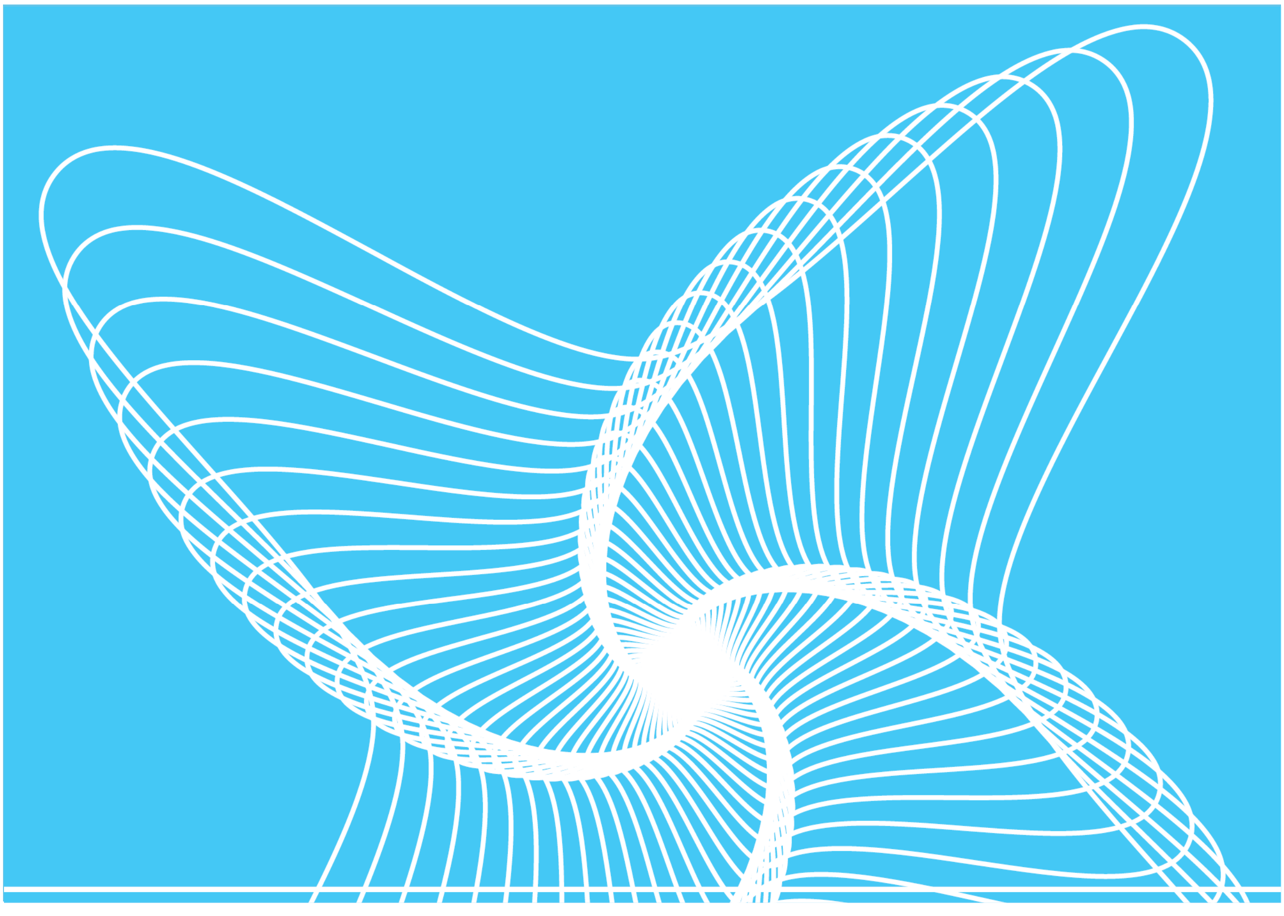
DNV·GL

SESAM USER MANUAL

PET - Pipeline Engineering Tool

The definitive tool for early phase pipeline design

Valid from program version 4.1



SAFER, SMARTER, GREENER

Sesam User Manual

PET – Pipeline Engineering Tool

Date: 27 February 2018

Valid from PET version 4.1

Prepared by DNV GL – Digital Solutions

E-mail support: software.support@dnvgl.com

E-mail sales: software@dnvgl.com

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1 INTRODUCTION

1.1 What is PET

PET is a easy to use and quick concept evaluation and decision making tool for technical support during field developments. Convenient interface to include PET results in design reports.

PET contains a wide set of easy to use calculation modules for quick assessments of offshore pipeline design. The following calculation modules are included:

- Design Checks in accordance with DNVGL-ST-F101 and its older version DNV-OS-F101 (please ote that the code is selected in the DNV-OS-F101 Design Checks module)
- Weight and Volume
- Expansion
- Simplified stability calculations according to DNV-RP-F109
- Reel Straining
- Reel Packing
- Cathodic protection
- J-Lay and S-Lay
- Upheaval Buckling
- Simplified free span calculations according to DNV-RP-F105

1.2 How to read the Manual

- Read section 2 to learn about the features of PET.
- Read section 3 to learn the basics of using PET.
- Read section 4 for information on how to use the the induvidual modules.

1.3 Frequently Asked Questions

There exists for PET as for other Sesam programs a list of Frequently Asked Questions (FAQs). Access this information by clicking the customer login link in our website www.dnvgl.com/software/.

1.4 Acronyms and symbols frequently used in the User Manual

The table below lists a few acronyms and symbols that are frequently used in the User Manual.

Table 1-1 Definition of Parameters

D	Steel pipe outer diameter.
t	Steel wall nominal thickness.
D_{po}	Overall outer diameter of pipe including all coating layers.
A_s	Steel area = $\frac{\pi}{4}\left(D^2 - (D - 2\cdot t)^2\right)$
I	Steel second order moment of inertia = $\frac{\pi}{64}\left(D^4 - (D - 2\cdot t)^4\right)$
$SMYS$	Specified minimum yield stress.
$SMTS$	Specified minimum tensile strength.
E	Young's modulus.
ν	Poisson's ratio.
α	Coefficient of thermal expansion.
w_s	Pipe submerged weight including all coating layers, additional submerged weight and weight of content where appropriate.
S_{eff}	Total effective compressive force = $H + S_T + S_\nu + S_{pA}$.
H	Lay tension (negative as tension).
S_T	Axial force component due to temperature elevation = $\alpha \cdot \Delta T \cdot E \cdot A_s$
S_{pA}	Axial force component due to the end cap effect = $\Delta p_i \cdot \frac{\pi \cdot (D - 2\cdot t)^2}{4}$
S_ν	Axial force component due to the Poisson's effect = $\Delta p_i \cdot \frac{D - 2\cdot t}{2\cdot t} \cdot \nu \cdot A_s$
ΔT	Temperature elevation from installation condition to relevant condition for calculations, typically design condition or system pressure test condition.
Δp_i	Internal pressure elevation from installation condition to relevant condition for calculations, typically design condition or system pressure test condition.

2 FEATURES OF PET

The following calculation modules are incuded in PET:

- Design Checks in accordance with DNVGL-ST-F101 and its older version DNV-OS-F101:
  - The calculation module performs calculation for the following limit states (failure modes): Burst - during operation as well as during system pressure test- , Collapse, Propagating buckling and Combined loading. The later includes: load and displacement controlled combination for combinations a and b.
- Weight and Volume:
  - The calculation module calculates the volume, mass and dry weight of the components that constitute a pipeline, i.e. steel, coating layers and content. Volume, mass and dry weight are calculated individually and totally, per metre pipeline and totally for a given length of the pipeline.
- Expansion:
  - The calculation module calculates end expansion due to temperature and internal pressure. The virtual anchor length is also calculated. These two results are presented for the system pressure condition and the design condition.
- Upheaval Buckling
  - The purpose of the calculation module is to estimate the safety level with respect to upheaval buckling for the given set of input, predict the temperature, internal pressure and imperfection height that will trigger upheaval buckling and estimate the cover height to prevent upheaval buckling for a given safety level.
- Simplified stability calculations according to DNV-RP-F109:
  - This module estimates the safety level with respect to stability for the given set of input, added weight coating and wall thickness required to ensure stability for 10D displacement criterion.
- Reel Straining:
  - The calculation module calculates maximum bending strain on the reel including a code check according to to DNVGL-ST-F101 and its older version DNV-OS-F101, corresponding ovality and accumulated plastic strain during reeling, unreeling, aligning and straightening.
- Reel Packing:
  - The calculation module calculates the amount of pipe that can be packed on a reel/carousel.
- J-Lay and S-Lay:
  - The calculation module calculates the following during pipe J-lay and S-lay respectively: The actual top tension (axial force in pipeline) during laying, horizontal top tension, maximum curvature and moment in the sag bend including utilisation ratio according to to DNVGL-ST-F101 and its older version DNV-OS-F101, horizontal distance from touch down to barge, length of pipe in the free span and minimum horizontal lay radius.

- Simplified free span calculations:
    - The purpose of this module is to calculate the allowable free span length considering in-line and cross-flow vortex induced vibrations. The module also gives the buckling length (pinned-fixed condition) for the given effective axial force.

- Cathodic protection.

Note that iterated results (required wall thickness, concrete coating thicknesses, etc.) should always be checked by implementing them as input in the final calculation.

All calculation modules features a reporting tool which may be used in design reports.

3 USER'S GUIDE TO PET

3.1 Licensing

PET is licensed through FlexLM License Manager. A valid license file is required to run PET. Please contact Software.Support@DNVGL.com if any questions.

3.2 Getting Started

PET uses input files to run the program. After installation, an example file named *pet_input.xml* is located in your documents folder on the hard drive. When opening PET for the first time, this file will be shown in the "Open project" window, see Figure 3-1. Double click *More files* and open Windows Explorer to locate other project files. Next time PET is opened, the last saved project will be listed first in the "Open project" window.

