessel power. About half of the Dutch fleet are small low-powered (less than 500HP) vessels working the inshore regions for shrimps. There are, however, well over 100 vessels with powers in the range 2000-4500HP and displacements ranging up to a maximum of about 900 tonnes. Current legislation limits the power of newly registered vessels to 2000HP, so, in theory, the trend for ever larger and more powerful Dutch vessels should be stemmed. This may not necessarily be the case in practice, as engines can be derated for registration and then uprated to full power after registration.

Dutch beam trawling activity is generally limited to southern waters with Dutch vessels generally trawling south of 56° latitude and rarely venturing farther north than 58° latitude.

Belgian beamers fish a much wider area and will travel north to fishing grounds to the east of Aberdeen. The Scottish beamers based in the north-east coast ports also concentrate efforts on the area east of Aberdeen. Scottish beam trawl activity has, however, been recorded in West of Shetland also. The English beam trawlers fish a wide range of areas including both the southern and central grounds fished by the Dutch and to the east of Aberdeen.
The following sections develop the parameters describing the trawl gear and vessels for the beam trawl fleets. The Dutch beam trawls are considered separately as the trawls and vessels are generally larger than those of the other fishing fleets and the Dutch fishing effort is confined to the southern and central regions of the North Sea.

11.4 BEAM TRAWL PARAMETER TABLES

The following sections contain the tables of relevant parameters for Dutch heavy beam trawls and other beam trawls, ie, Belgian and UK. The tables give parameters for typical minimum, mean and maximum configurations. The warp length and angle given are typical values. Depending on water depth and skipper preference, the warp length could be a minimum of 2.5 times water depth or a maximum of 4.5 times water depth.

Dimensions
The dimensions given for the trawl gear refer to the dimensions required for the pullover analytical model\(^1\). These dimensions are illustrated in Figure 6.

![Figure 6](image)

**Figure 6**
Definition of beam shoe dimensions

11.5 DUTCH HEAVY BEAM TRAWLS

The parameters for the Dutch heavy beam trawl fleet shown in Table 3 are shown below.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>units</th>
<th>Smallest config.</th>
<th>Mean config.</th>
<th>Largest config.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel mass</td>
<td>tonnes</td>
<td>500</td>
<td>690</td>
<td>1000</td>
</tr>
<tr>
<td>Gear mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total beam mass</td>
<td>kg</td>
<td>2100</td>
<td>4300</td>
<td>5800</td>
</tr>
<tr>
<td>Mass of nets, chains, etc</td>
<td>kg</td>
<td>1900</td>
<td>2100</td>
<td>2500</td>
</tr>
<tr>
<td>Added mass coefficient</td>
<td></td>
<td>3.7</td>
<td>2.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Gear dimensions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>L1</td>
<td>m</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>L2</td>
<td>m</td>
<td>0.42</td>
<td>0.46</td>
<td>0.51</td>
</tr>
<tr>
<td>L3</td>
<td>m</td>
<td>0.97</td>
<td>1.16</td>
<td>1.34</td>
</tr>
<tr>
<td>D1</td>
<td>m</td>
<td>0.32</td>
<td>0.37</td>
<td>0.41</td>
</tr>
<tr>
<td>D2</td>
<td>m</td>
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<td>0.36</td>
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<td>m</td>
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<td>0.25</td>
</tr>
<tr>
<td>Warps and winches</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warp diameter</td>
<td>mm</td>
<td>30</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>Warp mass</td>
<td>kg/m</td>
<td>3.1</td>
<td>3.6</td>
<td>4.1</td>
</tr>
<tr>
<td>Length v water depth (note 1)</td>
<td>0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Warp angle to horizontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal trawl load (note 2)</td>
<td>tonnes</td>
<td>8.5</td>
<td>12.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Max load limiter setting (note 3)</td>
<td>tonnes</td>
<td>15</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Breaking load (note 4)</td>
<td>tonnes</td>
<td>53 (106)</td>
<td>62 (186)</td>
<td>69 (207)</td>
</tr>
</tbody>
</table>

Note 1: The warp length and angle given are typical values. Depending on water depth and skipper preference, the warp length could be a minimum of 2.5 times water depth or a maximum of 4.5 times water depth.

Note 2: Normal trawl load data are not readily available. These data are from a single source, namely the NAM tests on the K7-FA-1/K8-FA-1 pipeline in 1984. Those data relate to 3.5-3.8 tonne beams with total gear masses of 7 tonnes.

Note 3: Beam trawlers are rarely fitted with load limiting devices on winches. The loads stated in the table are vessel bollard pulls.

Note 4: Warps are run in either double or triple configurations. The stated breaking load is for the warp wire itself and the figure in brackets shows the actual load required to break the wire in the rigged configuration.

### 11.6 OTHER BEAM TRAWLS

The parameters for the Belgian and UK beam trawl fleets are shown in Table 4. The UK beams are of similar design to the Dutch beams and generally of higher mass than the Belgian beams. The Belgian beam shoes are also of slightly different geometry to those used by the Dutch or UK fleets. The dimensions given for the minimum and mean beam sizes are based on the Belgian shoe geometry, whereas the maximum beam dimensions are based on a UK style beam shoe.
### Table 4

Parameters for UK and Belgian beam trawls

<table>
<thead>
<tr>
<th>Parameter</th>
<th>units</th>
<th>Smallest config.</th>
<th>Mean config.</th>
<th>Largest config.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel mass</td>
<td>tonnes</td>
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<td>430</td>
<td>700</td>
</tr>
<tr>
<td>Gear mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total beam mass</td>
<td>kg</td>
<td>1950</td>
<td>3089</td>
<td>4740</td>
</tr>
<tr>
<td>Mass of nets, chains, etc</td>
<td>kg</td>
<td>1030</td>
<td>1907</td>
<td>2330</td>
</tr>
<tr>
<td>Added mass coefficient</td>
<td></td>
<td>4.0</td>
<td>3.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Gear dimensions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>m</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>L2</td>
<td>m</td>
<td>0.41</td>
<td>0.55</td>
<td>0.48</td>
</tr>
<tr>
<td>L3</td>
<td>m</td>
<td>0.96</td>
<td>1.32</td>
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<td>D1</td>
<td>m</td>
<td>0.31</td>
<td>0.45</td>
<td>0.39</td>
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<tr>
<td>D2</td>
<td>m</td>
<td>0.31</td>
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<td>0.38</td>
</tr>
<tr>
<td>R</td>
<td>m</td>
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<td>0.35</td>
<td>0.25</td>
</tr>
<tr>
<td>Warps and winches</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warp diameter</td>
<td>mm</td>
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<td>32</td>
<td>34</td>
</tr>
<tr>
<td>Warp mass</td>
<td>kg/m</td>
<td>2.9</td>
<td>3.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Length v water depth (note 1)</td>
<td></td>
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<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Warp angle to horizontal</td>
<td></td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Normal trawl load (note 2)</td>
<td>tonnes</td>
<td>8.5</td>
<td>12.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Max load limiter setting (note 3)</td>
<td>tonnes</td>
<td>6</td>
<td>18</td>
<td>42</td>
</tr>
<tr>
<td>Breaking load (note 4)</td>
<td>tonnes</td>
<td>43</td>
<td>62 (124)</td>
<td>70 (140)</td>
</tr>
<tr>
<td>Trawl parameters</td>
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<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>m/s</td>
<td>2.6</td>
<td>3.1</td>
<td>3.6</td>
</tr>
<tr>
<td>Duration</td>
<td>hours</td>
<td>2.75±1.25</td>
<td>2.75±1.25</td>
<td>2.75±1.25</td>
</tr>
</tbody>
</table>

Note 1: The warp length and angle given are typical values. Depending on water depth and skipper preference, the warp length could be a minimum of 2.5 times water depth or a maximum of 4.5 times water depth.

Note 2: Normal trawl load data are not readily available. These data are from a single source, namely the NAM tests on the K7-FA-1/K8-FA-1 pipeline in 1984. These data relate to 3.5-3.8 tonne beams with total gear masses of 7 tonnes.

Note 3: Beam trawlers are rarely fitted with load limiting devices on winches. The loads stated in the table are vessel bollard pulls.

Note 4: Warps are run in either single or double configurations. The stated breaking load is for the warp wire itself and the figure in brackets shows the actual load required to break the wire in the rigged configuration.

### 11.7 OTTER TRAWLING

Otter trawling is used for the capture of round fish, such as cod, haddock, whiting and coley, that live close to the seabed. Otter trawling uses boards (also known as doors) attached ahead of the net which, by combination of hydrodynamic loading and frictional shear with the seabed, provide the lateral forces required to hold the mouth of the net open.

Trawl speeds are significantly slower than beam trawling and the duration of a trawl is greater. Otter trawlers are able to hunt for fish shoals using sonar. Once the fish are in the path of the
gear they are herded by the otter doors, bridlees and net wings in towards the mouth of the net. The fish then swim ahead of the net mouth until they tire and fall back into the cod end of the net.

Many of the fleets based around the North Sea use otter trawling and this is employed throughout the North Sea and West of Shetland. The main fleets are the Scottish, French, Danish, Norwegian, English and German. Vessels are generally smaller than those used for beam trawling although some French and German vessels have power and displacements comparable with Dutch heavy beam trawlers.

11.8 OTTER TRAWL DESCRIPTION

A typical demersal otter trawl is illustrated in Figure 7.

As the fish can swim some distance off the seabed, the top of the mouth of the net is held up by floats on the head line so that a height of up to 6 metres can be achieved. The bottom of the net is held in contact with the seabed by use of a weighted ground line.

![Figure 7](attachment:image.png)

**Figure 7**

Typical demersal otter trawl

11.9 OTTER TRAWL PARAMETER TABLES

The following sections contain the tables of relevant parameters for vee, polyvalent and bison otter boards giving minimum, mean and maximum values for each parameter. As with the beam trawl tables, the parameters are generally coupled, i.e., the lightest gear with the smallest dimensions will correspond to the minimum vessel mass, etc. A number of parameters do not
necessarily follow this relationship, namely, the warp length and angle, and the trawl speed and duration.

**Dimensions**
The dimensions given for the trawl gear refer to the dimensions required for the pullover simulation model\(^1\). These dimensions are illustrated in Figure 8.

![Figure 8: Definition of otter board dimensions](image)

**11.10 VEE DOORS**
The parameters for the vee doors are shown in Figure 5. Fleets included in these calculations are the Scottish light, English, Danish and Norwegian.
### Table 6

<table>
<thead>
<tr>
<th>Parameter</th>
<th>units</th>
<th>Smallest config.</th>
<th>Mean config.</th>
<th>Largest config.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vessel mass</strong></td>
<td>tonnes</td>
<td>25</td>
<td>220</td>
<td>350</td>
</tr>
<tr>
<td><strong>Gear mass</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total door mass</td>
<td>kg</td>
<td>152</td>
<td>640</td>
<td>1800</td>
</tr>
<tr>
<td>Mass of net, etc</td>
<td>kg</td>
<td>800</td>
<td>2500</td>
<td>3500</td>
</tr>
<tr>
<td>Added mass coefficient (for attack angle)</td>
<td>o</td>
<td>35.0</td>
<td>35.0</td>
<td>35.0</td>
</tr>
<tr>
<td><strong>Gear dimensions</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>m</td>
<td>0.736</td>
<td>1.06</td>
<td>1.48</td>
</tr>
<tr>
<td>L2</td>
<td>m</td>
<td>0.92</td>
<td>1.33</td>
<td>1.85</td>
</tr>
<tr>
<td>L3</td>
<td>m</td>
<td>1.83</td>
<td>2.65</td>
<td>3.70</td>
</tr>
<tr>
<td>D1</td>
<td>m</td>
<td>0.55</td>
<td>0.81</td>
<td>1.35</td>
</tr>
<tr>
<td>D2</td>
<td>m</td>
<td>0.55</td>
<td>0.81</td>
<td>1.35</td>
</tr>
<tr>
<td>R</td>
<td>m</td>
<td>0.25-0.5</td>
<td>0.3-0.8</td>
<td>0.3-1.3</td>
</tr>
<tr>
<td><strong>Warps and winches</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warp diameter</td>
<td>mm</td>
<td>10</td>
<td>16</td>
<td>28</td>
</tr>
<tr>
<td>Warp mass</td>
<td>kg/m</td>
<td>0.34</td>
<td>0.92</td>
<td>2.71</td>
</tr>
<tr>
<td>Length v water depth (note 1)</td>
<td></td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Warp angle to horizontal</td>
<td>o</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Normal trawl load (note 2)</td>
<td>tonnes</td>
<td>1.0</td>
<td>3.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Max load limiter setting (note 3)</td>
<td>tonnes</td>
<td>1.5</td>
<td>5.7</td>
<td>30</td>
</tr>
<tr>
<td>Breaking load (note 4)</td>
<td>tonnes</td>
<td>5.5</td>
<td>14</td>
<td>43</td>
</tr>
<tr>
<td><strong>Trawl parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>m/s</td>
<td>2.1±0.5</td>
<td>2.1±0.5</td>
<td>2.1±0.5</td>
</tr>
<tr>
<td>Duration</td>
<td>hours</td>
<td>3.5-5.0</td>
<td>3.5-5.0</td>
<td>3.5-5.0</td>
</tr>
</tbody>
</table>

**Note 1:** The warp length and angle given are typical values. Depending on water depth and skipper preference, the warp length could be a minimum of 2.5 times water depth or a maximum of 4.5 times water depth.