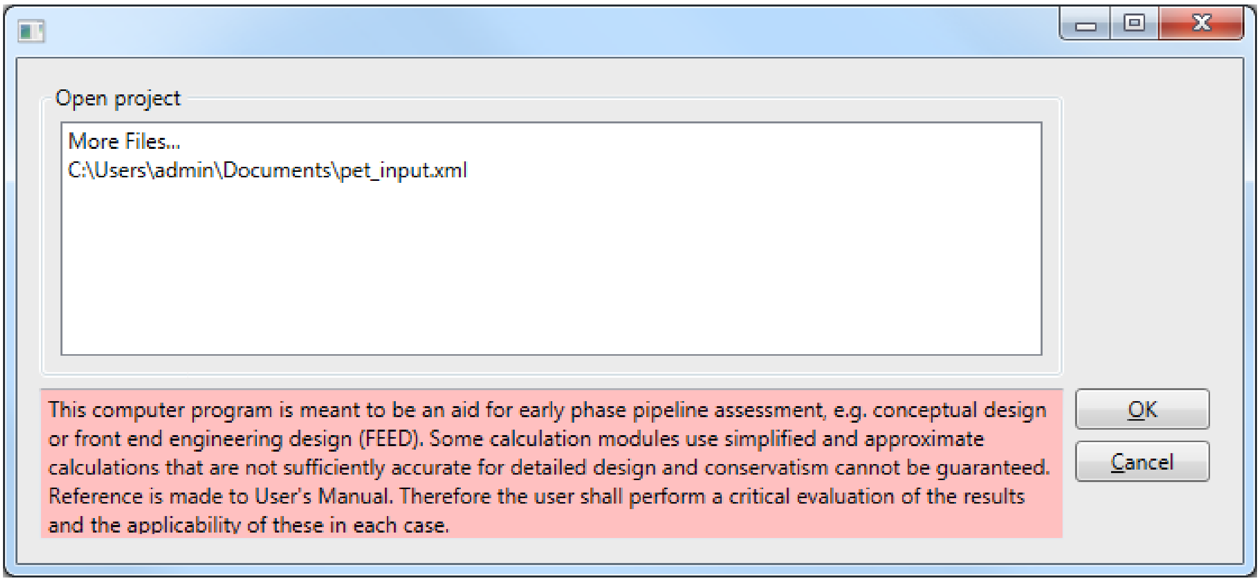


Figure 3-1 PET when opened

After opening the input file, the DNV-OS-F101 calculation module opens by default, see Figure 3-2. The top menu contains, *File*, *Engineering*, and *Help*, see Figure 3-2. The *File* menu gives options on opening, saving and exiting projects. The *Engineering* menu gives access to the calculation modules. The *Help* menu gives access to user manual and information on program version.

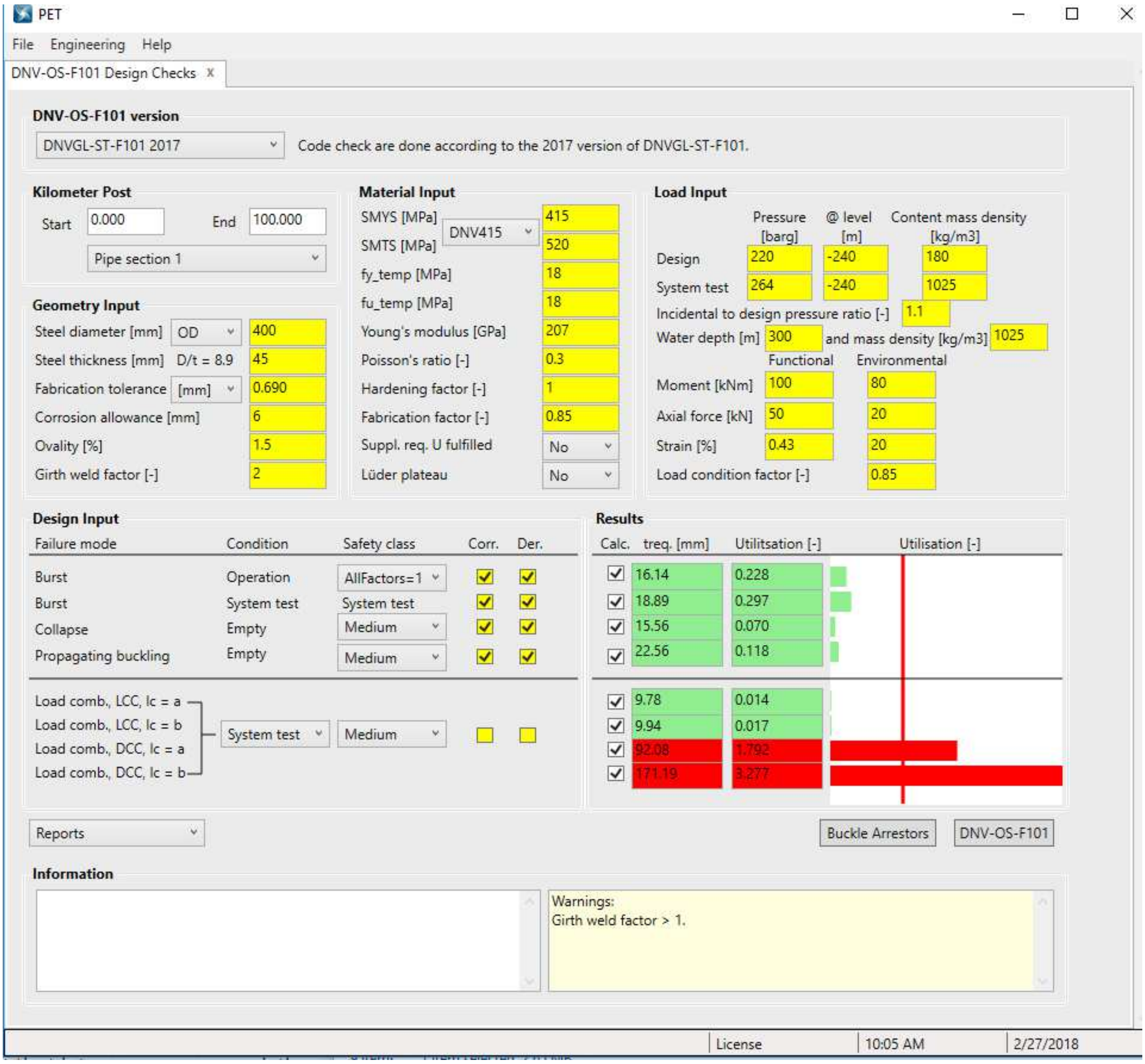


Figure 3-2 PET opens OS-F101 calcualtion module by default

3.3 When using PET

When using PET, the following apply:

- Yellow text boxes are user input to the calculations.
- Input values are checked and response is given in the lower right field on the window. If a warning is given, the calculations are performed, on error the calculations are terminated.
- When an input cell gets focus, some information for this input parameter is given in the lower left field on the window.
- SI system assumed in all formulae presented, units are given on PET module windows.

3.4 Sectioning tool

The sectioning tool can be used to demonstrate calculations of different geometries of pipelines. The sections will be available in the different calculation modules. The sectioning tool in found in the *Engineering* window and is shown in Figure 3-3. The yellow cells illustrate cells changeable or operable.

Create section by using the split *Split Section* function. Enter which section number to split, change section name of new section and choose which data to be used for the new section. The process is outlined in Figure 3-4.

Alternatively you can delete sections by using the *Merge Sections* function. Enter which section number to split and then which section data to apply to the remaining section.

The sections available for input in the calculation module are seen in the *New Pipeline Sections*. Yellow cells are editable and Section namses, KP starts and data for pipline section might be changed. KP ends can be changed by. New sections are shown in

Remember to *Save new sectioning* before closing the sectioning tool.

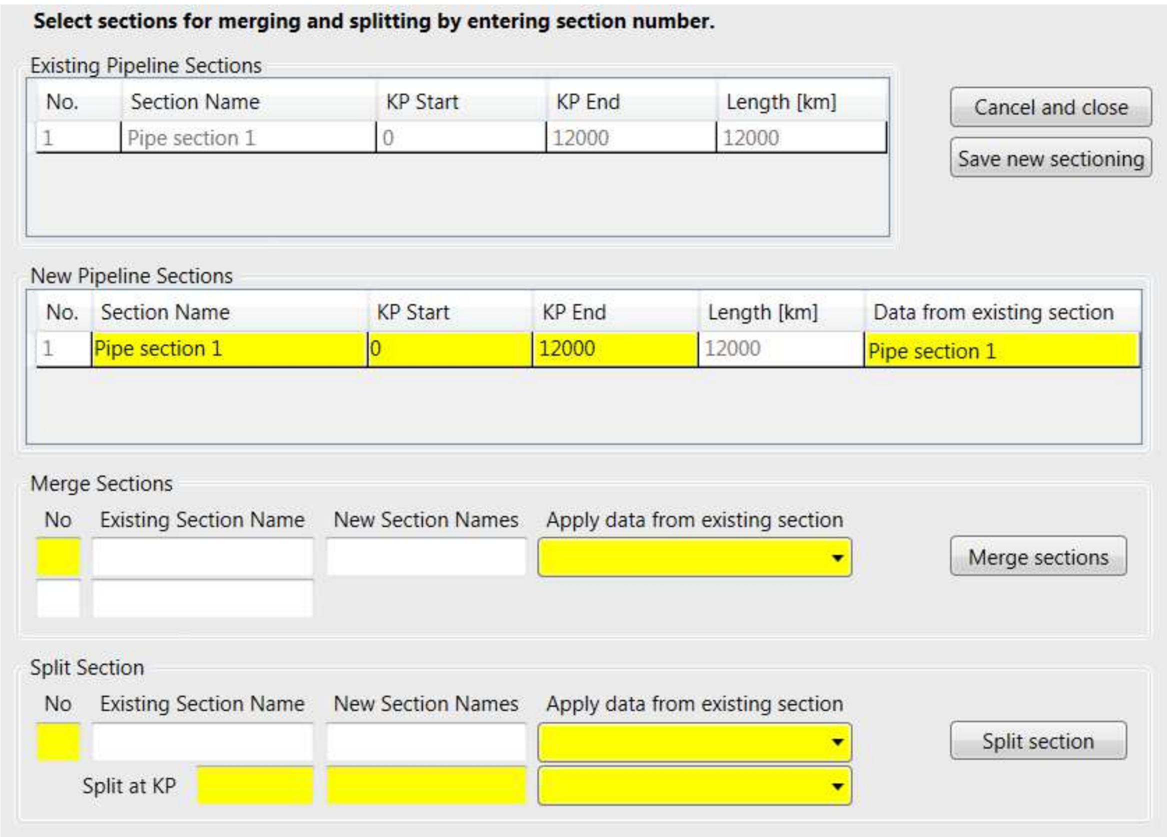


Figure 3-3 Sectioning tool

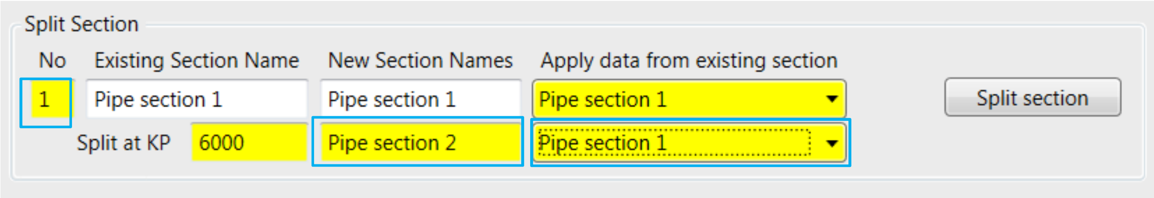


Figure 3-4 Split section

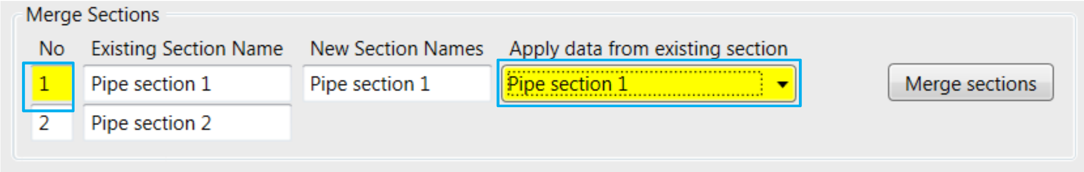


Figure 3-5 Merge sections

3.5 User's note

The *User's Notes* might be used to take notes. The *User's notes* are found in the *Enginnering* menu and is shown in Figure 3-6.