**Note 2:** Normal trawl load data are not readily available. These data are from a single source, namely the NAM tests\(^3\) on the K7-FA-1/K8-FA-1 pipeline in 1984. These data relate to 1.1 tonne rectangular doors.

**Note 3:** Only the winches of the Norwegian trawler fleet are generally fitted with load limiting devices. The English and Scottish fleets rarely use these devices and there is no information to suggest that winches on Danish vessels are fitted with load limiters. The loads stated in the table are therefore based on vessel bollard pulls rather than load limiter settings.

### 11.11 POLYVALENT DOORS

The parameters for the polyvalent doors are shown in Table 6. Polyice and arc doors, which are of very similar design, are also included in these calculations. Fleets that use these doors are the French, German, Norwegian, UK heavy and English light.
Table 6
Parameters for polyvalent door trawls

<table>
<thead>
<tr>
<th>Parameter</th>
<th>units</th>
<th>Smallest config.</th>
<th>Mean config.</th>
<th>Largest config.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel mass</td>
<td>tonnes</td>
<td>85</td>
<td>350</td>
<td>4800</td>
</tr>
<tr>
<td>Gear mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total door mass</td>
<td>kg</td>
<td>320</td>
<td>1400</td>
<td>2500</td>
</tr>
<tr>
<td>Mass of net, etc</td>
<td>kg</td>
<td>800</td>
<td>3000</td>
<td>4000</td>
</tr>
<tr>
<td>Added mass coefficient</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(for attack angle)</td>
<td>°</td>
<td>3.3</td>
<td>5.0</td>
<td>5.9</td>
</tr>
<tr>
<td>Gear dimensions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>m</td>
<td>0.76</td>
<td>1.36</td>
<td>1.84</td>
</tr>
<tr>
<td>L2</td>
<td>m</td>
<td>0.95</td>
<td>1.70</td>
<td>2.30</td>
</tr>
<tr>
<td>L3</td>
<td>m</td>
<td>1.90</td>
<td>3.40</td>
<td>4.60</td>
</tr>
<tr>
<td>D1</td>
<td>m</td>
<td>0.53</td>
<td>1.05</td>
<td>1.25</td>
</tr>
<tr>
<td>D2</td>
<td>m</td>
<td>0.53</td>
<td>1.05</td>
<td>1.25</td>
</tr>
<tr>
<td>R</td>
<td>m</td>
<td>0.65</td>
<td>1.17</td>
<td>1.59</td>
</tr>
<tr>
<td>Warps and winches</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warp diameter</td>
<td>mm</td>
<td>12</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>Warp mass</td>
<td>kg/m</td>
<td>0.5</td>
<td>1.65</td>
<td>3.61</td>
</tr>
<tr>
<td>Length v water depth (note 1)</td>
<td></td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Warp angle to horizontal</td>
<td>°</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Normal trawl load (note 2)</td>
<td>tonnes</td>
<td>1.0</td>
<td>3.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Max load limiter setting (note 3)</td>
<td>tonnes</td>
<td>8</td>
<td>12</td>
<td>57.6</td>
</tr>
<tr>
<td>Breaking load (note 4)</td>
<td>tonnes</td>
<td>6.8</td>
<td>28</td>
<td>50</td>
</tr>
<tr>
<td>Trawl parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>m/s</td>
<td>2.1±0.5</td>
<td>2.1±0.5</td>
<td>2.1±0.5</td>
</tr>
<tr>
<td>Duration</td>
<td>hours</td>
<td>4.0±1.0</td>
<td>4.0±1.0</td>
<td>4.0±1.0</td>
</tr>
</tbody>
</table>

Note 1: The warp length and angle given are typical values. Depending on water depth and skipper preference, the warp length could be a minimum of 2.5 times water depth or a maximum of 4.5 times water depth.

Note 2: Normal trawl load data are not readily available. These data are from a single source, namely the NAM tests on the K7-FA-1/K8-FA-1 pipeline in 1984. These data relate to 1.1 tonne rectangular doors.

Note 3: The winches of the French, Norwegian and UK heavy trawler fleets are generally fitted with load limiting devices typically set in the range of 8 - 19 tonnes. Although the loads stated in the table are based on vessel bollard pulls rather than load limiter settings, the minimum to mean loads stated are very much in line with the load limiter settings used. The maximum load is based on the German heavy class trawler. This vessel class does not usually fish the North Sea although sightings have been recorded. It is, therefore, an extreme case.

11.12 BISON DOORS

The parameters for the bison doors are shown below. These are used by the Scottish light trawler fleet.
Table 7
Parameters for bison door trawls

<table>
<thead>
<tr>
<th>Parameter</th>
<th>units</th>
<th>Smallest config</th>
<th>Mean config</th>
<th>Largest config</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel mass</td>
<td>tonnes</td>
<td>90</td>
<td>220</td>
<td>350</td>
</tr>
<tr>
<td>Gear mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total door mass</td>
<td>kg</td>
<td>330</td>
<td>685</td>
<td>1120</td>
</tr>
<tr>
<td>Mass of net, etc</td>
<td>kg</td>
<td>1500</td>
<td>2500</td>
<td>3500</td>
</tr>
<tr>
<td>Added mass coefficient (for attack angle)</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Gear dimensions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>m</td>
<td>0.6</td>
<td>0.76</td>
<td>0.9</td>
</tr>
<tr>
<td>L2</td>
<td>m</td>
<td>0.75</td>
<td>0.95</td>
<td>1.12</td>
</tr>
<tr>
<td>L3</td>
<td>m</td>
<td>1.49</td>
<td>1.90</td>
<td>2.23</td>
</tr>
<tr>
<td>D1</td>
<td>m</td>
<td>0.49</td>
<td>0.625</td>
<td>0.74</td>
</tr>
<tr>
<td>D2</td>
<td>m</td>
<td>0.49</td>
<td>0.625</td>
<td>0.74</td>
</tr>
<tr>
<td>R</td>
<td>m</td>
<td>0.25</td>
<td>0.25</td>
<td>0.3</td>
</tr>
<tr>
<td>Warps and winches</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warp diameter</td>
<td>mm</td>
<td>10</td>
<td>16</td>
<td>23</td>
</tr>
<tr>
<td>Warp mass</td>
<td>kg/m</td>
<td>0.34</td>
<td>0.92</td>
<td>1.91</td>
</tr>
<tr>
<td>Length v water depth (note 1)</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Warp angle to horizontal</td>
<td>°</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Normal trawl load (note 2)</td>
<td>tonnes</td>
<td>1.0</td>
<td>3.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Max load limiter setting (note 3)</td>
<td>1.5</td>
<td>5.7</td>
<td>12.25</td>
<td></td>
</tr>
<tr>
<td>Breaking load (note 4)</td>
<td>tonnes</td>
<td>5.5</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>Trawl parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>m/s</td>
<td>1.8±0.3</td>
<td>1.8±0.3</td>
<td>1.8±0.3</td>
</tr>
<tr>
<td>Duration</td>
<td>hours</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Note 1: The warp length and angle given are typical values. Depending on water depth and skipper preference, the warp length could be a minimum of 2.5 times water depth or a maximum of 4.5 times water depth.

Note 2: Normal trawl load data are not readily available. These data are from a single source, namely the NAM tests on the K7-FA-1/K8-FA-1 pipeline in 1984. These data relate to 1.1 tonne rectangular doors.

Note 3: The winches of the Scottish light trawler fleet are not generally fitted with load limiter devices. The loads stated in the table are, therefore, based on vessel bollard pulls.

11.13 TWIN RIG OTTER TRAWLING

Fishing practices are changing in some areas and vessels are being built for, or are converting to, twin rig otter trawling (Figure 9) which introduces a further type of gear to be considered, the clump weight.
There are numerous designs of clump weight being used. Figure 10 illustrates one of the designs commonly seen in the North Sea and Figure 11 illustrates a design commonly used West of Shetland. Other designs may present more severe profiles for both impact and pullover.
Figure 11
Morgere Clump Weight

11.14 REFERENCES

2. Recent investigations concerning the effect of bottom trawl-gear crossings on submarine pipeline integrity, Shell investigation 523300100, publication 786, January 1987.
3. Test report - the interaction of bottom fishing gear and pipelines (NAM K7-FA-1/K8-FA-1), Shell report 2915.02.3/4, May 84.
12. APPENDIX B  DENT TEST RESULTS

The following dent test results have been made available to the JIP.

12.1 PIPE 1

Table 8
Pipe configuration - pipe 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline OD</td>
<td>323.9mm</td>
</tr>
<tr>
<td>Pipeline wall thickness</td>
<td>14.3mm</td>
</tr>
<tr>
<td>Pipeline SMYS</td>
<td>413 MPa</td>
</tr>
<tr>
<td>Exterior coating</td>
<td>3mm PP</td>
</tr>
<tr>
<td>Internal pressure</td>
<td>151.3 barg</td>
</tr>
</tbody>
</table>

Table 9
Test results - pipe 1

<table>
<thead>
<tr>
<th>Test number</th>
<th>Indentor energy (kJ)</th>
<th>Dent depth (mm)</th>
<th>Dent depth (% of OD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.6</td>
<td>6</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>24.6</td>
<td>8.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Notes on pipe 1 results

1. A 12 metre section of pipe was tested by dropping a weight vertically onto it. The pipe was bedded into sand for the test.
2. An accumulator was attached to the pressurised pipe to prevent hydraulic lock.

12.2 PIPE 2

Table 10
Pipe configuration - pipe 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline OD</td>
<td>323.9mm</td>
</tr>
<tr>
<td>Pipeline wall thickness</td>
<td>14.3mm</td>
</tr>
<tr>
<td>Pipeline SMYS</td>
<td>413 MPa</td>
</tr>
<tr>
<td>Exterior coating</td>
<td>3mm PP</td>
</tr>
<tr>
<td>Internal pressure</td>
<td>20 barg</td>
</tr>
</tbody>
</table>
Table 11
Test results - pipe 2

<table>
<thead>
<tr>
<th>Test number</th>
<th>Indenter energy (kJ)</th>
<th>Dent depth (mm)</th>
<th>Dent depth (% of OD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34.4</td>
<td>7</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>34.4</td>
<td>8</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>24.6</td>
<td>16</td>
<td>4.9</td>
</tr>
<tr>
<td>4</td>
<td>14.8</td>
<td>16</td>
<td>4.9</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>16</td>
<td>4.9</td>
</tr>
<tr>
<td>6</td>
<td>34.4</td>
<td>12</td>
<td>3.7</td>
</tr>
<tr>
<td>7</td>
<td>24.6</td>
<td>6</td>
<td>1.8</td>
</tr>
<tr>
<td>8</td>
<td>19.6</td>
<td>4</td>
<td>1.2</td>
</tr>
<tr>
<td>9</td>
<td>14.8</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>10</td>
<td>9.8</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>11</td>
<td>5</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>12</td>
<td>34.4</td>
<td>7.5</td>
<td>2.3</td>
</tr>
<tr>
<td>13</td>
<td>24.6</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>14</td>
<td>19.6</td>
<td>7</td>
<td>2.1</td>
</tr>
<tr>
<td>15</td>
<td>14.8</td>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>16</td>
<td>9.8</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>17</td>
<td>5</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>18</td>
<td>5</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>19</td>
<td>14.8</td>
<td>5.5</td>
<td>1.7</td>
</tr>
<tr>
<td>20</td>
<td>24.6</td>
<td>12.5</td>
<td>3.8</td>
</tr>
<tr>
<td>21</td>
<td>34.4</td>
<td>16</td>
<td>4.9</td>
</tr>
<tr>
<td>22</td>
<td>34.4</td>
<td>14</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Notes on pipe 2 results

1. A 12 metre section of pipe was tested by dropping a weight vertically onto it. The pipe was bedded onto sand for the test.
2. An accumulator was attached to the pressurised pipe to prevent hydraulic lock.
3. Tests 2 to 5 were repeated impacts at the same location, with decreasing impact energies. The total dent depth after each impact is noted.
4. Tests 18 to 21 were repeated impacts at the same location, with increasing impact energies. The total dent depth after each impact is noted.