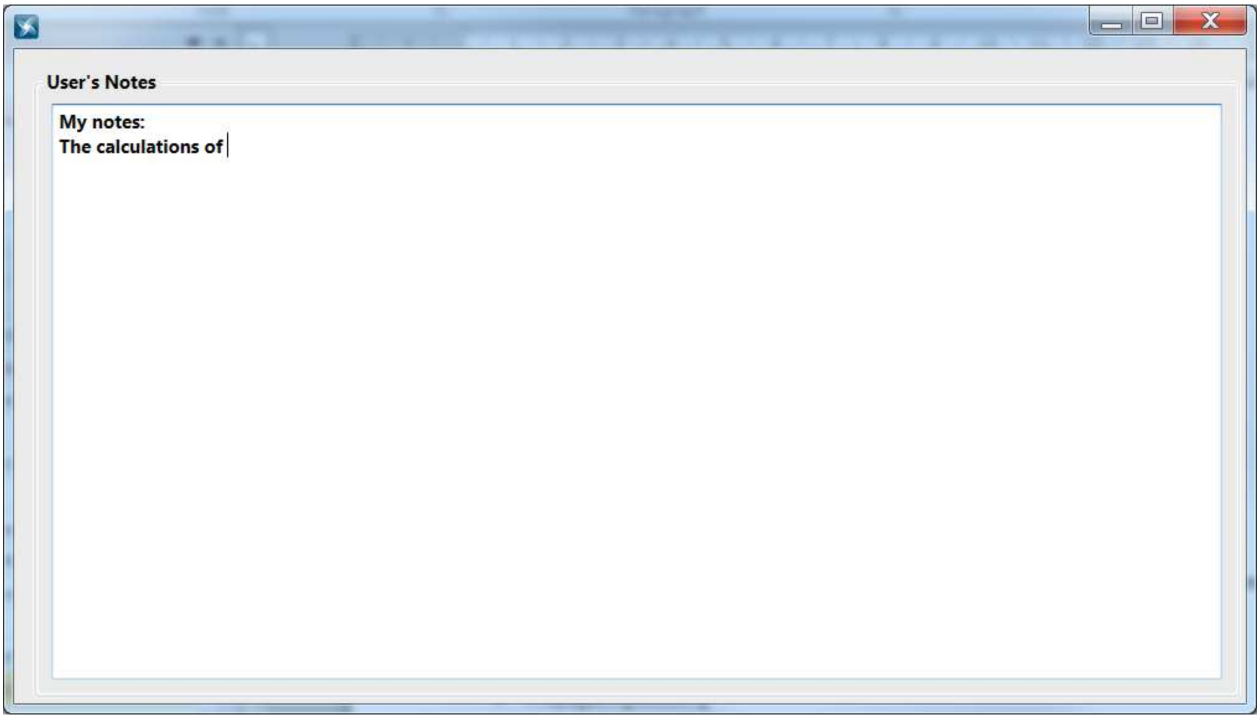


Figure 3-6 User's note

4 EXECUTION OF PET

4.1 DNV-OS-F101 Design Checks

This module performs design checks according to the following four limit states (failure modes):

- Burst, during operation (design conditions) and during the system pressure test.
- Collapse
- Propagating buckling
- Load combination: load controlled and displacement controlled, load combinations a and b.

The calculation module is shown in Figure 4-1. The input and calculations are in accordance to DNVGL's *Standard DNVGL-ST-F101 Submarine Pipeline Systems*, Ref. /3/, and its previous versions . In the calculations it is assumed that the incidential pressure is limited by the pressure containment criterion and not by the system pressure test nor the mill pressure test. See term one of equation 5.6 in ref. /3/. If both the system pressure test and the mill pressure test have been performed according to the standard, the pressure containment criteria will be governing (which is the normal case). For the test pressure, it is assumed that it is limited by the system pressure test and not the mill pressure test. See term one of equation 5.7 in ref. /3/.

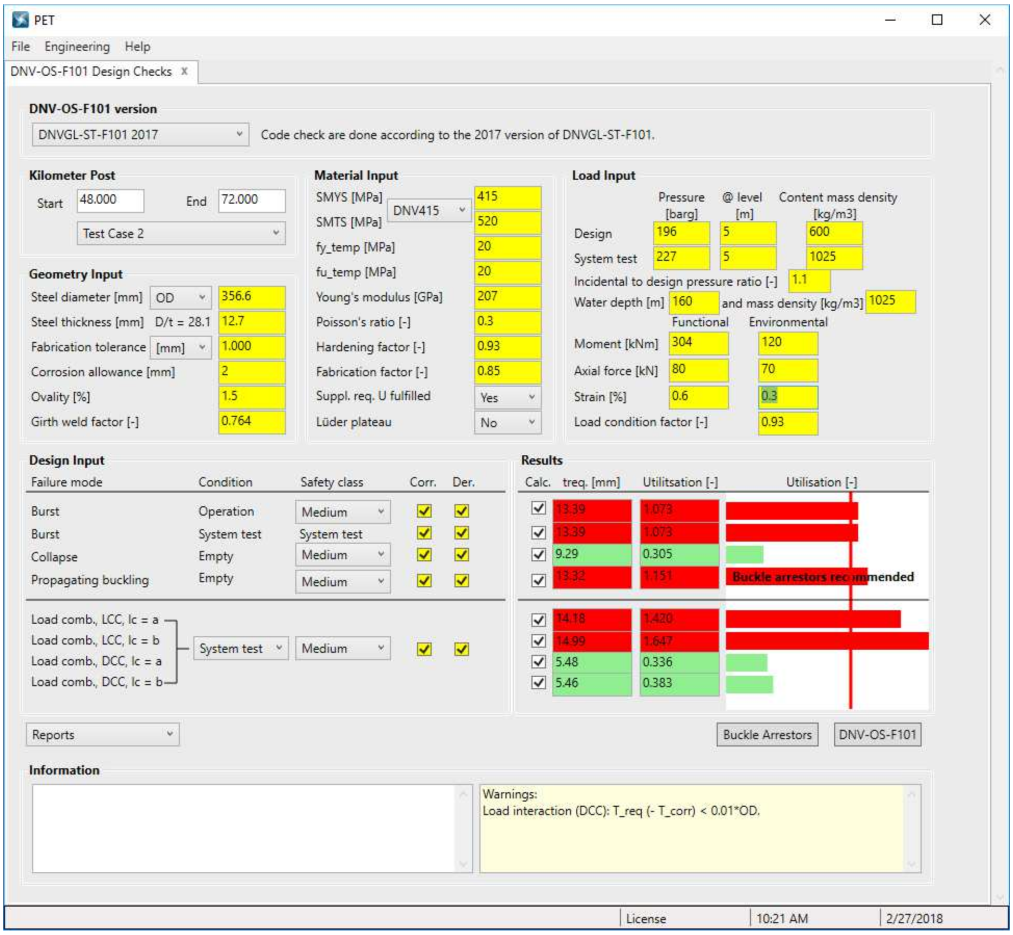


Figure 4-1 DNV-OS-F101 calculation module

Minimum required wall thickness and utilisation are given for eight set of design checks:

1. Burst during operation.
2. Burst during the system pressure test.
3. Collapse.
4. Propagating buckling.
5. Load combination, load controlled (LCC), load combination a.
6. Load combination, load controlled (LCC), load combination b.
7. Load combination, displacement controlled (DCC), load combination a.
8. Load combination, displacement controlled (DCC), load combination b.

Utilisation is also presented graphically in a lateral column diagram. The vertical red line represents unity, whereas the eight lateral columns present the proportional utilisation for each design check. The columns appear in a green colour if the utilisation ratio is less than or equal to one, i.e. the design check is passed, and in a red colour if utilisation is greater than one, i.e. the design check is violated.

Note that the user can check off the design checks that one will apply (to the left of the graphical presentation). Input boxes that are required for the design checks will appear with a yellow colour.

Report sheets can be generated and printed for the various limit states. This can be done by choosing in the "Reports" drowpdown menu, as seen in the bottom left of the module.

For the calcuation of local buckling, i.e list item 5, 6, 7 and 8 given above, and for external overpressure, it should be noted that the the minimum internal pressure in DNVGL-ST-F101 is the minimum which can be sustained. This is normally taken as zero as for installation except for cases where the pipeline is installed water filled. In order to be conservative, PET uses and minimum internal pressure as zero.

Buckle arrestors:

When the required thickness due to propagating buckling is larger than the nominal specified thickness, the required thickness for buckle arrestors may be calculated. The calculations are calculated according to DNVGL-ST-F101, ref. /3/. Thickness for up to three buckle arrestors can be calculated simultaniously.

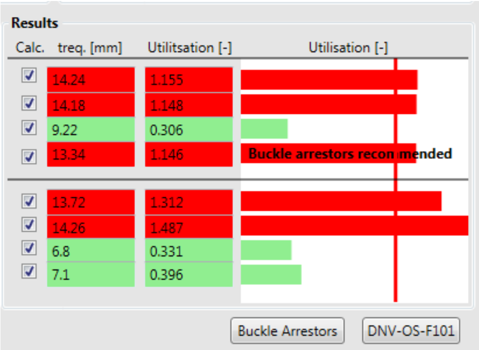


Figure 4-2 Buckle arrestors recommended

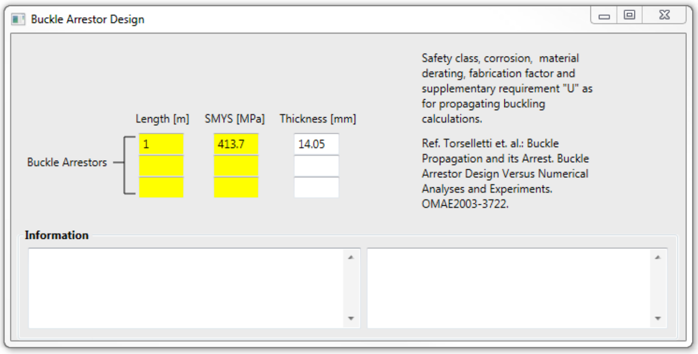


Figure 4-3 Buckle arrestor calculations

4.2 Weight and Volume

4.2.1 Introduction

The main purpose of this module is to calculate the volume, mass and dry weight of the components that constitute a pipeline, i.e. steel, coating layers and content. Volume, mass and dry weight are calculated individually and totally, per metre pipeline and totally for a given length of the pipeline.