12.3 PIPE 3

Table 12
Pipe configuration - pipe 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline OD</td>
<td>168.3mm</td>
</tr>
<tr>
<td>Pipeline wall thickness</td>
<td>11.0mm</td>
</tr>
<tr>
<td>Pipeline SMYS</td>
<td>413 MPa</td>
</tr>
<tr>
<td>Exterior coating</td>
<td>0.5mm FBE</td>
</tr>
<tr>
<td>Internal pressure</td>
<td>0 barg</td>
</tr>
</tbody>
</table>
Table 13
Test results - pipe 3

<table>
<thead>
<tr>
<th>Test number</th>
<th>Indentor energy (kJ)</th>
<th>Dent depth (mm)</th>
<th>Dent depth (% of OD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38</td>
<td>4</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>3.5</td>
<td>2.1</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Notes on pipe 3 results
1. A 12 metre section of pipe was tested by dropping a weight vertically onto it. The pipe was bedded into sand for the test.

12.4 PIPE 4

Table 14
Pipe configuration - pipe 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline OD</td>
<td>219.1mm</td>
</tr>
<tr>
<td>Pipeline wall thickness</td>
<td>18.3mm</td>
</tr>
<tr>
<td>Pipeline SMYS</td>
<td>413 MPa</td>
</tr>
<tr>
<td>Exterior coating</td>
<td>0.5mm FBE</td>
</tr>
<tr>
<td>Internal pressure</td>
<td>0 barg</td>
</tr>
</tbody>
</table>

Table 15
Test results - pipe 4

<table>
<thead>
<tr>
<th>Test number</th>
<th>Indentor energy (kJ)</th>
<th>Dent depth (mm)</th>
<th>Dent depth (% of OD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Notes on pipe 4 results
1. A 12 metre section of pipe was tested by dropping a weight vertically onto it. The pipe was bedded into sand for the test.

12.5 PIPE 5

Table 16
Pipe configuration - pipe 5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline OD</td>
<td>273.1mm</td>
</tr>
<tr>
<td>Pipeline wall thickness</td>
<td>20.6mm</td>
</tr>
<tr>
<td>Pipeline SMYS</td>
<td>413 MPa</td>
</tr>
<tr>
<td>Exterior coating</td>
<td>45mm 4 layer PP</td>
</tr>
<tr>
<td>Internal pressure</td>
<td>0 barg</td>
</tr>
</tbody>
</table>
Table 17
Test results - pipe 5

<table>
<thead>
<tr>
<th>Test number</th>
<th>Indentor energy (kJ)</th>
<th>Dent depth (mm)</th>
<th>Dent depth (% of OD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Notes on pipe 5 results
1. A 12-metre section of pipe was tested by dropping a weight vertically onto it. The pipe was bedded into sand for the test.

12.6 PIPE 6

Table 18
Pipe configuration - pipe 6

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pipeline OD</td>
<td>406.4mm</td>
</tr>
<tr>
<td>pipeline wall thickness</td>
<td>19.1mm</td>
</tr>
<tr>
<td>pipeline SMYS</td>
<td>413 MPa</td>
</tr>
<tr>
<td>exterior coating</td>
<td>none</td>
</tr>
<tr>
<td>internal pressure</td>
<td>0 barg</td>
</tr>
</tbody>
</table>

Table 19
Test results - pipe 6

<table>
<thead>
<tr>
<th>Test number</th>
<th>Indentor energy (kJ)</th>
<th>Dent depth (mm)</th>
<th>Dent depth (% of OD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.7</td>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>17.4</td>
<td>8</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>12.8</td>
<td>5.4</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>8.9</td>
<td>3.6</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>5.7</td>
<td>1.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Notes on pipe 6 results
1. A section of pipe was tested in a pendulum form of impact rig. The pipe was supported directly behind the impact point using a highly reinforced block of concrete fastened to the laboratory floor.
13. APPENDIX C FATIGUE ASSESSMENT OF DENTS

13.1 FOWLER'S METHOD

In order to quantify the fatigue resulting from a dent, we refer to work performed by Fowler. Fowler developed a range of stress concentration factors for various depths of dent in pipe. Figure 12, Figure 13 and Figure 14 present the results developed for the range of typical pipeline D/t ratios, mean operating pressures and dent depths up to 10%. The maximum dent depth occurring during impact (ie ignoring push-out due to internal pressure) should be used in conjunction with these graphs.

![Graph showing stress concentration factors for various dent depths.](image)

**Figure 12**

Stress/internal pressure ratios for plain dents operating at 500psi (3.45 MPa)
Figure 13
Stress/internal pressure ratios for plain dents operating at 1000psi (6.90 MPa)

Figure 14
Stress/internal pressure ratios for plain dents operating at 1500psi (10.35 MPa)

Fowler's work included the testing of dents in girth and seam welds. The fatigue life of dents in longitudinal welds did not differ significantly from plain dents in the pipe away from welds. Dents in girth welds, however, were seen to have fatigue lives reduced to as low as 9% of that of the plain dents in the pipe body.
The fatigue life for a dent can be calculated using Miner’s rule in conjunction with a suitable S-N curve. Fowler concluded that the DOE B curve gave the best correlation with test data whilst still being conservative. The B curve gives the number of cycles \( N \) to failure for a given stress range \( \Delta \sigma \) (MPa) as:

\[
\log N = 15.006 - 4 \cdot \log \Delta \sigma
\]

The stress range \( \Delta \sigma \) is to include the effects of stress concentration and should be determined from the graphs above.

In considering dents on a girth weld the number of cycles to failure should be reduced as follows:

\[
N_{\text{weld}} = 0.09 \cdot N
\]

The accumulated fatigue damage \( D_{\text{fatigue}} \) is given by:

\[
D_{\text{fatigue}} = \sum_{i=1}^{k} \frac{n(\Delta \sigma_i)}{N(\Delta \sigma_i)}
\]

where \( k \) is the number of stress bands, \( n(\Delta \sigma_i) \) is the number of cycles within the stress range band \( \Delta \sigma_i \), and \( N(\Delta \sigma_i) \) is the number of cycles to give failure for stress range \( \Delta \sigma_i \).

### 13.2 ALLOWABLE FATIGUE DAMAGE

In line with standard practice for fatigue damage at a location that does not have access for inspection, the allowable fatigue damage is 0.1.

### 13.3 ALTERNATIVE METHODS

Alternative methods may be used for the derivation of stress concentration factors. If alternative methods are used, the fatigue life should be assessed using the DOE F2 curve, unless physical tests have been performed that show a safe correlation with a less conservative curve. The F2 curve allows for weld toe defects and therefore no further reduction in determined fatigue life is required for dents on welds.
14. APPENDIX D EXAMPLE ANALYSIS

The use of the guidelines is illustrated here by the following example.

14.1 PIPELINE DATA

The example is of a 10" production flowline with the following properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pipeline OD</td>
<td>273.1mm</td>
</tr>
<tr>
<td>pipeline wall thickness</td>
<td>20.6mm</td>
</tr>
<tr>
<td>corrosion allowance</td>
<td>5.5mm</td>
</tr>
<tr>
<td>pipeline SMYS</td>
<td>413 MPa</td>
</tr>
<tr>
<td>exterior coating</td>
<td>45mm, 4 layer PP</td>
</tr>
<tr>
<td>mean contents temperature</td>
<td>55°C</td>
</tr>
<tr>
<td>ambient temperature</td>
<td>3°C</td>
</tr>
<tr>
<td>design pressure</td>
<td>25.7 MPa</td>
</tr>
<tr>
<td>ambient pressure</td>
<td>1.4 MPa</td>
</tr>
</tbody>
</table>

14.2 FIRST PASS FILTER

The pipeline has a thick insulation coating, and so it passes the first condition. It fails the other two conditions however, since a fishing study has shown that beam trawling will occur in the area, and it is operating at a temperature of over 50°C. Further investigation is therefore required to see if the pipeline may be left untrencched.

14.3 FURTHER ANALYSIS

14.3.1 Denting due to impact

Since the pipe has a thick foam coating, it is protected from impact damage and no further analysis is needed for denting. However, for the purposes of illustration, denting will be considered further.

A fishing study of the area has given the types of fishing gear that are likely to strike the pipeline. Pullover force/time histories are computed for these gear types using the Trenching Guidelines JIP pullover model. This model also computes the impact energies, and the highest computed energy, in this case 24.5 kJ for a beam trawl impact.

Since this is a beam trawl and will impact the pipeline at two locations, we use two thirds of this value as the energy in one impact. The denting energy is then 50% of this impact energy, a value of 8.2 kJ.

We use the Ellinas and Walker equation for predicting dent depth. This calculation shows that the predicted dent depth is 4.0% of pipeline OD, and that the D/t ratio is 13. The acceptable dent depth is 4%, so this pipeline could be left untrenched and uncoated.
For a degree of extra comfort, Appendix B. Dent test results, pipe 5 was similar to the above pipe except with a 38 kJ impact energy rather than 24.5 kJ, and there was no measurable dent.

### 14.3.2 Pullover and lateral buckling

Pullover force/time histories are computed for a range of trawl gear types and for the pipeline on the seabed and spanning. The worst case force time history is selected, in this case it occurs for a 5.28 tonne beam trawl at 5 knots, pulling over the pipeline at a span height of one pipeline diameter.

<table>
<thead>
<tr>
<th>Table 21</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Worst case pipeline impulses</strong></td>
</tr>
<tr>
<td>Span height</td>
</tr>
<tr>
<td>100 %</td>
</tr>
</tbody>
</table>

A finite element model of the pipeline is then constructed and used to analyse the lateral buckling of the pipeline followed by the pullover of the beam trawl. In this case ABAQUS is used for the analysis and the input deck is given below.

The results of the analyses are shown below.

<table>
<thead>
<tr>
<th>Table 22</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Results of pullover analysis</strong></td>
</tr>
<tr>
<td>Gear type</td>
</tr>
<tr>
<td>5.28 tonne beam</td>
</tr>
</tbody>
</table>

The strains in the pipe due to the combination of lateral buckling and pullover need to satisfy the following

\[
\frac{1.3e_{bc}}{e_{bc}} + \frac{P}{P_e} + \left( \frac{P_c}{P_{se}} \right)^n \leq 1 \quad \text{where}
\]

\[e_{bc} = \text{bending strain}
\]

\[e_{bc} = \text{critical bending strain} = 15 \left( \frac{t}{D} \right)^2
\]

\[P = \text{external overpressure}
\]

\[P_e = \text{characteristic pressure to cause hydrostatic collapse given by :}
\]

\[
\left( \frac{P_e}{P_c} \right) - 1 \left( \frac{P_c}{P_y} \right)^2 - 1 = 2 \cdot \frac{P_c}{P_y} \cdot \left( \frac{f_y \cdot D}{t} \right)
\]

\[P_e = \frac{2 \cdot E}{(1 - \nu^2)} \left( \frac{t}{D} \right)^3
\]

\[P_y = 2 \cdot \sigma_y \cdot \frac{t}{D}
\]
\( F_x = \) local axial compressive force (= 0 if tensile)
\( F_{se} = \) critical axial compressive force = \( \pi \cdot (D - t) \cdot t \cdot \sigma_y \\
\( n = 1 + 300 \cdot \frac{t}{D} \)

\( D = \) outside diameter
\( t = \) nominal wall thickness
\( E = \) Elastic modulus
\( \nu = \) Poisson's ratio
\( \sigma_y = \) yield stress
\( f_b = \) the initial ovalisation of the pipe cross section

In this case there is no external overpressure and so we have the following

\( \varepsilon_x = 0.65\% \)
\( \varepsilon_{bc} = 8.53\% \)
\( F_x = 828 \text{ kN} \)
\( F_{se} = 6749 \text{ kN} \)
\( n = 23.63 \)

so we calculate:

\[
\frac{1.3 \varepsilon_b}{\varepsilon_{bc}} + \left( \frac{F_x}{F_{se}} \right)^n = 0.099
\]

This is less than unity and so is acceptable.

### 14.3.3 Hooking

Two analyses need to be done. The first is for the initial snagging load, and in this case the force is computed to be 686.5 kN. This exceeds the tensile capacity of the warp, which in this case is 608.2 kN. This lower force is then used for the initial snagging load, and is applied at the appropriate angle to the horizontal. The bending strain computed by FE analysis for this load is 1.1\%, and the critical bending strain is 8.53\%. We then compute:

\[
\frac{1.1\%}{8.53\%} = 0.13
\]

Since this is less than unity, the strain is acceptable.