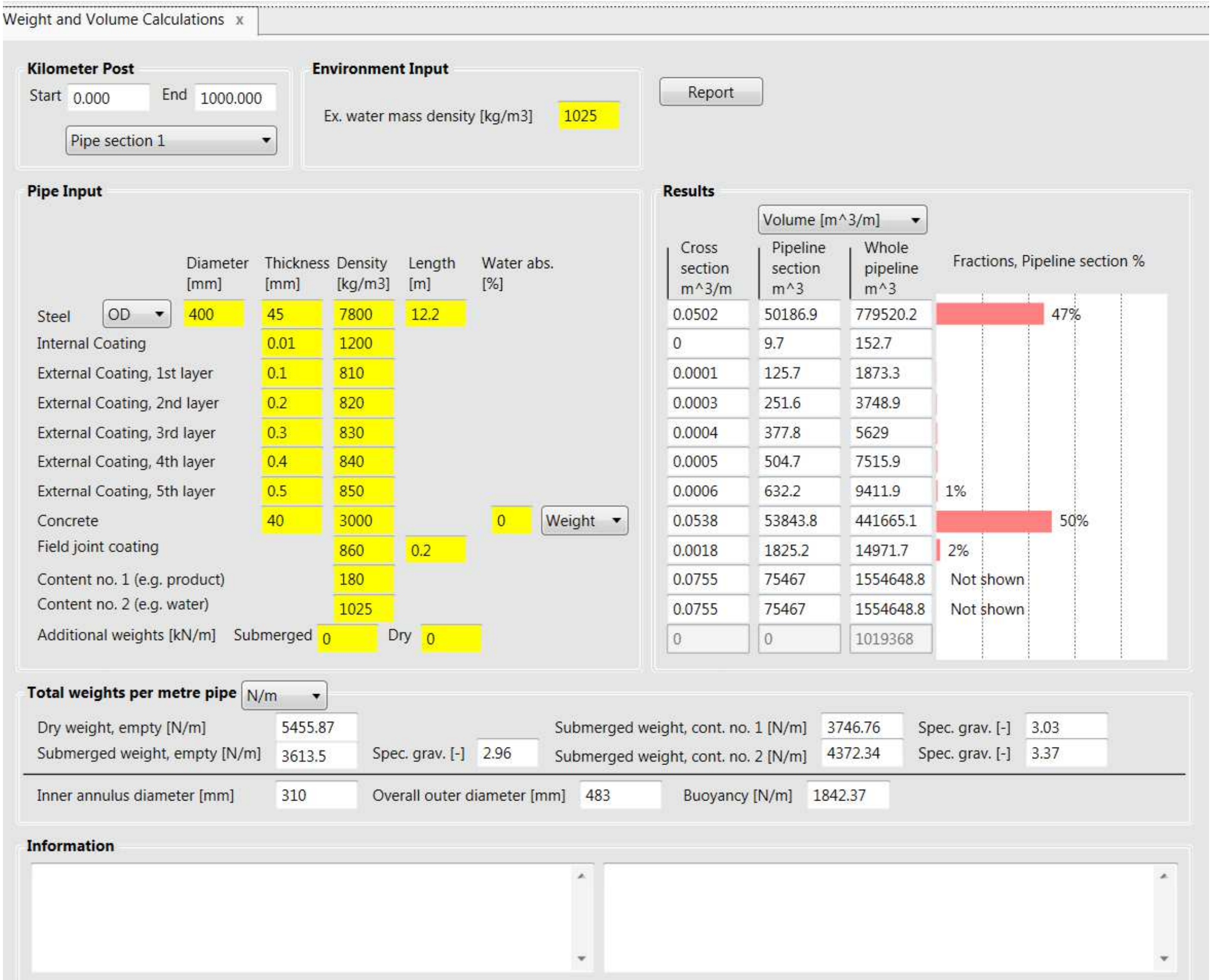


Figure 4-4 Weight and Volume calculation module

4.2.2 Input

The size of the pipe is determined by the steel diameter. Input is typically the thickness (per millimeter) of each layer, inner coating, steel, outer coating, concrete coating and additional weights, e.g. anodes.

Concrete coating water absorption can be given in per cent of concrete volume or concrete weight.

The joint length and cut back length are given in order to determine the relative volume of concrete coating and field joint coating.

Mass density is given in order to calculate buoyancy.

4.2.3 Results

The volume of each layer is calculated per metre as:

$$V_i = \frac{\pi}{4}\left(D_{o,i}^2 - D_{i,i}^2\right)\cdot L_i \qquad \textbf{(4.1)}$$

where $D_{o,i}$ and $D_{i,i}$ are the outer and inner diameter of layer no. *i* and L_i is the length of the layer. The sequence of the layers from the inside and outward is:

1. internal coating
2. steel
3. external coating no. 1
4. external coating no. 2
5. external coating no. 3
6. external coating no. 4
7. external coating no. 5
8. concrete and field joint coating

L_i is only different from unity for the concrete and field coating. The volumes of these layers are smeared over the unit length according to their partial lengths over one pipe joint length. If the pipe joint length is denoted L_{jt} and the cut back length is denoted L_{cb}, then

$$L_{concrete} = \frac{L_{jt} - 2\cdot L_{cb}}{L_{jt}} \text{ and } L_{fieldcoat} = \frac{2\cdot L_{cb}}{L_{jt}} \qquad \textbf{(4.2)}$$

The mass and weight of each layer is calculated per metre as:

$$m_i = \rho_i \cdot V_i \qquad \textbf{(4.3)}$$

where ρ_i is the mass density of layer no. *i*.

$$w_i = g \cdot m_i \qquad \textbf{(4.4)}$$

where *g* is the acceleration of gravity (= 9.81m/s^2).

The volume of the content is calculated according to (4.1) with an inner diameter equal to zero.

Buoyancy per metre pipe is calculated according to the following formula:

$$w_b = g \cdot \rho_w \cdot \frac{\pi}{4} \cdot D_o^2 \text{ - Additional Submerged weight + Additional Dry weight} \qquad \textbf{(4.5)}$$

where ρ_W is the mass density of water and D_o is the outer diameter of the outer-most layer defined.

The results are given individually for each pipe component, including steel, all coating layers, two defined contents and additional weights, by following a horizontal line from the input frame at the left to the result frame at the right, see figure below. The results can be given as volume, mass or weight depending on the choice in the combo box above the results. One column gives the result per metre pipeline and one column gives the results for the whole pipeline profile.

The results per metre pipeline are also displayed graphically to the very right.

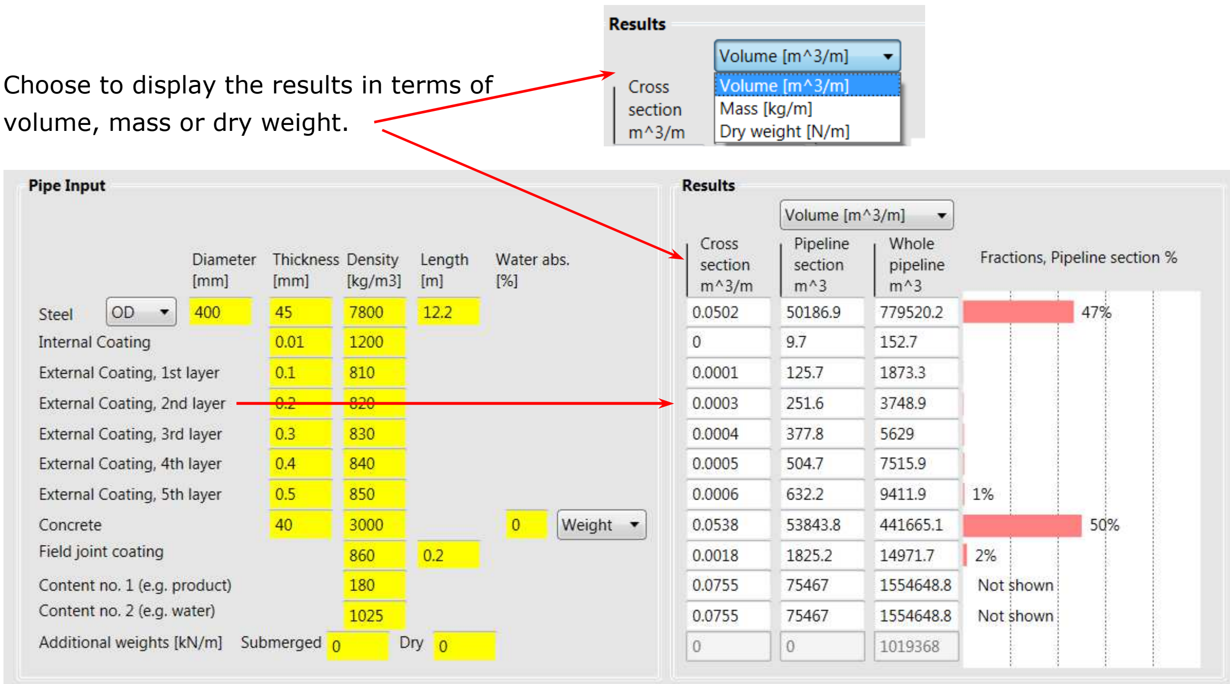


Figure 4-5   Pipe Input and results

At the lower part of the window, some additional results are given:

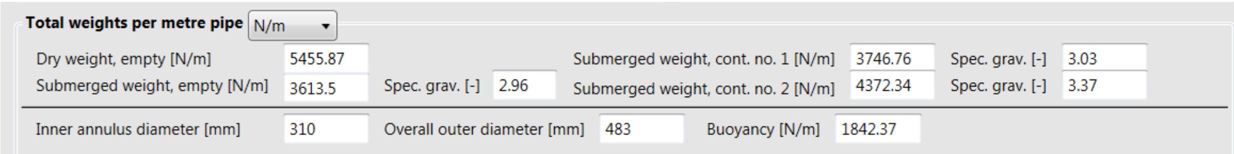


Figure 4-6 Results

The following notes apply:

- Absorbed water in concrete is not included in the mass and dry weight results.
- The field coating length is measured from the end of the concrete coating to the weld, i.e. the total field coating length on one pipe joint is twice the given length.
- Additional dry weight is not included in submerged weight results.
- Additional submerged weight is not included in mass and dry weight results.
- Volume is not calculated for additional weights.

4.3 Expansion

4.3.1 Introduction

The purpose of this module is to calculate the end expansion due to temperature and internal pressure. The anchor length is also calculated. These two results are presented for the system pressure condition and the design condition.

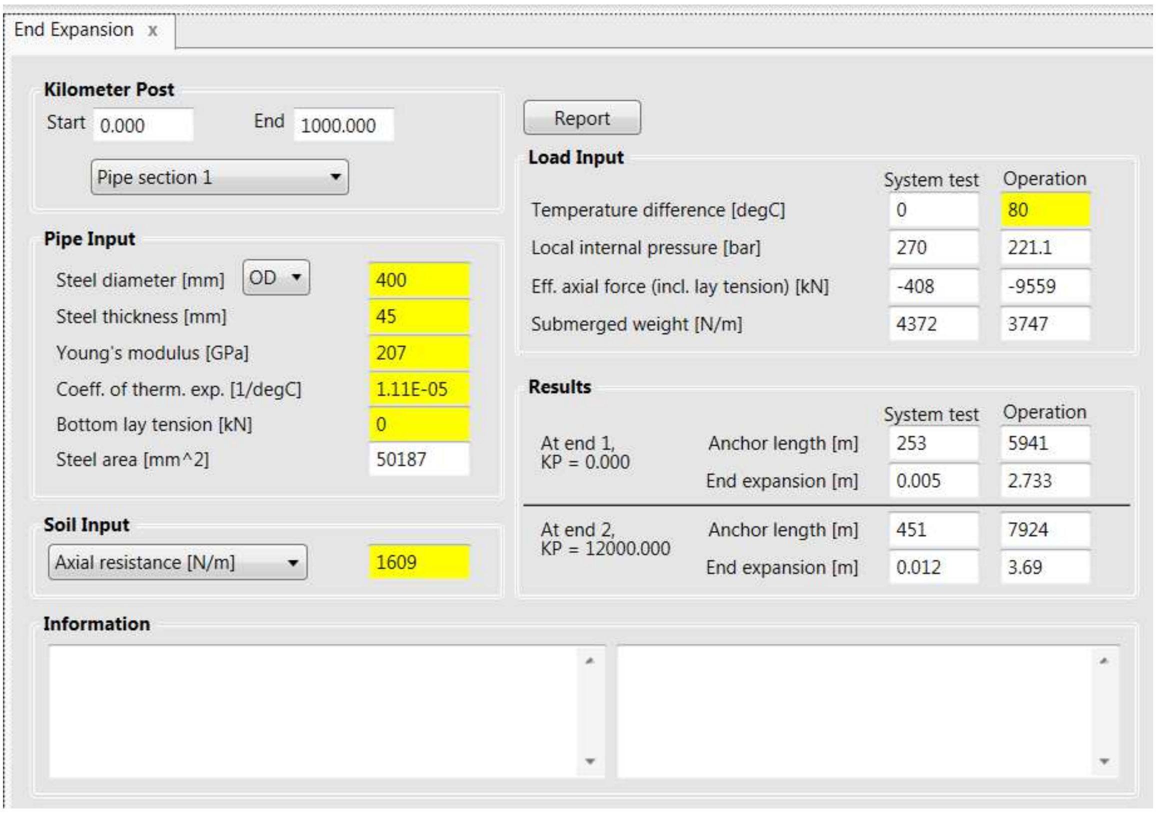
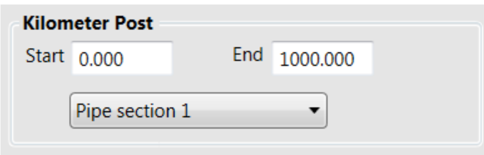


Figure 4-7 Expansion calculation module

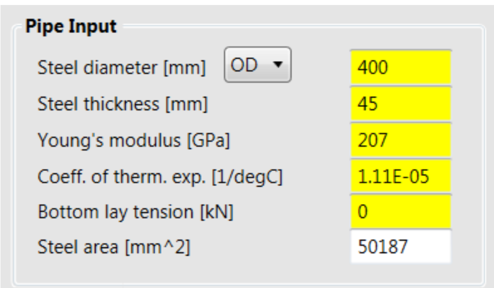
4.3.2 Input

Pipe length:



L_p Pipe length in km (to be inputed in Sectioning).

Steel cross section:



D Steel pipe diameter [mm]. Note that the user may specify inner or outer diameter depending on the selection of the combo box.

t Steel wall thickness [mm].

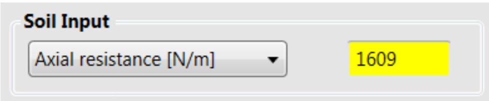
A_s Steel area [mm^2]= $\pi(D^2 - (D - 2 * t)^2)/4$ is calculated, not specified by user.

E Young's modulus [GPa].

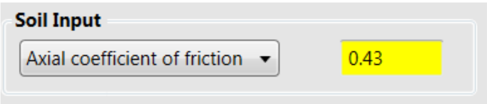
α Coefficient of thermal expansion.

S_{Bottom} Bottom laytension [kN]

Soil parameters:



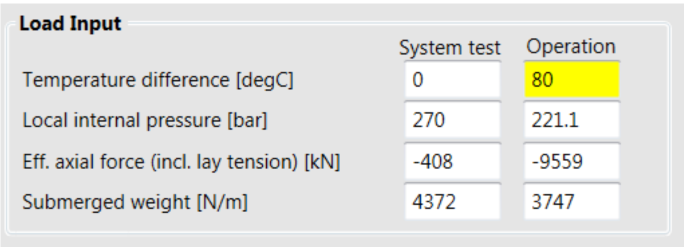
f_a Axial resistance.



μ Axial coefficient of friction.

The soil parameter input can be chosen as either axial resistance or axial friction coefficient. In the latter case, the resistance is calculated as $f_a = \mu \cdot w_s$.

Load input:



ΔT Temperature difference (set to 0 for system test)

Δp_i Local internal pressure [bar] (auto calculate)

S_{eff} Effective axial force [kN] (auto calculate)

w_s Submerged weight [N/m]

Effective axial force and submerged weight enters the equation for anchor length and end expansion.

Reference is made to the Weight and Volume module regarding calculation of submerged weight w_s and the input parameters for this calculation.

Parameters that determine internal pressure difference Δp_i and hence the associated components in the effective axial force, (reference pressure, content mass density, depth etc.) are given on the DNV-OS-F101 Design Check Module.

4.3.3 Results

The results produced by this module:

Results

		System test	Operation
At end 1, KP = 0.000	Anchor length [m]	217	5933
	End expansion [m]	0.004	2.73
At end 2, KP = 12000.000	Anchor length [m]	336	7568
	End expansion [m]	0.009	3.524

L_a Anchor length (whole pipelines)

δ_e End expansion (whole pipelines)

The anchor length L_a and end expansion δ_e are calculated according to the following formulae, note that the anchor length does not exceed half the given pipeline length:

$$L_a = \frac{S_{eff}}{f_a} \leq \frac{L_p}{2} \qquad \textbf{(4.6)}$$

and

$$\delta_e = \frac{1}{2} \cdot \frac{S_{eff} \cdot L_a}{E \cdot A_s} \qquad \textbf{(4.7)}$$

where the contributing effective axial force is

$$S_{eff} = H - (1 - 2 \cdot \nu) \cdot A_i \cdot \Delta p_i - E \cdot A_s \cdot \alpha \cdot \Delta T \qquad \textbf{(4.8)}$$

Note that the temperature ΔT and the internal pressure Δp_i are both assumed to be elevations compared to the installation condition.

D is in the equation above the *outer* steel wall diameter irrespective of which diameter is specified by the user.

4.4 Upheaval Buckling

4.4.1 Introduction

The purpose of this module is to:

- estimate the safety level with respect to upheaval buckling for the given set of input,
- predict the temperature, internal pressure and imperfection height that will trigger upheaval buckling and
- estimate the cover height to prevent upheaval buckling for a given safety level.

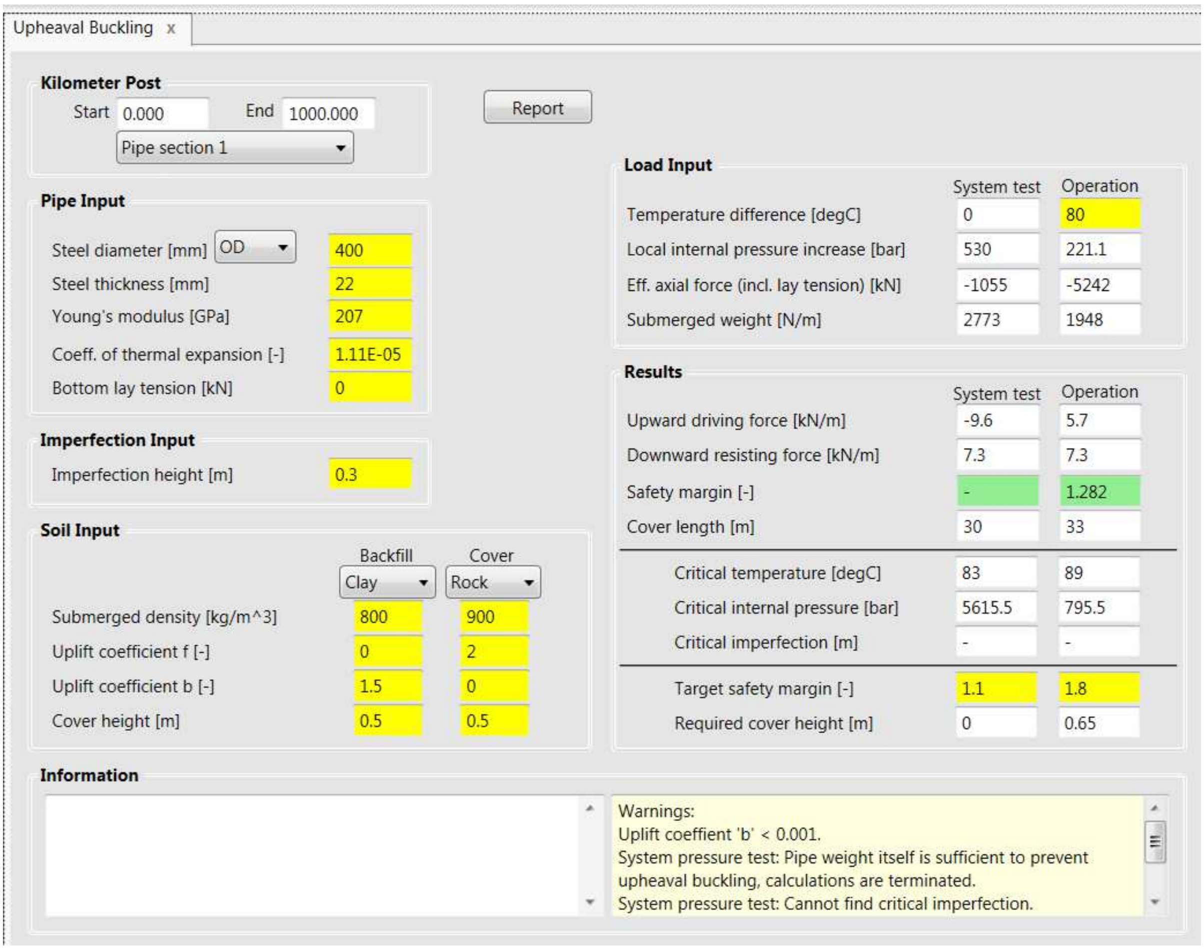


Figure 4-8 Upheaval Buckling calculation module

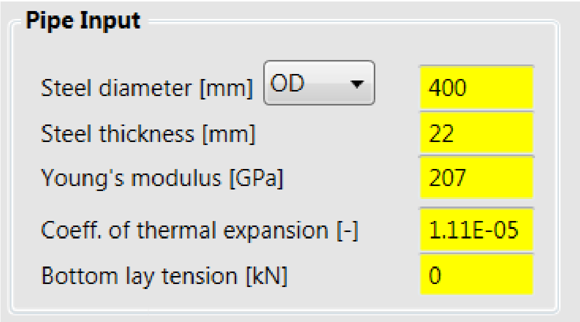
The model used here is a modification of that described in Ref. /6/ and Ref. /7/.