The second analysis is of a vertical pull of the pipeline by half the length of the largest otterboard that may become trapped under the pipeline. In this case the required lifting height is 2 metres. The analysis shows that in this case the peak bending strain in the pipeline is 0.15\%, and so the strain is acceptable.
15. APPENDIX E FE ANALYSIS INPUT DECKS

The following ABAQUS input decks are reproduced below

SH01F03A-01A  Lateral buckling analysis of 10" pipe
SH01F03A-02A  2 metre vertical pull due to hooking of 10" pipe
SH01F03A-03A  Inclined pull of 602.2 kN due to hooking of 10" pipe
SH01F03A-04A  Pullover analysis of 10" pipe

15.1 LATERAL BUCKLING ANALYSIS

** TREVOR JEE ASSOCIATES
** ABAQUS INPUT FILE
** PIPELINE LATERAL BUCKLING AND PULLOVER ANALYSIS
******************************************************************************

** TRENCHING GUIDELINES JIP
** NON-TRENCHING STUDY EXAMPLE ANALYSIS
** PIPELINE: 10" RIGID FLOWLINE
** CASE: 5.28 TONNE BEAM TRAWL AT 5 KNOTS, 55 DEGREES CONTENTS
** TEMPERATURE
******************************************************************************

** CALCULATION NO.: SH01F03A
** CASE NO.: 01A
******************************************************************************

** REVISION: A
** BY:
**
** CHECKED:
**
** DATE
******************************************************************************

**
** GENERAL
**
*heading
** Next line is a title, which will appear on all output
PIPELINE LATERAL BUCKLING AND PULLOVER ANALYSIS - SH01F03A/01A
** restart, write will create a RES file - post-processing
  *restart,write,overlay
**

** MODEL DEFINITION
**
*node
  1,  0.0, 0.0, 0.0
  61, 1500.0, 0.0, 0.0
  81, 1700.0, 0.0, 0.0
  121, 1800.0, 0.0, 0.0
  371, 2050.0, 0.0, 0.0
  411, 2150.0, 0.0, 0.0
  461, 2650.0, 0.0, 0.0
  511, 2775.0, 0.0, 0.0
  636, 2900.0, 0.0, 0.0
*ngen, nset=pipen
  1, 61
  61, 81
  81, 121

51
121, 371
371, 411
411, 461
461, 511
511, 636
*nset, nset=init
636
*element, type=pipe31, elset=pipel
1, 1, 2
*elgen, elset=pipel
1, 635
*elset, elset=init
635
*elset, elset=beams
629, 630
** Rigid surface nodes
*node
9000, 0.0, 0.0, 0
9001, -0.5e3, -0.5e3, 0
9002, +0.5e3, -0.5e3, 0
9003, +0.5e3, +0.5e3, 0
9004, -0.5e3, +0.5e3, 0
*element, type=r3d4, elset=seabed
9001, 9002, 9003, 9004
*rigid body, ref=9000, elset=seabed
** Contact definitions
*contact node set, name=pipac
papen,
*contact definition, name=seabedc
seabed,spos
*contact pair, interaction=mud
pipac, seabedc
**
******************************************************************************
** PIPELINE MATERIAL INPUT DATA
**
*beam section, elset=pipel, section=pipe, material=steel
** Outer Rad, wall thickness
0.13653, 0.0206
*material, name=steel
*elastic
** Young's Modulus, Poisson's Ratio
207.0e9, 0.3
*density
** Effective density of linepipe (taking account of coatings and contents)
12350
*plastic
** SMYS at zero plastic strain
413e6, 0.0
** Second point defining plastic stress strain relationship
517e6, 0.24
*expansion
** Coefficient of thermal expansion
1.17e-5,
**
** SEABED/ENVIRONMENTAL PROPERTIES
**
*surface interaction, name=mud
*friction, anisotropic
** Axial friction coefficient, Lateral friction coefficient
0.65,0.65
*surface behavior, softened
0.03,200.0
*aqua
** Seabed reference level, sea surface level, gravity constant, density of sea water
-0.1,130,9.81,1025
**
** PULOVER LOADS
**
** amplitude of force functions
** time (seconds) v proportion of peak load
** horizontal load
*AMPLITUDE, NAME=PULSE1
 0.0,0.0, 1.125,1.0, 1.425,0.0, 4.0,0.0
** vertical load
*AMPLITUDE, NAME=PULSE2
 0.0,0.0, 0.975,-1.08, 1.275,1.0, 1.425,0.0
 4.0,0.0
**
** LOADING HISTORY DEFINITION
**
** FIRST STEP - APPLY GRAVITY
*step,nlgeom,unsymm=yes,inc=20
*static
0.2,1.0
*boundary
 1, encastré
 636, xsymm
 4, pipen
9000, encastré
*load
** gravity, acting in -ve Z, adjusted to allow for buoyancy
  pipel, grav, 4.621,0.0,0.0,0.0,-1.0
*node print,f=0
*el print, f=0
*el file, f=0
*node file, f=0
*monitor, dof=2, node=636
*endstep
**
** SECOND STEP - APPLY DEFLECTION
*step,nlgeom,unsymm=yes,inc=50
*static
0.2,1.0,1.0e-6
** put in initiator for lateral buckle
*boundary,op=mod
  616,2,0.003
  617,2,0.011
  618,2,0.025
  619,2,0.043
  620,2,0.067
  621,2,0.094
  622,2,0.125
  623,2,0.159
  624,2,0.194
  625,2,0.231
  626,2,0.269
  627,2,0.306
628.2, 0.341
629.2, 0.375
630.2, 0.406
631.2, 0.433
632.2, 0.457
633.2, 0.475
634.2, 0.489
635.2, 0.500

*node print,f=0
*el print,f=0
*node file,f=1,nset=init
U
*el file,f=1,elset=beams
S,E
SE
*el file,f=1,elset=init
S,E
SE
*endstep
**

** THIRD STEP - RELEASE DEFLECTION **
*step, nlgeom, unsymm=yes, inc=50
*static
0.10, 1.0, 1.0e-5
*bound, op=new
1, encastre
636, xsymm
pencil, 4
9000, encastre
*node print,f=0
*el print,f=0
*node file,f=1,nset=init
U
*el file,f=1,elset=beams
S,E
SE
*el file,f=1,elset=init
S,E
SE
*endstep
**

** FOURTH STEP - APPLY PRESSURE **
*step, nlgeom, unsymm=yes, inc=50
*static
0.20, 1.0, 1.0e-6
*load
** Net internal pressure, 24.3e6 acting on ID
pencil, pl, 24.30e6, 0.23185
*node print,f=0
*el print,f=0
*node file,f=1,nset=init
U
*el file,f=1,elset=beams
S,E
SE
*el file,f=1,elset=init
S,E
SE
*endstep
**
** FIFTH STEP - RAISE TEMPERATURE
**
*step,ntgeom,unsym=y,inc=5000
*static,rik
0.05,1.0,1.0e-8,1.0
** Raise all nodes to 55 degrees (52 above ambient)
*temperature,op=mod
piper, 52.0
*node print,f=0
*el print,f=0
*node file,f=1,nset=init
U
*el file,f=1,elset=beams
S,E
SE
*el file,f=1,elset=init
S,E
SE
*endstep

15.2 VERTICAL PULL

** TREVOR JEE ASSOCIATES
** ABAQUS INPUT FILE
** PIPELINE HOOKING ANALYSIS
******************************************************************************************
** Trenching Guidelines JIP
** Study of vertical pull due to hooking
** CASE: 2.0 metre vertical pull
******************************************************************************************
** CALCULATION NO.: SH01F03A
** CASE NO.: 02A
******************************************************************************************
** REVISION: A
** BY:
**
** CHECKED:
**
** DATE
******************************************************************************************
**
** GENERAL
**
*heading
** Next line is a title, which will appear on all output
PIPELINE HOOKING ANALYSIS - VERTICAL PULL OF 2 METRES
** restart, write will create a RES file - post-processing
*restart,write,overlay
**
** MODEL DEFINITION
**
*node
1, 0.0, 0.0, 0.0
61, 1500.0, 0.0, 0.0
81, 1700.0, 0.0, 0.0, 0.0
121, 1800.0, 0.0, 0.0, 0.0
371, 2050.0, 0.0, 0.0, 0.0
411, 2150.0, 0.0, 0.0, 0.0
461, 2650.0, 0.0, 0.0, 0.0
511, 2775.0, 0.0, 0.0, 0.0
636, 2800.0, 0.0, 0.0, 0.0
*ngen
1, 61
61, 81
81, 121
121, 371
371, 411
411, 461
461, 511
511, 636
*nset, nset=init
636
*nset, nset=pipen, generate
1, 635, 1
*element, type=pipe31, elset=pipen
1, 1, 2
*elgen, elset=pipen
1, 635
*elset, elset=init
635
**
** Rigid surface nodes
*node
9000, 0.0, 0.0, 0.0
9001,-0.5e3, -0.5e3, 0
9002,+6.5e3, -0.5e3, 0
9003,+6.5e3, +6.5e3, 0
9004,-0.5e3, +6.5e3, 0
*element, type=3d4, elset=seabed
9001,9002,9003,9004
*rigid body, ref=9000, elset=seabed
** Contact definitions
*contact node set, name=pipec
pipen,
*surface definition, name=seabedc
seabed,spos
*contact pair, interaction=mud
pipec, seabedc
**
 **********************************************************************************************************************************************************************************

** PIPELINE MATERIAL INPUT DATA
**
*beam section, elset=pipen, section=pipe, material=steel
** Outer Rad, wall thickness
0.13853, 0.0206
*material, name=steel
*elastic
** Young's Modulus, Poisson's Ratio
207.0e9, 0.3
*density
** Effective density of linepipe (taking account of coatings and contents)
12350,
*plastic
** SMYS at zero plastic strain 
413E6,0.0 
** Second point defining plastic stress strain relationship 
517E6,0.24 
** 
** SEABED/ENVIRONMENTAL PROPERTIES 
** 
*surface interaction, name=mud 
*friction, anisotropic 
** Axial friction coefficient, Lateral friction coefficient 
0.85,0.85 
*surface behavior, softened 
0.03,200.0 
** 
*AQUA 
**Seabed reference level, sea surface level, gravity constant, density of sea water 
-0.1, 130, 9.81, 1025 
** 
**LOADING HISTORY DEFINITION 
** 
** FIRST STEP - APPLY GRAVITY 
*step, nlgeom, unsymm=yes, inc=20 
*static 
0.11,1.0 
*battery 
1, encastr 
636, xsymm 
636, 2 
pipen, 2 
pipen, 4 
9000, encastr 
*dload 
** gravity, acting in -ve Z, adjusted to allow for buoyancy 
pipel,grav,4.621,0.0,0.0,0.0,-1.0 
*node print,f=0 
*el print,f=0 
*el file,f=1,elset=init 
S,PE 
*monitor, dof=3, node=636 
*endstep 
** 
** SECOND STEP - APPLY PRESSURE 
** 
*step, nlgeom, unsymm=yes, inc=50 
*static 
0.20,1.0,1.0e-6 
*dload 
** Internal pressure, 24.30e6 acting on ID 
pipel,pi,24.30e6, 0.23185 
*node print,f=0 
*el print,f=1,elset=init 
E 
*node file,f=1,nset=init 
U 
*el file,f=1,elset=init 
S,PE 
*endstep 
** 
** THIRD STEP - LIFT VERTICALLY BY 2.0 METRES
15.3 INCLINED PULL