Warning: The user is warned that this simplified method is semi-empirical, and that on its own will normally not be adequate for design. It has been calibrated against more refined models, but does not always yield conservative results, especially if there is a possibility of plastic deformation of the pipe wall.

4.4.2 Input

The input parameters are separated in four groups:

1: Input related to the steel cross section:



D Steel pipe diameter. Note that the user may specify inner or outer diameter depending on the selection of the combo box.

t Steel wall thickness.

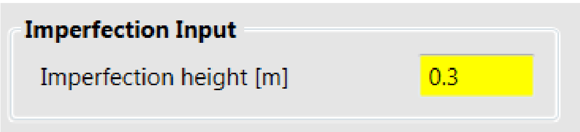
E Young's modulus.

ν Poisson's ratio.

α Coefficient of thermal expansion.

H Lay tension.

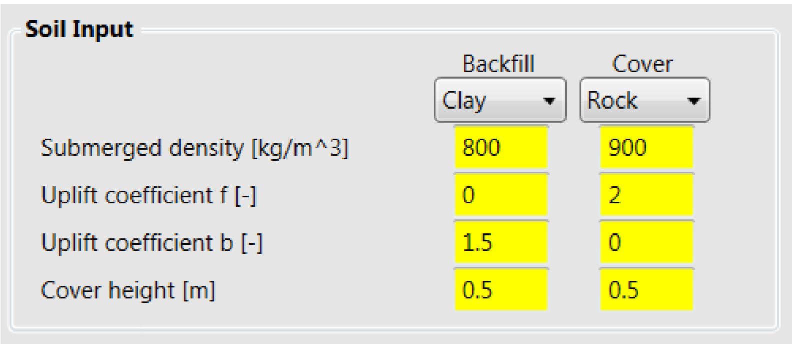
2: Input related to imperfection:



δ_{imp} Imperfection height.

3: Input related to soil cover:

Typical input values are inserted by the program depending on the user's selection on the two combo boxes. In the following the sub scripts "*bf*" and "*c*" are used to denote back fill and cover for the two columns of input.



ρ_{bf} and ρ_c The soils' submerged mass density

f_{bf} and f_c Uplift coefficient.

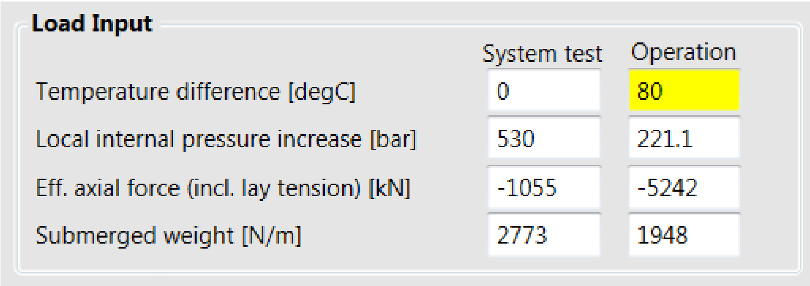
b_{bf} and b_c Uplift coefficient.

h_{bf} and h_c Cover height.

The following values are recommended for the uplift coefficients:

Cover type	*f*	*b*
Rock and gravel	0.5	1.0
Sand and silt	0.1	1.0
Clay	0.0	1.5

4: Input related to loads contributing to the effective axial compression:



ΔT — Temperature elevation relative to the installation condition.

Δp_i — Local internal pressure which is calculated, not specified by the user. Editing is done on the DNV-OS-F101 Design Check Module.

Note that depending on the specification of the condition in the column, internal pressure is taken from the design condition or the system pressure test condition.

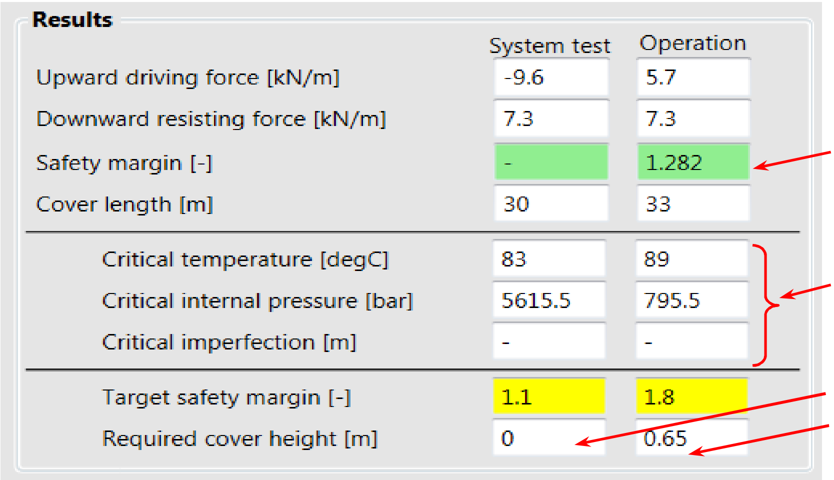
Δp_e — Local external pressure which is calculated as $\rho_w \cdot g \cdot d$, not specified by the user. Editing is done on the DNV-OS-F101 Design Check Module.

S_{eff} — These are intermediate parameters for estimating the safety level with respect to upheaval buckling. All are calculated automatically by the program, and not specified by the user.

w_s — Submerged weight which is calculated, not specified by the user. Reference is made to the Weight and Volume Module.

4.4.3 Results

The results produced by this module are:



Safety margin with respect to upheaval buckling for the given set of input.

The temperature, internal pressure and imperfection height that will trigger upheaval buckling.

Required cover height to prevent upheaval buckling for a given safety level (the target safety margin is user input).

The safety margin with respect to upheaval buckling is defined as:

$$SM_{uh-b} = \frac{W_{d-r}}{W_{u-l}} \quad \textbf{(4.9)}$$

where the downward resistance W_{d-r} and the uplifting driving load W_{u-l} are defined as follows:

$$W_{d-r} = (h_{bf} \cdot \rho_{bf} \cdot b_{bf} + h_c \cdot \rho_c \cdot b_c) \cdot D_o \cdot g + \left(h_{bf}^2 \cdot \rho_{bf} \cdot f_{bf} + h_c^2 \cdot \rho_{bf} \cdot f_c\right) \cdot g \quad \textbf{(4.10)}$$

and

$$W_{u-l} = 1.16 \cdot S_{eff} \cdot \sqrt{\frac{\delta_{imp} \cdot w_s}{EI}} - 4.76 \cdot w_s \quad \textbf{(4.11)}$$

See Eq. (4.8) for calculation of effective axial force S_{eff}.

Note that the uplifting load may be negative and thus give a negative safety margin displayed by [-].

Note also that that the specification of certain properties for backfill *and* cover will lead to a somewhat lower safety margin compared to the case where backfill *or* cover is specified with the same properties and the same total height. This is due to the non-linear relation between h_i and resistance and the fact that $h_{bf}^2 + h_c^2 \leq \left(h_{bf} + h_c\right)^2$

Critical temperature is the temperature that initiates upheaval buckling for the given set of input (including the given internal pressure and imperfection height).

Critical internal pressure is the pressure that initiates upheaval buckling for the given set of input (including the given temperature and imperfection height).

Critical imperfection height is the imperfection height that initiates upheaval buckling for the given set of input (including the given temperature and internal pressure).

These three parameters are found by an iterative algorithm. For extreme input data, the program may fail in finding these parameters.

Warning: The user is warned that this simplified method is semi-empirical, and that on its own will normally not be adequate for design. It has been calibrated against more refined models, but does not always yield conservative results, especially if there is a possibility of plastic deformation of the pipe wall.

4.5 Stability

4.5.1 Introduction

This module estimates the:

- safety level with respect to stability for the given set of input,
- weight coating required to ensure stability for a given safety level and
- steel wall thickness required to ensure stability for a given safety level.

The Stability calculation module interprets DNVGL-RP-F109, ref. /4/, by running the same calculation procedure as StableLines. The stability module in PET includes generalised method and calculates the minimum weight to obtain a 10D displacement criterion. Only a limited input and output is provided. For 5D displacement, Intermediate satbility criterion, absolute stability criterion and useful input, output and plots, please contact DNV GL software for more details about the StableLines software.

It should be noted that when opening the new stability module with an PET V3.1-01 or older input file, several input will be set to dummy values.