** TREVOR JEE ASSOCIATES
** ABAQUS INPUT FILE
** PIPELINE HOOKING ANALYSIS

** Trenching Guidelines JIP
** Study of pull due to hooking
** CASE: inclined pull of 602.2 kN

** CALCULATION NO.: SH01F03A
** CASE NO.: 03A

** REVISION: A
** BY:
**
** CHECKED:
**
** DATE

** GENERAL
**
heading
** Next line is a title, which will appear on all output
PIPELINE HOOKING ANALYSIS - INCLINED PULL OF 602.2 kN
** restart, write will create a RES file - post-processing
*restart,write,overlay
**
** MODEL DEFINITION
**
*node
  1, 0.0, 0.0, 0.0
  61, 1500.0, 0.0, 0.0
  81, 1700.0, 0.0, 0.0
  121, 1800.0, 0.0, 0.0
  371, 2050.0, 0.0, 0.0
  411, 2150.0, 0.0, 0.0
  461, 2650.0, 0.0, 0.0
  511, 2775.0, 0.0, 0.0
  636, 2900.0, 0.0, 0.0
*ngeo
1, 81
61, 81
81, 121
121, 371
371, 411
411, 461
461, 511
511, 636
*nset, nset=init
636
*nset, nset=pipeg, generate
1,635,1
*element, type=pipe31, elset=pipeg
1, 1, 2
*elgen, elset=pipeg
1,635
*elset, elset=init
635
**
** Rigid surface nodes
*node
9000, 0.0, 0.0, 0
9001,-0.5e3, -0.5e3, 0
9002,+0.5e3, -0.5e3, 0
9003,+0.5e3, +0.5e3, 0
9004,-0.5e3, +0.5e3, 0
*element, type=r3d4, elset=seabed
9001,9001,9002,9003,9004
trigid body, ref=9000, elset=seabed
** Contact definitions
*contact node set, name=pipc
piper,
*surface definition, name=seabedc
seabed,spos
*contact pair, interaction=mud
piper, seabedc
**
************************************************************************************************************************************
** PIPELINE MATERIAL INPUT DATA
**
*beam section, elset=pipeg, section=pipe, material=steel
** Outer Rad, wall thickness
0.13853, 0.0206
*material, name=steel
*elastic
** Young's Modulus, Poisson's Ratio
207.0e9,0.3
*density
** Effective density of linepipe (taking account of coatings and contents)
12350,
*plastic
** SMYS at zero plastic strain
413E6,0.0
** Second point defining plastic stress strain relationship
517E8,0.24
**
** SEABED/ENVIRONMENTAL PROPERTIES
**
*surface interaction, name=mud
*friction, anisotropic
** Axial friction coefficient, Lateral friction coefficient
0.85, 0.85
*surface behavior, softened
0.03, 200.0
**
*AQUA
** Seabed reference level, sea surface level, gravity constant, density of sea water
-0.1, 130, 9.81, 1025
**
**LOADING HISTORY DEFINITION
**
** FIRST STEP - APPLY GRAVITY
*step, nlgeom, unsymm=yes, inc=20
*static
0.05, 1.0
*boundary
1, encastre
636, xsymm
pipe, 4
9000, encastre
*dload
** gravity, acting in -ve Z, adjusted to allow for buoyancy
pipe, grav, 4, 621, 0.0, 0.0, -1.0
*node print, f=0
*el print, f=0
*el file, f=1, elset=init
S, PE
*monitor, dof=3, node=636
*endstep
**
** SECOND STEP - APPLY PRESSURE
**
*step, nlgeom, unsymm=yes, inc=50
*static
0.20, 1.0, 1.0e-6
*dload
** internal pressure, 24.30e6 acting on ID
pipe, pl, 24.30e6, 0.23185
*node print, f=0
*el print, f=1, elset=init
E
*node file, f=1, nset=init
U
*el file, f=1, elset=init
S, PE
*endstep
**
** THIRD STEP - INCLINED PULL OF 602.2 kN
**
*step, nlgeom, unsymm=yes, inc=50
*static
0.001, 1.0, 1.0e-6
*dload
** half model, so half load
init, 2, 292.11e3
init, 3, 73.03e3
*node print, f=0
*el print, f=1, elset=init
15.4 PULLOVER

** TREVOR JEE ASSOCIATES
** ABAQUS INPUT FILE
** PIPELINE LATERAL BUCKLING AND PULLOVER ANALYSIS
*******************************************************************************
** TRENCHING GUIDELINES JIP
** NON-TRENCHING STUDY EXAMPLE ANALYSIS
** PIPELINE: 10" RIGID FLOWLINE
** CASE: 5.28 TONNE BEAM TRAWL AT 5 KNOTS, 55 DEGREES CONTENTS TEMPERATURE
*******************************************************************************
** CALCULATION NO.: SH01F03A
** CASE NO.: 04A
*******************************************************************************

** REVISION: A
** BY:
**
** CHECKED:
**
** DATE
*******************************************************************************

** GENERAL
**
*heading
** Next line is a title, which will appear on all output
PIPELINE LATERAL BUCKLING AND PULLOVER ANALYSIS - SH01F03A/04A
** restart, write will create a RES file - post-processing
*restart,write,overlay,read
**
** MODEL DEFINITION
**
*aqua
**Seabed reference level, sea surface level, gravity constant, density of sea water
-0.1, 130, 9.81, 1025
**
** PULLOVER LOADS
**
** amplitude of force functions
** time (seconds) y proportion of peak load
** horizontal load
*AMPLITUDE,NAME=PULSE1
0.0,0.0, 1.125,1.0, 1.425,0.0, 4.0,0.0
** vertical load
*AMPLITUDE,NAME=PULSE2
0.0,0.0, 0.975,-1.09, 1.275,1.0, 1.425,0.0
4.0,0.0
**
**LOADING HISTORY DEFINITION

61
** SIXTH STEP - APPLY PULLOVER LOADING **

*step,nlgeom,inc=5000
dynamic,haftol=500000.0
 0.01,4.0,0.1
cload,amp=pulse1
d30,2,84.7e3
cload,amp=pulse2
d30,3,-17.25e3
dload

** Added mass
pipe,fi,1,0.3641,3,29,2,29,
** Drag
pipe,fdd,1,0.3641,1,2,1,

*el file,f=1,elset=init
S,SINV,E
SE
*el file,f=1,elset=beams
S,SINV,E
SE
*node file,f=1,nset=init
U,V
*el print, freq=0
*node print, freq=0
*endstep
16. APPENDIX F TEST SPECIFICATION

16.1 SCOPE

This is a specification for impact testing of coated pipe in order to simulate the effects of trawl gear impact.

16.2 HAMMER

The hammer consists of a 2 to 5 tonne (steel/ballast) weight lifted vertically and dropped a height \( h \) given by:

\[ h = \frac{E}{mg} \]

where \( E \) is the impact energy, \( m \) is the mass of the hammer, and \( g \) is the acceleration due to gravity.

The impactor attached under the hammer has the following configuration:

- Width: 60 mm
- Breadth: greater than pipeline diameter
- Edges: 6 mm radius
- Height: 350 mm

16.3 PIPELINE CONFIGURATION

- 12m length, laid horizontally and 50% embedded in bed of wet compacted sand
- Each end loosely constrained to prevent gross movements of the pipe.
• At normal room temperature
• Rigid lines non-pressurised.
• Flexibles may need to be pressurised to minimum operating pressure in order to give representative results, in which case attach an accumulator to avoid hydraulic lock.

16.4 RECORDINGS

16.4.1 Prior to testing
• Wall thickness by ultrasonic thickness measurement at all impact locations
• Tensile yield strength tests in the axial and radial directions to be performed for each pipeline section.

16.4.2 During Impacting
• Record the hammer weight and height.
• Measure amount of hammer ‘bounce’ for each impact.
• Photograph damage after each impact.
• Profiles of steel in axial and hoop directions, showing dent depth, width and length.
• Diameter measurements of the pipeline at the dent and at 90° to the dent, before and after the impact.
• If pressurised, then, internal pressure versus time to pick up hydraulic lock.
17. APPENDIX G SUMMARY REPORT

17.1 EXECUTIVE SUMMARY

Traditionally all pipelines less than 16" diameter have been trenched in the North Sea. New guidelines have been developed by the Trenching Guidelines Joint Industry Project (JIP) to assist in evaluating the consequences of leaving pipelines exposed to trawl loads and to provide a rationale for leaving smaller lines untreched if it is safe and cost effective to do so. This report records the activities of the JIP, the steps taken in the development of the guidelines, the key decisions made and the reasons why.

Not only are there potential cost savings to be made from not trenching a small diameter pipeline but technical benefits can also result. This is particularly so with hot flowlines where the avoidance of upheaval buckling of buried pipelines may be difficult and costly.

The Trenching Guidelines JIP was set up with industry wide support from operators, design houses and the HSE. The JIP was set up with 2 principal objectives:

- To produce a set of design guidelines giving a safe and rational method for assessing whether pipelines need to be trenched.
- To promote the use of the guidelines in the North Sea.

These objectives identified the need for addressing not only the technical issues associated with introducing a change in design practices but also the 'people' issues.

To meet the first objective the JIP developed analytical methods for simulating the interaction of trawl gear on pipelines and criteria for assessing the acceptability of the resultant pipeline responses. The second objective required that the interfaces with regulatory bodies, other design codes and other users of the sea, specifically the fishing community, were considered and where necessary addressed.

These guidelines are being published by the HSE for general circulation.

17.2 INTRODUCTION

17.2.1 Purpose

This document summarises the work of the Trenching Guidelines JIP and the development of the 'Guidelines for trenching design of submarine pipelines', Trevor Jee Associates' report SH01R17B, October 1998. These guidelines are to be published by the HSE.

The purpose of this document is:
- to introduce the subject of trawl gear interaction analysis
- to help project managers understand whether analysis is required or appropriate for his project
- to help engineers understand the reasons behind the guidelines
- to provide hyperlinks to the JIP design documents and related information sources for detailed reference (electronic copy only).
17.2.2 Background

Trenching of subsea pipelines is employed to improve on-bottom stability and to provide protection against trawling activities. In the water depths typical of the central and northern North Sea trenching is rarely required for stability reasons but, with there being extensive fishing activity, trenching is used to provide protection. The loads that can be applied by fishing gear on untrenched pipelines can be substantial.

In the late 1960s and early 1970s all pipelines were trenched in the North Sea. This followed largely from the import of US technology from the Gulf of Mexico and was necessary in the shallow waters of the Southern North Sea to ensure stability. The first line not to be trenched was the Shell 36” FLAGS line in 1979. Shell demonstrated that in the deeper waters of the Northern North Sea the pipeline was stable and could resist the loads imposed by fishing gear. Indeed in 1980 the work was extended to include diameters down to 16”, with the recommendation that further work was needed to prove smaller diameters. In 1984 the UK Department of Energy guidelines seeded the perception of a 16” rule with the phrasing “The Pipelines Inspectorate will consider applications not to trench a pipeline provided that...the pipeline is at least 16” in diameter”. Whilst this was never law it resulted in virtually all pipelines less than 16” diameter being trenched for the next decade. The background of this research is described in detail in SH01R02C.

In 1995 Shell once again looked at the trenching situation and found that the pipelines market was moving towards many smaller fields with tie-backs of small diameter pipelines, some of which also had additional technical problems such as upheaval buckling if constrained. They therefore helped Trevor Dee Associates put together a Joint Industry Project with the vision that “the Oil Industry will be able to install subsea pipelines without trenching if it is safe and cost effective to do so”.

17.2.3 Trenching Guidelines JIP

The trenching guidelines Joint Industry Project (JIP) was set up with two principal objectives:

1. To produce a set of design guidelines giving a safe and rational method for assessing whether pipelines need to be trenched.

2. To promote the use of the guidelines in the North Sea.

The two objectives identified the need for addressing not only the technical issues associated with introducing a change in design practices but also the ‘people’ issues. The first objective required the development of new methods by which the interaction of trawl gear on pipelines could be analysed and the interaction loads and pipeline response to those loads could be predicted. The second objective required that the interfaces with regulatory bodies, other design codes and other users of the sea, specifically the fishing community, were considered and where necessary addressed.

The JIP attracted support from across the Industry as shown in Table 1 with technical contributions as shown in Table 24.
### Table 23

**Trenching Guidelines JIP Sponsors**

<table>
<thead>
<tr>
<th>Amerada Hess</th>
<th>Amoco</th>
<th>Arco British</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>Brown &amp; Root</td>
<td>Conoco</td>
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<tr>
<td>Elf</td>
<td>HSE</td>
<td>Exxon</td>
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<tr>
<td>McDermott</td>
<td>Mobil</td>
<td>Phillips</td>
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<tr>
<td>Shell</td>
<td>Snamprogetti</td>
<td>Texaco</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
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</tbody>
</table>

### Table 24

**Trenching Guidelines JIP Technical Contributors**

<table>
<thead>
<tr>
<th>Trevor Jee Associates</th>
<th>DNV</th>
<th>Brown &amp; Root</th>
</tr>
</thead>
<tbody>
<tr>
<td>McDermott Marine</td>
<td>Seafish Industry Authority</td>
<td>Andrew Palmer &amp; Associates</td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td>MCS</td>
</tr>
</tbody>
</table>

### 17.2.4 Documents

The following technical documents have been produced by the JIP.

### Table 25

**JIP documents**

<table>
<thead>
<tr>
<th>Report No.</th>
<th>Title</th>
<th>By</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH01R02C</td>
<td>Non-trenching of pipelines - Review of current North Sea position</td>
<td>TJA</td>
</tr>
<tr>
<td>SH01R04A</td>
<td>Trenching of submarine pipelines - Guidelines for trenching design</td>
<td>TJA</td>
</tr>
<tr>
<td>SH01R05A</td>
<td>Fishing issues associated with non-trenching of subsea pipelines</td>
<td>TJA</td>
</tr>
<tr>
<td>SH01R06A</td>
<td>Pullover analytical model - predicting trawl gear motion and pipeline response</td>
<td>TJA</td>
</tr>
<tr>
<td>SH01R07A</td>
<td>Trawl gear impact study - effects on coated and non-coated pipelines</td>
<td>TJA</td>
</tr>
<tr>
<td>SH01R08B</td>
<td>Sensitivity study - Risks and costs of non-trenched pipelines</td>
<td>TJA</td>
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<tr>
<td>SH01R10A</td>
<td>Fishing equipment - Typical configurations, parameters and behaviour</td>
<td>TJA</td>
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<td>SH01R11A</td>
<td>Pullover loads - Interaction of trawl board with flexing pipe</td>
<td>TJA</td>
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<tr>
<td>SH01R12A</td>
<td>Review of pipeline survey data - A reality check of pipeline response to trawl gear interactions</td>
<td>TJA</td>
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<td>SH01R13A</td>
<td>Look-up table of bending strains - Pipe response to pullover loads</td>
<td>TJA</td>
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<tr>
<td>SH01R14A</td>
<td>Impact testing specification</td>
<td>TJA</td>
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<tr>
<td>SH01R15A</td>
<td>Go no-go filter</td>
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<td>SH01R17B</td>
<td>Guidelines for trenching design of submarine pipelines</td>
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<td>SH01R18A</td>
<td>Acceptance criteria for trenching guidelines</td>
<td>TJA</td>
</tr>
<tr>
<td>1273.04/01</td>
<td>Verification report for risk and cost model</td>
<td>APA</td>
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<tr>
<td>618.11.2/R1</td>
<td>Lateral buckling</td>
<td>APA</td>
</tr>
<tr>
<td>N0411</td>
<td>Report on flume tank trials of trawl door pull-over</td>
<td>McD</td>
</tr>
<tr>
<td>2-1-4-080</td>
<td>Trenching study for flexible pipe</td>
<td>MCS</td>
</tr>
<tr>
<td>97-3481 r02</td>
<td>Acceptance criteria</td>
<td>DNV</td>
</tr>
<tr>
<td>R-B&amp;R-TJA-001</td>
<td>Trawl gear hooking interaction assessment</td>
<td>B&amp;R</td>
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</tbody>
</table>
17.2.5 Acknowledgement
We would like to thank BP Exploration, Shell UK Exploration and Production and Amoco (UK) Exploration Company for their kind funding of this summary report.