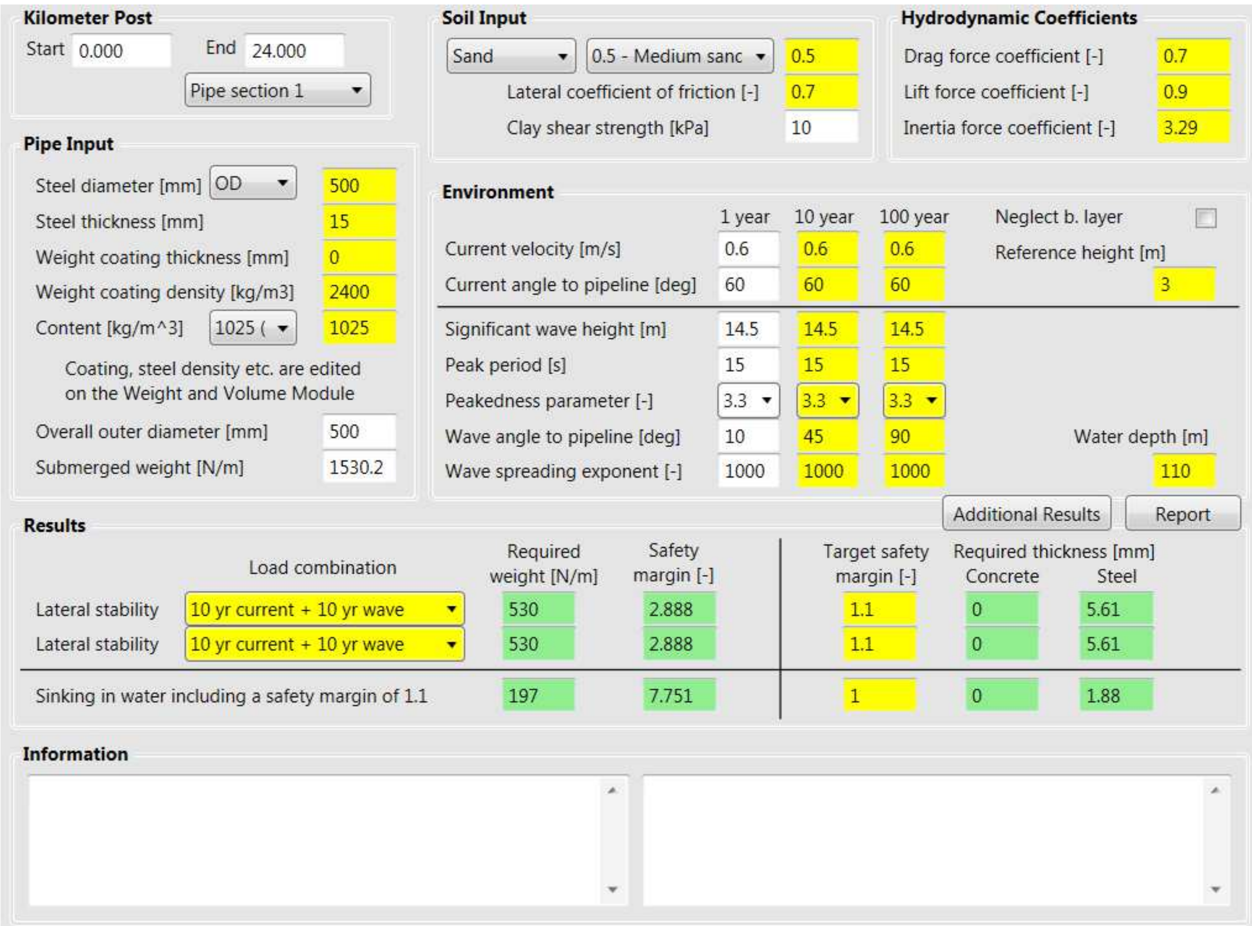
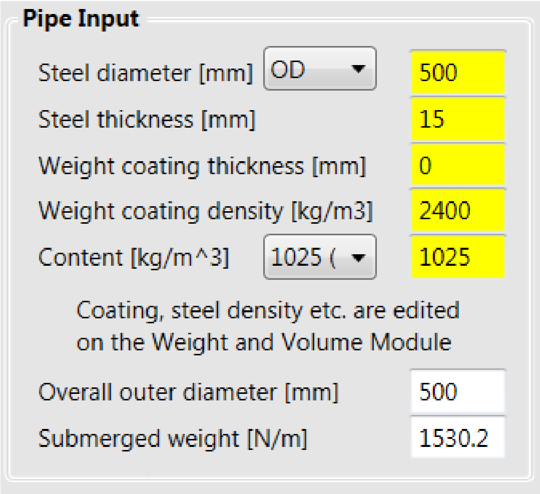


Figure 4-9 On bottom stability calculation module

4.5.2 Input

The input parameters (excluding the choice of load cases) are separated in four groups:

1: Input related to the steel cross section:



D — Steel pipe diameter. Note that the user may specify inner or outer diameter depending on the selection of the combo box.

t — Steel wall thickness.

t_w — Weight coating thickness.

ρ_w — Weight coating mass density.

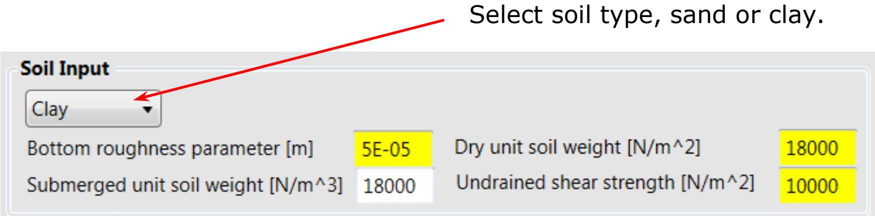
ρ_i — Content mass density.

D_{po} — Pipe outer diameter including all external coating layers is calculated, not specified by the user. Reference is made to the Weight and Volume Module.

w_s — Submerged weight is calculated, not specified by the user. The weight calculations are based on data provided from the Weight and Volume calculation module. However, internal coating and additional weights are not included in the Stability module. FJC is calculated based on 12.2 pipe joints.

2: Input related to soil:

Select soil type, sand or clay.



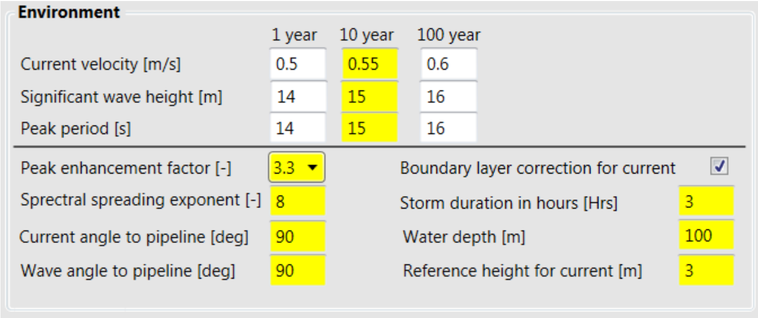
z_0 — Seabed roughness, depending on soil

γ_s' — Submerged unit soil weight (sand)

γ_s — Dry unit soil weight (clay)

s_u — Un-drained clay shear strength

3: Environmental data:



u_{cr} Extreme current velocity with 1, 10 and 100 years return period

H_s Extreme values for significant wave height with 1, 10 and 100 years return period

T_p Associated peak periods

γ Associated peak enhancement factor

s Spectral spreading exponent

Θ_c Associated current angle to pipeline

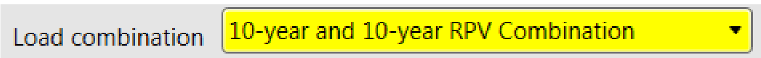
Θ_w Associated wave angle to pipeline

T_{storm} Storm duration specified in hours

Check box if boundary layer correction for current is to be included in calculations.

d Water depth

z_r Reference height above seabed at which current velocities are given.

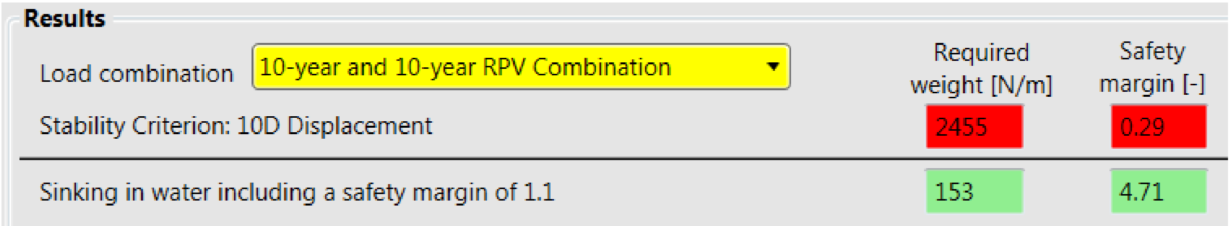


A pull down menu allow the user to choose from the following Design conditions:

- 1-year and 1-year RPV Combination
- 1-year and 10-year RPV Combination
- 1-year and 100-year RPV Combination
- 10-year and 10-year RPV Combination
- 10-year and 100-year RPV Combination
- 100-year and 100-year RPV Combination

4.5.3 Results

The main results produced by this module are the required weight and safety margins with respect to lateral stability and sinking in sea water.



The safety margin with respect to lateral stability is defined as the ratio between actual submerged weight (see pipe input data) and the required weight calculated by the program:

$$SM_{stb-l} = \frac{w_s}{w_{req-l}} \qquad \textbf{(4.12)}$$

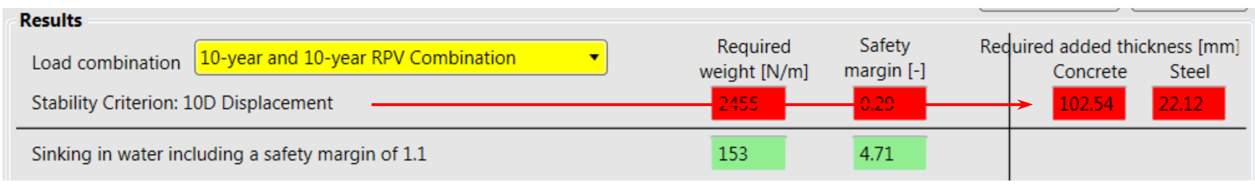
The safety margin with respect to sinking is defined as the ratio between actual submerged weight (see pipe input data) and the required weight calculated by the program, including a safety factor of 1.1:

$$SM_{stb-v} = \frac{w_s}{w_{req-v}} \qquad \textbf{(4.13)}$$

The required submerged weight is taken as:

$$w_{req-v} = 0.1 \cdot \frac{\pi \cdot D_{po}^2}{4} \cdot \rho_w \cdot g \qquad \textbf{(4.14)}$$

Other results produced by this module are the required added steel or concrete with respect to lateral stability. It is important that the required added thickness is implemented into the input in order to confirm the result.



The lateral stability calculations does not calculate required weight with initial penetration.

Warning and error messages are shown in the bottom right of the Stability module. Error messages terminates calculations while warning messages don't. Note that both warning messages and error messages can be shown at the same time.

4.6 Free Span

4.6.1 Introduction

The purpose of this module is to calculate the allowable free span length considering in-line and cross-flow vortex induced vibrations. The module is valid for both operational and temporary phase. The module also gives the buckling length (pinned-pinned, pinned-fixed and the approximate response for pipeline on the seabed given in DNV-RP-F105, ref. /5/. Please note that the screening criterion in DNVGL-RP-F105 is the same as in DNV-RP-F105 2006) for the given effective axial force. Note that this method should be applied only for screening analysis. For detail engineering more detailed analysis should be performed.