17.2.6 This report
The remainder of this report addresses the following topics
• Interaction of trawl gear and pipelines
• Interfaces between the oil and fishing industries
• Approach, scope and structure of guidelines
• Development of the interaction models
• Development of acceptance criteria
• Validation of the models
• The application of risk analysis to trenching design
• The way forward.

17.3 TRAWL GEAR INTERACTION
Whilst offering various technical and cost benefits, leaving a small diameter pipeline on the surface of the seabed rather than trenching or burying it does expose the pipeline to loads from demersal trawl gear. These loads can be substantial.

17.3.1 Trawl practices and gear
There are two main types of demersal trawling practised in the North Sea, namely, beam trawling and otter trawling. Briefly:

• Beam trawling is employed for the capture of flat fish and uses a steel beam to hold the net open. The beam is held off the seabed at each end by a skid-like shoe assembly.
• Otter trawling is employed for the capture of round fish and the net is held open by two otter doors which use a combination hydrodynamic force and friction with the seabed to create a spreading force on the mouth of the net. Otter trawling may also employ a central clump weight if two nets are being towed by a single vessel, ie twin-rig otter trawling.

17.3.2 Loads
When crossing a pipeline the loading exerted by trawl gear on the pipeline is considered in two phases:

• an initial impact loading as the gear first contacts the pipeline
• a pullover force as the trawl door or beam is pulled over the top of the pipeline. The pipeline response may be amplified by locked-in thermal loads.

In some circumstances, a further type of loading could result if the gear were to snag or hook on the pipeline rather than cross it. In this condition a significant sustained loading could be applied as the vessel attempted to haul its gear free of the pipeline. This loading could greatly exceed the pullover load expected during a normal crossing of the pipeline.

17.3.3 Consequences
The potential consequences of the above loadings on small diameter pipelines would be:
• **Impact** The initial hammer blow could cause a dent in the pipe wall. In the extreme case, this could impede the passage of pigs, or cause a stress concentration leading to a fatigue failure due to operational cycles.

• **Pullover** Forces as the trawl board or beam is pulled over the top of the pipe could lead to displacement of the line, and bending at the point of contact. This could result in yielding of the line pipe and, in the extreme case, could lead to a local buckle.

• **Hooking** Hooking of a trawl door or beam under a pipeline could initially result in the large lateral deflection of the pipeline. If bought to rest by the hooking, the fishing vessel could fall back and exert a large vertical load on the pipeline whilst attempting to haul the gear free. Both of these occurrences could lead to yielding of the pipeline in bending and ultimately to local buckling.

The project was therefore concerned with developing methods by which the interaction of trawl gear on pipelines could be analysed and the loads and pipeline response could be predicted. During the course of the project other related technical issues, such as lateral buckling, were identified and addressed. Acceptance criteria and filters were developed and design guidelines produced.

### 17.4 FISHING ISSUES

#### 17.4.1 Fishermen’s views

From the beginning, the JIP recognised the importance of persuading people and taking their views into account in order to translate technical solutions into accepted practice. The JIP therefore sought to obtain and consider the views of the fishermen, the other users of the sea with whom the oil and gas community principally interacts. As an early activity, the main fishermen associations were contacted to establish their views on the trenching guidelines, to identify any problem issues, and to recommend solutions (see *Fishing issues associated with non-trenching of subsea pipelines*, SH01R05A). Whilst this initial study considered some of the wider issues of concern to the fisherman, the main issues relating to the non-trenching of pipelines are summarised in the following.

**Organisations**

There are two main organisations who represent the majority of UK fishermen between them, namely the Scottish Fishermen’s Federation (SFF) representing the fishermen out of the Scottish, Shetland and Hebridean ports and the National Federation of Fishing Organisations (NFFO) representing the English and Welsh fishermen.

Normally the fishing organisations would deal with individual oil companies via the oil companies’ fishing liaison officers. In general they have built up a good rapport and relationship with these officers. For broader issues (such as abandonment), they deal with the oil industry via the UKOOA Fishing Liaison Committee. The general feeling is that there is a good relationship between the fishing and the oil and gas communities.

** Decommissioning of pipelines**

The major issue of concern for the Scottish fishermen is how pipelines will be decommissioned. The disaster scenario which they fear is if the pipelines are left on the seabed or partially exposed, that they will corrode leaving jagged edges, spalling concrete or exposed rebar to snag their gear. Their position is that pipelines should be removed or buried leaving a clear seabed: “Nothing left proud”
In contrast, the English Fishermen take the view that structures and pipelines are acting as fish breeding grounds and are benefiting the fishermen. Even debris and disturbed seabed provide habitats for crabs and lobsters. As a result, they are now amending their environmental policy in favour of leaving pipelines and structures in place post-decommissioning.

Whilst the views of neither party give rise to particular concerns for non-trenching small diameter pipelines during the operational life of the pipeline, the decommissioning activities may be significantly influenced by whether the pipeline is on the surface of the seabed or not.

**Liability of fishermen for damage to pipelines**
Under maritime law, the fishermen are liable for damage done to the pipelines. Whilst no Operator has taken a fisherman to court, this remains a possibility and a concern for the fishermen.

Many fishermen due however actively seek and trawl along pipelines. This is because a pipeline is a feature on the seabed which attracts the fish giving the trawler a better catch than in open ground. This type of activity is not necessarily harmful to the pipelines but, whilst the fishing is more efficient, the fisherman runs a potentially increased risk of snagging his gear.

**Involvement with the JIP**
Whilst being a force to be reckoned with, it was apparent from the initial contacts that the fishermen wished to be co-operative with the JIP. As a consequence, representatives of the fishing organisations and the UKOOA fishing liaison officer attended the Steering Committee meetings throughout the course of the project so that they could be kept fully informed of the developments and could voice their views (reported above).

**17.4.2 Fishing gear and practices**
The loads that can be exerted by demersal trawl gear on pipelines are greatly dependent on the type of gear, the size of the gear, the size of the vessel and the trawl velocity. To form a basis for many of the development activities of the JIP it was necessary therefore to identify the fishing methods employed and the ranges of vessels and gear being used in the North Sea. Fishing intensity data and trawl gear parameters were therefore compiled from existing fishing studies provided by JIP participants and reported in *Fishing equipment - Typical configurations, parameters and behaviour*. The fishing studies used were appropriate for the mid 1990s and covered all UK North Sea sectors and West of Shetlands. The study included data for vessels from all nations fishing in the North Sea at that time.

The data compiled in this study have been updated through contributions from the fishing representatives and new fishing data that were supplied through the course of the JIP and now form an appendix in the guidelines document. These data can be used for preliminary design purposes but should not be considered an alternative to performing a detailed fishing study for the specific location. As fishing practices and gear are changing it is necessary to work with up to date data and to anticipate trends as best as possible.

**17.4.3 Monitoring**
It is also necessary to monitor developments in gear and fishing activity throughout the life of a pipeline to ensure that the design remains safe.

Reliable data on fishing activity in the vicinity of installations could be compiled by accurate recording of vessel sitings from installations both during drilling and during operation. In
addition, Operators have, for some time, gathered information on vessel movements from the radars on oil installations. This data has been processed by Safetec with a view to using it for collision risk assessment. It would be feasible to operate a similar system for the monitoring the intensity of fishing activities, particularly around the oil patch.

17.4.4 Industry awareness

It became apparent in the early stages of the project that engineers within the oil industry mostly had little understanding of the practices of trawling. Likewise, fishermen had little appreciation of pipeline practices in the North Sea and how gear may behave when encountering pipelines. To increase oil industry awareness of fishing practices the NFFO and Seafood Industry Authority hosted one of the JIP steering committee meetings in Hull and included a tour and demonstration of the flume tank facilities used to train fishermen.

The flume tank facilities were subsequently used by the JIP for performing scale tests on different gear types crossing a range of pipeline configurations. These tests are explained in greater detail later in this report. To enhance awareness both within the oil and the fishing industries a video was produced based on these tests which demonstrated the effects of interaction of trawl gear with pipelines both in terms of the effects on the gear and the loads on the pipeline. The video has been distributed to the JIP members, the fishing organisations and to the four UK fishermen training centres. Copies may be obtained from Trevor Jee Associates.

17.4.5 The Westhaven incident

Whilst the project was ongoing the Scottish fishing vessel ‘Westhaven’ hooked an otter door under a span on a large diameter untrenched pipeline and, whilst in the process of attempting to recover its gear, capsized and sank with the loss of all four crew.

Although the effects of hooking were being considered by the JIP in terms of the effects on small diameter pipelines, the safety of fishermen had not previously been considered an issue as there had been no previous occurrence of such an event. This incident obviously raised questions as to whether the JIP should address the question of fisherman safety. Following much discussion which included the fishing representatives it was decided that the guidelines should remain essentially a design document considering the design integrity of the pipeline. Indeed, at the time, the incident was subject to a Marine Accident Investigation Board (MAIB) enquiry and details of the incident known outside of that enquiry were largely hearsay and speculative. It was however decided that the issue of fisherman safety should be mentioned within the guidelines and accordingly the following statement is included:

‘Whilst not addressed within the scope of these guidelines, the designer does also need to consider the implications of the pipeline design and the trenching/burial status of the pipeline on the safety of fishermen and other users of the sea.’

Other study work, outside of the JIP, was initiated to investigate the incidents and evidence of hooking and factors that may influence the risks of hooking trawl gear on pipelines. This work is ongoing and cannot be reported in detail here. However, the general trends seen in the preliminary stage of work are as follows:

- pipeline hooking appears to be limited to otter boards rather than beam trawls
- the permanent hooking of gear appears to be mainly associated with the larger diameter lines of 16” and above
- hooking may be linked to fishing practices, and in particular to vessels fishing along the pipeline rather than across it.
This work is being performed by Trevor Jec Associates, whom you may contact if you require further information. Public domain information will be available on our website (www.tja.co.uk).

17.5 THE DESIGN GUIDELINES

17.5.1 General
At the start of the project an outline design guideline was prepared to establish the process and sequence of events that would be necessary to produce a trenching design decision. This outline identified those areas that would require technical development in order that the trenching design could be performed. Through the course of the JIP, the perceived overall design process changed as the design methods were derived and as technical developments and experience of the trenching design process identified new areas of significance.

This section describes the overall approach and methodology that evolved and explains the development of the guidelines. The development of the individual design models and methods are explained in detail later in this report.

17.5.2 Approach to design
Models versus formulae
The original vision for the guidelines had been to produce a set of simple to use formulae or graphs which could be used in determining the case for whether a pipeline could be left on the seabed untroughed. This would have led to the simple application of the guidelines by engineers at all stages of design. Whilst it was recognised at an early stage that both the motion of the trawl gear and the response of the pipe are complex, as explained later in this report, it was believed that these could be parameterised sufficiently to produce simple predictive algorithms.

Activities were performed to investigate the feasibility of producing simple equations for the trawl-pipeline interaction process, but it was established that, relying on many input variables, to simplify to the point of being able to produce a graph or equation would mean making conservative assumptions. Whilst certain filters and design aids, such as 'look-up' tables, were produced to help the engineer in the early stages of design, the design methodology developed relies on detailed engineering models rather than simple equations or graphs.

Coping with change
Through the contribution of the fishing representatives and through work being performed outside the scope of the JIP it was identified that trawl gear and fishing practices are changing and will continue to do so. Therefore the design process needs to cope with a changing design load. This strengthens the need for design models that can analyse appropriate trawl gear configurations rather than fixed design curves.

17.5.3 Methodology
The methodology is shown in Figure 15 below.
Figure 15
Design methodology

The design process is based on three analyses:

- To assess the pullover force-time-history and the resultant pipe bending
- To assess the impact energy and the resultant dent in the pipe.
- To assess the loads and consequent bending due to hooking of trawl gear.
Inherent in the methodology are three levels of assessment. The levels are:

- **Simple first pass filter**  This is a coarse ‘go/no-go’ filter which identifies extreme cases for which the trenching design can be specified without the requirement for detailed analysis.

- **Deterministic assessment**  The deterministic assessment conducts a detailed analysis for the combination of parameters giving the worst case condition. If the pipeline can be shown to withstand this load case it will withstand all others.

- **Risk/cost assessment**  If the pipeline design fails the deterministic analysis, i.e. is shown to fail under worst case loadings, the risk/cost assessment can be applied to determine the probability of failure and the lifetime costs associated with that failure. This gives a means by which the costs of providing protection can be assessed against the increased risk and associated costs of not providing protection.

As explained above, fishing gear and practices are continually changing, and cannot be reliably predicted in the long term. It follows that the loads on an untreated pipeline will change. It is therefore necessary to monitor the fishing activities throughout the design life of the pipeline to ensure that loads do not exceed safe levels.

17.5.4 The guidelines

During the course of the project, DNV announced that they too were to set-up a JIP to produce trenching design guidelines. Their JIP would be based solely on work already performed by Statoil and DNV and would involve writing the guidelines only. Discussions were entered into with DNV to explore the options of combining or sharing the results of work and of producing a single guideline document. It was perceived that a single guideline would gain wider acceptance than two ‘competing’ guidelines.

Following extensive discussion and negotiation, DNV and Statoil choose to pursue their own JIP as they considered that they already had sufficient data to produce their guidelines. The avenue was left open, however, for later collaboration once the technical studies for this JIP were complete. It was agreed that the DNV guidelines would be updated to incorporate the work from this JIP and then reissued as a ‘Recommended Practice’ document.

Discussions with DNV continued throughout the course of the JIP, with the aim of agreeing workscopes and costs for the issue of the combined guidelines. Whilst there was broad agreement between the DNV and TJA approaches to trenching design, the Trevor Dee Associates JIP wished to incorporate additional scope within the guidelines including areas such as flexible pipe, small diameter, high pressure/high temperature pipelines and generic trawl gear data. It was clear that major modifications would be required to the DNV guidelines to incorporate the TJA JIP methodology and criteria. Whilst it was agreed that Trevor Dee Associates would carry-out those modifications, DNV would have the right to reject modifications and would require their internal costs to be covered. Given the high level of the DNV internal costs and the inability to guarantee a guideline document that fully reflected the findings and methodology of the JIP it was decided to drop attempts of collaboration with DNV. The trenching guidelines were therefore produced as a JIP document and are to be published by the HSE for general distribution.

17.5.5 Design software

Design software was produced by the JIP for various simulation and analytical functions. Whilst suitable for the purpose of a trenching design, the software models were produced as several non-integrated items which are not particularly robust or user friendly and which required running on other commercially available software packages.
The JIP members saw a requirement for a single integrated stand-alone user-friendly software application which would produce a trenching design in accordance with the guidelines. The development of this software is currently being pursued by Trevor Jee Associates as a separate activity outside the scope of the JIP.

### 17.5.6 Flexibles

Flexibles are included within the scope of the guidelines, although the level of detail and, hence, the available applicability are limited.

It was originally intended that flexibles be excluded from the scope of the JIP. However, as the interest and level of participation in the JIP grew the possibility of including flexibles within the studies was investigated. Being of a proprietary nature it was clear that the only way in which the response of flexibles to trawl gear interaction could be accurately assessed was by the flexible manufacturers themselves.

Wellstream and Coflexip Stena Offshore (CSO) were approached and both expressed interest in joining the JIP, supplying data as payment-in-kind for the participation fee. Both companies attended steering committee meetings whilst the terms of contract and the specific details of the data to be supplied were negotiated. Following negotiations Wellstream chose to withdraw from the JIP.

An agreement was reached with CSO as to what data should be provided as payment in kind. However, CSO wished to impose a Condition Precedent, disclaiming liability for the accuracy or validity of the data supplied, to which all other JIP participants would have to agree prior to the data being supplied. This would have imposed considerable administrative and legal burdens on the other JIP participants. Despite extensive negotiations, CSO chose not to withdraw their requirement for the Condition Precedent. Given the considerable difficulties that such a legal requirement would impose, the ‘paid-up’ members of the JIP decided that this should not be accepted and that CSO should be excluded from the JIP.

The JIP therefore commissioned a study from MCS (report no 2-1-4-080/SR01) which looked at the failure modes for flexibles and their ability to withstand trawl loads. Whilst of a generic nature, this study showed that flexibles have a relatively poor resistance to trawl loads, particularly impact. It is expected that in most cases flexibles will require protection.

### 17.6 INTERACTION MODELLING

#### 17.6.1 Background

When crossing a pipeline the loading exerted by trawl gear on the pipeline is considered in two phases:

- an initial impact loading as the gear first contacts the pipeline
- a pullover force as the trawl gear is pulled over the top of the pipeline

Fundamental to the process of trenching design is to determine the magnitude of the impact and pullover loads and the response of the pipe to those loads. This section describes the development of the models for simulating the trawl gear pullover and the resultant pipeline deflection.
17.6.2 Interaction loads

Approach
The research performed by Shell in the 1970s and early 1980s included model and full scale pullover tests and force-time histories were measured for a number of practical cases. These tests targeted specific pipeline applications and none were performed on small diameter pipelines. For this JIP it was necessary to devise a means of determining a pullover load for any diameter of pipeline, any type and size of trawl gear and any condition of embedment or spanning of the pipeline. Given the range of potential cases, the use of physical tests was considered impractical. Results from physical tests would also become outdated as gear changed and evolved. The selected method for determining pullover loads was, therefore, a computer-based simulation model.

The crossing of trawl gear over a pipeline involves the interaction of two non-linear dynamic systems, namely, the pipeline and the trawl gear. The approach taken to analyse this was first to consider the two systems separately and then to see how they interact.

Models
As detailed in report SH01R06A, two separate models that were therefore developed. The first was an Excel spreadsheet which determined the motion of the trawl gear over the pipeline and the resultant impact and time varying reaction loads on the pipeline. The second was an ABAQUS finite element model to determine the response of the pipeline to the applied pullover force-time history. The response of the pipeline to the initial impact was considered separately and is described later in this report.

By considering the trawl door pullover and the resultant pipeline response separately the initial method implicitly ignored any relation between the movement of the pipe during the pullover period and the developed pullover force-time history. The analysis method was later refined therefore to account for the effects of the displacing pipeline on the pullover loading. This is detailed in report SH01R12A.

17.6.3 Pullover loads
The Joint Industry Project pullover model is a finite difference simulation of the trawl gear motion in 2-dimensions. An example of the force-time history output for a 5 tonne beam trawl crossing a 10.75" flowline is shown in Figure 16. The graph shows both the horizontal and vertical components. In this case the vertical force is initially upwards, then downwards as the gear moves over the top of the pipe.
Figure 16
Pullover force time history

The effects of the movement interaction between the trawl gear and the displacing pipeline were investigated in report SH01R12A. The pullover model was modified to include pipeline movement in the calculation of force-time loading. Using the existing pipe response model, an iterative approach was developed to find the stresses, strains and deflections in the pipe taking account of the flexing interaction with the trawl gear.

The interaction between the trawl gear motion and the flexing pipe reduces the magnitude of the pullover load and increases the duration of pullover as illustrated in Figure 17. This effect has been seen to have a significant increase on displacement and resultant strains with some small diameter pipeline configurations.

Figure 17
Force time history for flexing pipe
The initial stage of the motion analysis is a momentum balance on the trawl gear. From this may be found the loss in kinetic energy due to the impact and hence the maximum amount of energy available for denting of the steel pipe. The consequences of impact are addressed later.

Both the pullover load and the impact energy are significantly influenced by the diameter and height of the pipe and the leading radius of the trawl gear. The lower the pipe in relation to the trawl gear, the more glancing the interaction and the lower the loads.

17.6.4 Bending and lateral buckling

The pipe response to pullover loadings is modelled using an ABAQUS finite element model. This model takes account of:

- non-linear effects such as friction and yielding of the steel
- dynamic effects such as the inertia and added mass of the deflecting pipe, and
- axial effects such as the forces and strains due to internal pressure and temperature.

One of the drivers behind non-trenching of flowlines is to avoid upheaval buckling, however any hot pipe laid on the seabed is prone to lateral buckling instead. Because it is less constrained than upheaval buckling, the deflections and strains tend to be less dramatic for lateral buckling but nonetheless can be of concern to the designer. The effects of elevated temperature and lateral buckling were explored in reports SH01R12A and 618.11.2/R1. The effects of lateral buckling initiated by pullover loads was recognised as occurring at even moderate temperatures. In determining the deflected shape and resultant bending strains in the pipeline it is therefore necessary to consider both the effects of lateral buckling and the additional deflection due to trawl gear pullover loads.

The original pipe response model took the pipeline as being perfectly straight and therefore thermal loads were locked-in and subsequently released during the pullover, driving a localised thermal buckle. At even moderate temperatures (say 40°C) the predicted deflections and strains were high and largely insensitive to the applied pullover loads. This situation was considered unrealistic as thermal loads would be largely released by snaking of the pipeline on its first thermal cycle. A study was performed to assess the propensity to thermal snaking in small diameter flowlines (APA report 618.11.2/R1). Indeed the effects of thermal snaking were seen in practice, as shown in Figure 18.

![Sonar image of laterally buckled flowline](image)

Figure 18
Sonar image of laterally buckled flowline
The ABAQUS finite element model was therefore modified to produce thermal snaking in the line
prior to pullover. Figure 19 shows the deformed shape in the pipe, with the deflection magnified
ten times. This shape is developed by using a single small imperfection in an otherwise straight
pipeline as an initiator for the buckle. In practice there are likely to be many such initiators along
the length of the pipeline leading to a series of smaller buckles rather than just one large one.

![Lateral buckle - single defect at mid point](image)

**Figure 19**

Lateral buckle modelled by FE analysis

The response of the pre-buckled pipeline to the pullover load is then considered. The worst case
has been found to occur when the pullover occurs at the peak of the buckle. The finite element
model takes account not only of friction and plasticity but also of the dynamics and inertial
effects which lead to a considerably reduced strain compared to a static analysis.

### 17.6.5 Look-up table

An initial aim of the JIP was to produce a simple and quick method for performing trawl gear
interaction analyses. It became apparent that it was not feasible to produce simple formulae or
curves for determining pipeline response to trawl gear pullover. However, numerous trawl
interaction analyses were performed throughout the course of the JIP. These analyses take some
time to run and, so, the available analysis results were compiled in a look-up table of pipeline
responses to pullover loads for quick and easy reference. This look-up table is included in report
no SH01R13A and provides a first pass indication as to whether non-trenching may be justified.

### 17.7 IMPACT

#### 17.7.1 Background

The impact from trawl gear may dent a steel pipe. A review of available impact testing data was
performed and the available denting models evaluated (report no SH01R07A).

#### 17.7.2 Review of impact tests

There has been extensive testing of the impact resistance of concrete and thick insulation coatings
to trawl board impact. From these tests, and indeed from North Sea operational experience the
following are known to protect a pipe from denting.
- **Concrete coatings** with concrete or mastic field joints will protect the pipe steel against denting from both otter and beam trawls.
- **Pipe-in-pipe and bundles** protect the flowline against denting from both otter and beam trawls.
- **Insulation coatings** of thickness greater than 20mm will protect the pipe against denting by otter board or clump weight impacts (impact energy up to 14kN), and thicknesses greater than 45mm will protect the pipe against beam trawls (impact energy up to 38kN). Damage to the coating itself may result and therefore continued thermal or corrosion protection needs to be designed or tested for.

Few tests have been carried out on thin coatings and it is expected that these will provide negligible impact protection. Coating systems will need to be tested if specific impact test data are not available. An impact test specification has been developed (report no SH01R14A).

### 17.7.3 Denting models

A number of existing denting models were assessed and the Ellinas and Walker formula was identified as being the preferred method for predicting dent depth.

The initial assessment of accuracy through comparison with impact test results implied that the formula gave good predictions for larger diameter pipes with high D/t ratios (D/t>25) but became increasingly conservative for the smaller low D/t flowlines. However, later studies of denting mechanisms performed outside the scope of the JIP (Figure 20) showed that the Ellinas-Walker equation gave a good prediction of denting energy across a wide range of D/t ratios. With decreasing D/t ratio the local stiffness of the pipewall increases relative to the global stiffness of the pipe and therefore less of the overall impact energy is dissipated in denting and more is dissipated in global deformation of the pipe. The denting energy is therefore just a proportion of the available impact energy.

![Figure 20](image)

**FE analysis of denting due to impact**

Impact tests for non-coated pipe in the typical offshore pipeline diameter and D/t range showed resultant dents being less than half the predicted dent depth. This is equivalent to no more than one-third of the impact energy actually being dissipated in the formation of a dent. Therefore, an assumption that 50% of the impact energy is used in the formation of a dent will give a conservative, yet not excessive, prediction of dent depth.
17.7.4 Pop-out

The original study of impact looked at formulae for predicting the pop-out of the dent due to internal pressure. The Maxey formula was commonly used but was shown to be potentially non-conservative. In fairness, the Maxey formula was developed for large, high D/t pipes to predict what the original dent size would have been given the pressurised depth, so one would expect it to be non-conservative if used in reverse. A re-analysis of the original data points gave a revised formula.

In developing acceptance criteria for denting, fatigue was found to be the critical limit state (report no SH01R18A). The work performed by Fowler gave the best prediction of fatigue life for dented pipe sections. The Fowler methodology is based on the unpressurised dent depth and therefore the pop-out due to internal pressure is not relevant. The derived pop-out formula is not therefore used within the guidelines.

17.7.5 Test results

The results from a number of impact test programmes were made available to the JIP. Whilst far from comprehensive, these results may assist in initial studies and give indicative predictions to the impact response of a particular pipeline configuration. These impact test results have been compiled and included as an appendix in the guidelines document itself. To provide assistance in the setting up of impact tests a testing specification was prepared (report no. SH01R14A). The basis of the test specification is included as an appendix in the trenching guidelines.

17.8 HOOKING

17.8.1 Phases of hooking

Hooking is an accidental load condition on the pipeline and is when the gear comes fast on a pipeline and brings the vessel to a halt. This is rare, but can happen for any type of gear. As explained previously, this condition was addressed by the JIP solely from the view of the pipeline integrity. The issue of fishermen’s safety was outside the scope of the JIP.

A study was performed by Brown and Root looking at the consequences of hooking of gear on small diameter pipelines (report no. R-B&R-TJA-001).

The approach taken was to consider the displacement of the pipeline required to ensure that the trawl gear could free itself. The consequences of that displacement on the pipeline were then evaluated. This general approach was adopted in the guidelines with the addition that load limits were introduced and two load conditions were considered. Namely:

- bending in pipe due to the initial snagging load, and
- bending resulting from lifting the pipe vertically by a sufficient height to release the trawl gear

17.8.2 Initial snag load

Treating the warp as a spring, the initial snag load is that required to bring the vessel to rest.

This snagging load is limited by:

- the capacity of the trawl warps or, where fitted, the brake limiter setting on the trawl winches
- lifting of the pipe off the seabed by a sufficient height to allow the gear to release.
An otter door will release once the pipe has been raised a distance of half the door height or length (whichever is greater) off the seabed. A beam trawl will release as soon as the pipeline begins to lift.

The pipeline response is derived by static FE analysis.

17.8.3 Vertical lift

In the event of hooking of gear, and not being able to free it by pulling forwards backwards or sideways, the fishing vessel will haul vertically at the hooking location until the warps break.

With beams the gear would release as soon as the pipeline begins to raise. This case does not, therefore, need to be assessed for beams. The clump weight designs currently seen will behave similarly to beams. With otter doors, the maximum distance that the pipeline is raised before the door releases is the greater of half the door length or half the door height, as illustrated in Figure 21.

Again the load is limited by the breaking strain of the warp and the pipeline response is determined by static FE analysis.

![Diagram showing pipe movement after hooking](image)

**Figure 21**

Pipe Movement after Hooking

17.9 ACCEPTANCE CRITERIA

17.9.1 Approach

Acceptance criteria were initially prepared by DNV based on the DNV 1996 Rules for Submarine Pipelines and on their own trenching JIP document Guidelines 13 (DNV report *Interference between trawl gear and pipelines*, Sept 1997). The criteria developed did not, however, fit well with the analysis methods that evolved.

A further report of acceptance criteria was prepared therefore by TJA based on the principles of the DNV criteria but tailored towards the analysis methods and BS8010 part 3 (report SH01R18A).
Acceptance criteria were developed for the three load conditions

- impact
- pullover / lateral buckling
- hooking.

The approach for each load case was to identify the limits states which could result from each of the loading conditions. These were then quantified, and the most stringent for each load case taken as the acceptance criteria.

For impact damage the acceptance criteria were based primarily on fatigue with additional acceptance checks based on piggability and hydrostatic collapse. In most cases fatigue will be the limiting criteria.

For pullover, lateral buckling and hooking, the acceptance criteria are based on bending strain with the limiting state being local buckling. Criteria for pullover / lateral buckling treat the load as an functional condition whereas the criteria for hooking treat the load as an accidental condition.

### 17.9.2 Go no-go filter

A set of go no-go filters were developed to provide easily applied first pass filters to eliminate obvious cases from further analysis.

The first pass go no-go filters were based on the following:

- operating experience
- available test data
- specific case studies
- JIP studies and analyses
- supported by the results of trenching studies performed outside the scope of the JIP.

Limiting configurations and conditions were identified by applying the acceptance criteria to the available data. It became clear that lower bound (i.e., no-go) filters could not readily be identified for rigid pipelines although conservative upper bound (go) filters could. This led to a go filter being developed for rigid pipelines which required 3 requirements to be satisfied, namely a coating requirement, a minimum diameter requirement and an operational temperature requirement.

From the available data, it was apparent that piggy-backed small diameter lines and unarmoured flexible pipelines could not withstand trawling loads and, therefore, fell within a no-go category.

### 17.10 VALIDATION

A number of validation studies were performed to ensure that the derived analytical models gave realistic results.

#### 17.10.1 Pullover loads

When initially developed (report no. SH01R06A), a validation of the pullover model was made by comparison of pullover force-time histories measured during tests with those predicted by the pullover model. Various pullover test programmes, both full scale field tests and laboratory model tests, had been carried out. Test data were selected for comparison from the various VHL tests carried out between 1974 and 1979 and the NAM tests on the K7-FA-1/K8-FA-1 pipeline in
1984. The test data were selected to be most representative of the perpendicular crossing direction assumed by this pullover model. The pullover model generally gave good agreement with these pullover tests. A number of tests, however, gave loads up to 25% greater than those predicted by the model and pullover durations up to twice those predicted. Whilst these discrepancies were most likely due to the true span/embedment condition of the test pipeline not being accurately recorded (this was recorded where the vessel crossed the pipeline rather than where the gear crossed the pipeline) this initial study recommended the use of safety factors to ensure conservative prediction.

Further validation of the pullover model was performed by flume tank testing of model trawl gear crossing pipelines (report no N0411). These tests considered a range of trawl gear, pipeline configurations and approach angles. These tests showed that the motion of otter doors over pipelines was very much a 3-dimensional motion with rotation of the gear occurring around all three axes. It was evident from these tests that the 2-dimensional pullover model which constrained rotation to one plane only would give conservative predictions of both load and pullover duration. From these tests and from the revised analysis method which catered for the effects of the flexing of the pipeline on the trawl gear motion, it was decided that the safety factors originally suggested were no longer appropriate, and therefore do not appear in the guidelines.

![Figure 22](image)

Flume tank tests

17.10.2 Pipeline response
Validation of the pipeline response was performed in a number of ways. Firstly, the initial development model was cross-checked against Shell's in-house pipeline response model 'PULLOVER' (report no SH01R06A). This cross-checking was, however, limited and the Shell model had difficulties modelling large non-linear responses.
Further validation was performed by cross-checking against pipeline response curves developed and published by Statoil (report SH01R08B). Again, fair agreement was obtained between models at benign, low temperature, low pressure conditions, but the Statoil curves were developed for elastic pipe response only.

It was decided to gain further confidence in the model by performing a reality check on existing small diameter untrenched pipelines. This reality check therefore looked at pipeline survey data (report no SH01R12A).

Three small diameter (<16") untrenched pipelines were identified and survey data were compiled and reviewed. Of the three, only one pipeline showed evidence of trawling activity and pipeline movement. Trawl scars and light coating damage were observed and the pipeline had displaced in a number of locations, although these displacements were not coincidental with either trawl scars or coating damage. The displacements were attributed to thermally driven lateral snaking. Figure 19 shown previously in this report is an image of one of these lateral buckles.

The physics is similar to upheaval buckling and has been reproduced under scale model conditions at Cambridge University (report no. 618.11.2/R1) as illustrated in Figure 23. The FE analysis results correlated well with the observed displacement giving confidence that the analysis model gave realistic predictions with finite element analysis predictions.

![Figure 23](image)

Modelling of Lateral Buckling

17.11 RISK ANALYSIS

17.11.1 Background

At the time of setting up the JIP, it was perceived that risk and reliability methods could be used to good effect in making a trenching/non-trenching decision. Where the deterministic analysis shows that damage to a pipeline may be sustained from trawl gear interaction, risk analysis techniques can be applied to determine the probability of damage and to determine the subsequent lifetime costs of the pipeline. A combined risk analysis and cost model has been developed (report no 1273.04/DOC01). This model considers all the combinations of trawl gear type, size
and velocity with pipeline configuration, and assesses the frequency of exceeding given acceptance criteria, and the resultant cost implications.

17.11.2 Model overview

As a development tool the risk/cost model is in the form of a spreadsheet and will run either a Monte Carlo or a first order reliability method (FORM) probability assessment. The model will run a year-by-year probability assessment so that changing operating conditions, pipeline corrosion, embedment depths and fishing activities are accommodated. The structure of the risk/cost model is shown in Figure 24.

Given the large number of parameter distributions that are required by this risk/cost model it was found not to be particularly robust. Monte Carlo analyses were extremely slow to run with any degree of accuracy, and FORM analyses, whilst running faster, often failed to converge successfully.

At the time of development, hooking was not seen as being a significant condition and was not therefore included in the risk model. As explained later, this risk model has become largely redundant and therefore it was not up-dated to include hooking.

![Diagram of risk/cost model structure](Figure 24)

Structure of risk/cost model
17.11.3 Costs

The through lifetime costs can be calculated on a year-by-year basis and discounted back to nett present value to enable costs to be compared for trenched and non-trenched pipeline designs. All cost elements that may change due to trenching status need to be included in the estimate. Essentially it is necessary, therefore, to have designs for both trenched and non-trenched options. The following cost components may vary between the two pipeline design options:

Materials: for example, additional wall thickness or weight coating may be required for stability of a non-trenched design or additional anodes may be required for a buried pipeline.

Construction: in addition to the trenching costs themselves additional construction costs, such as rock-dumping for prevention of upheaval buckling of a trenched hot flowline, may be incurred.

Maintenance: routine maintenance costs such as freespan rectification may be expected to differ for trenched and non-trenched designs.

Inspection: routine inspection schedules will differ depending on trenching or burial status.

 Decommissioning: the costs associated with pipeline decommissioning will probably differ for trenched and non-trenched designs.

In addition to these costs, the risk costs associated with repair of damage inflicted by trawl gear will differ. The costs will differ for the differing failure modes, and cost elements will not only include the repair costs themselves but could include loss of production, non-delivery penalty charges or, in the extreme case of loss of containment, environmental clean-up costs and knock-on costs (such as loss of motor fuels sales) resulting from the subsequent bad publicity.

17.11.4 Use of risk assessment

A sensitivity analysis was performed to identify which parameter distributions had significant effects on the risk (report no SH01R08B). This study identified that the parameters that dominate the variability of pipeline response to the three load condition, ie impact, pullover and hooking, are:

- trawl gear type
- trawl gear size
- angle of approach of trawl gear
- spanning/embedment of pipeline.

A risk assessment, therefore, need only consider distributions in these parameters. Given the small number of variables that need to be considered, a far simpler risk analysis can be performed than that given by the JIP risk/cost model. The JIP risk/cost model is now therefore redundant.

The guidelines acknowledge this fact and therefore specify a simple hand calculation approach to risk analysis.

17.12 Further Information

These guidelines provide the methods and criteria necessary to make a decision on non-trenching of a pipeline. There are further sources of information available which the engineer or project manager wishing to consider non-trenching may find useful.
17.12.1 Guidelines
In addition to these guidelines, you may also wish to refer to the DNV guidelines *Interference between trawl gear and pipelines*, Sept 1997, Guidelines 13 which are commercially available from DNV.

17.12.2 Background information

**CD-ROM**
The JIP study reports described in this summary document are available on CD-ROM from Trevor Jee Associates. These documents will describe the basis upon which the guidelines have been developed. The CD-ROM provides hyperlinks between documents and relevant data sources.

**Video**
To enhance awareness of the interaction of trawl gear and pipelines, a video was produced based on the flume tank tests performed at the SeaFish Industry facilities in Hull. This video demonstrates the effects of this interaction both in terms of the effects on the gear and the loads on the pipeline. The video has been distributed to the JIP members, the fishing organisations and to the four UK fishermen training centres. Copies may be obtained from Trevor Jee Associates.