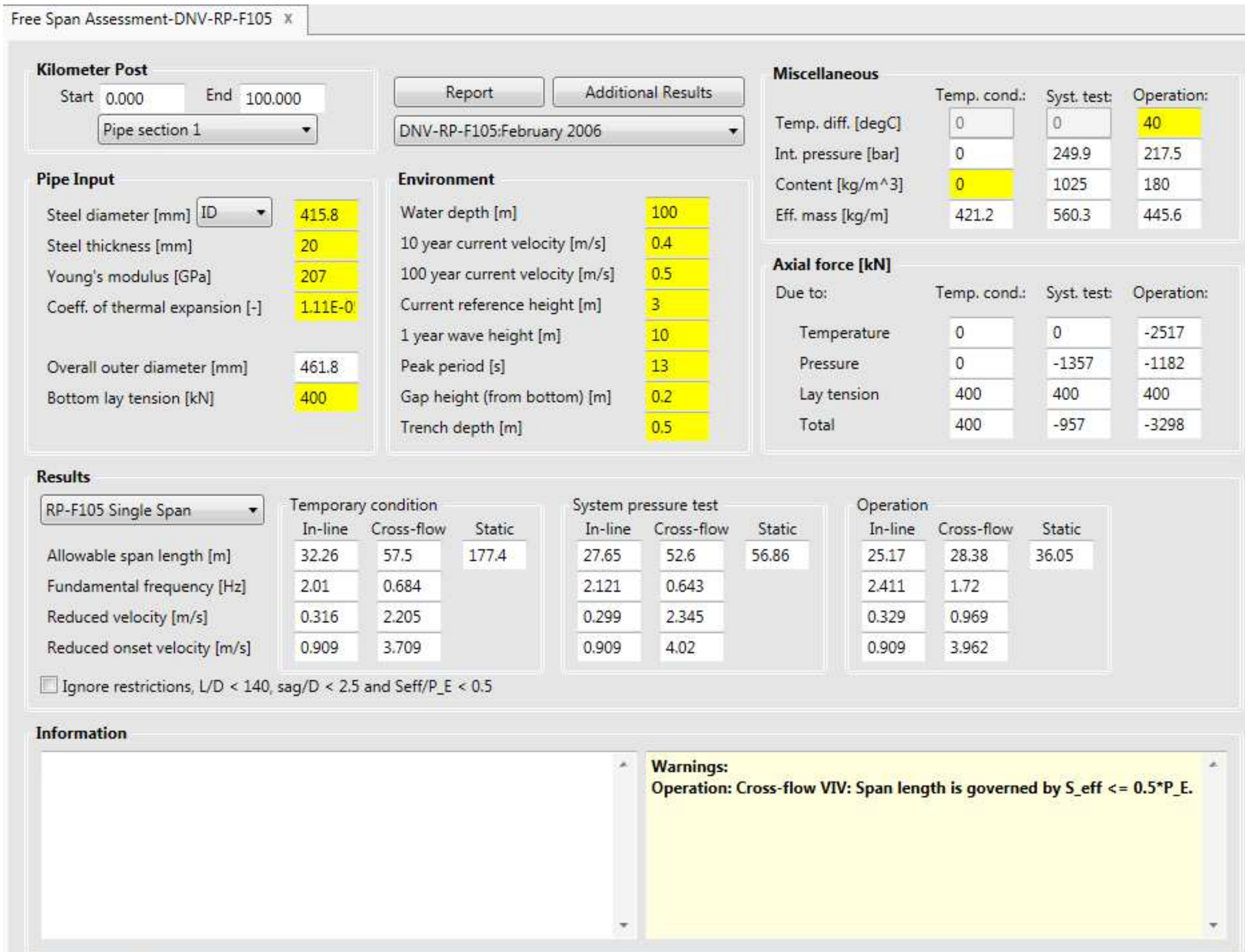
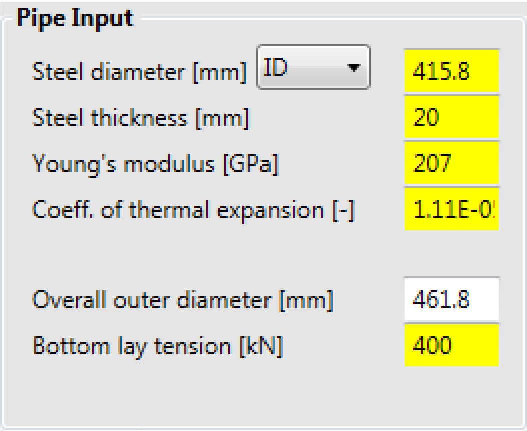


Figure 4-10 Free Span calculation module

4.6.2 Input

The input parameters are separated in four groups:

1: Input related to the pipe:



D Steel pipe diameter. Note that the user may specify inner or outer diameter depending on the selection of the combo box.

t Steel wall thickness.

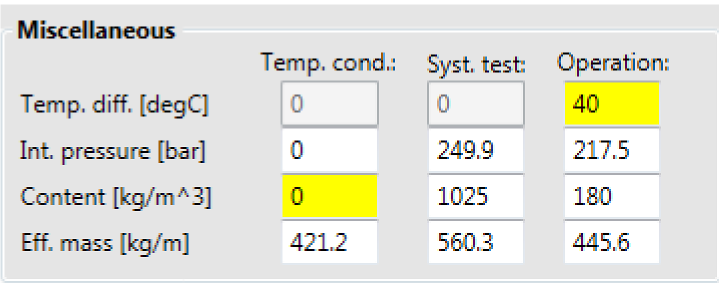
E Young's Modulus.

α Coefficient of thermal expansion.

D_{po} Pipe outer diameter including all external coating layers is calculated, not specified by the user. Reference is made to the Weight and Volume Module.

S_{lay} Lay tension.

2: Input related to the axial compressive force:



p_i Local internal pressure (edited on the DNV-OS-F101 Design Checks module).

ΔT Temperature difference.

ρ_c Content density.

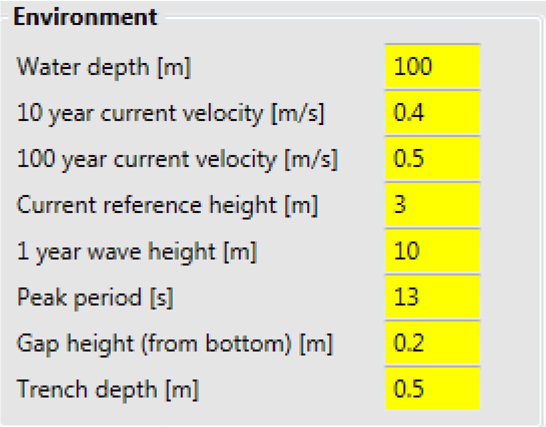
m_e Effective mass. It is calculated, not specified by the user. Reference is made to the Weight and Volume Module.

Internal pressure is provided in DNV-OS-F101 module. Local internal pressure is calculated based on water depth, see item 3. Operational pressure is taken as the design pressure provided in DNV-OS-F101 Design Checks module.

Temperature difference from as laid condition is zero by default.

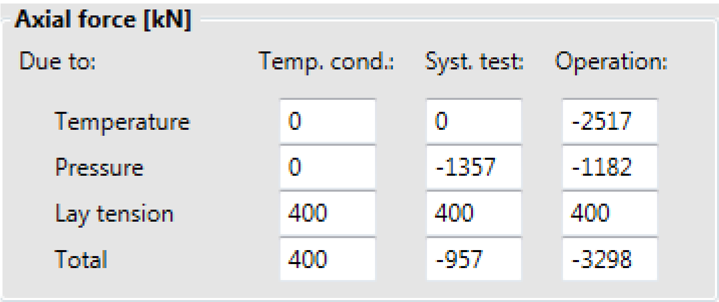
Content density for system pressure test and operational conditions are provided in DNV-OS-F101 Design Checks module. Operational content is taken as the design content.

3: Environmental data:



d	Water depth.
$U_{c,10yr}$	Extreme value for current velocity with 10 years return period.
$U_{c,100yr}$	Extreme value for current velocity with 100 years return period.
z_r	Reference height for the given current velocity.
$H_{w,1yr}$	Extreme value for significant wave height with 1 year return period.
T_p	Corresponding peak period.
e	Gap height between pipe and sea bed.
d_t	Trench depth taken three pipe diameters away from the pipe.

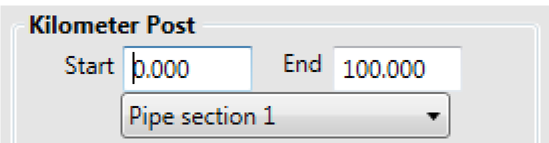
4: Compressive axial force components:



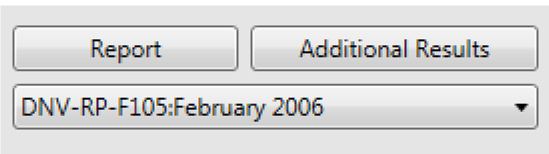
Tension is positive.

Note that these values are all calculated by the program and cannot be edited.

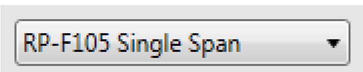
5: Additional input:



Selection of which pipeline section the calculations apply.



Selection of design code.



Boundary condition selection (pinned-pinned, fixed-fixed or approximation given in DNV-RP-F105 for single span on the seabed).

4.6.3 Results

The screening criterion as outlined in DNV-RP-F105 is applied with safety factors that have been calibrated against full fatigue analyses to provide fatigue life in excess of 50 years. This means that the method cannot readily be applied for shorter design lives, e.g. temporary phases. However, by applying 10 years return period value for current for the appropriate season instead of 100 years return period value, this method may also be used for temporary phases (as-laid/empty and flooded) provided that these will last for short durations.

Results

RP-F105 Single Span

	Temporary condition			System pressure test			Operation		
	In-line	Cross-flow	Static	In-line	Cross-flow	Static	In-line	Cross-flow	Static
Allowable span length [m]	32.26	57.5	177.4	27.65	52.6	56.86	25.17	28.38	36.05
Fundamental frequency [Hz]	2.01	0.684		2.121	0.643		2.411	1.72	
Reduced velocity [m/s]	0.316	2.205		0.299	2.345		0.329	0.969	
Reduced onset velocity [m/s]	0.909	3.709		0.909	4.02		0.909	3.962	

The main results from this module are allowable span lengths for in-line and cross-flow vibrations. In addition, the program gives the associated fundamental frequency, reduced velocity and at which reduced particle velocity vibrations are set on.

The allowable span lengths are limited by the two expressions below:

The in-line fundamental frequency f_{0-in} must fulfil:

$$\frac{f_{0-in}}{\gamma_f} \geq \frac{U_{c,Xyr}}{V^{il}_{R-onset}\cdot D}\cdot\left(1-\frac{L}{250\cdot D}\right)\cdot\frac{\gamma_{il}}{\overline{\alpha}} \qquad \textbf{(4.15)}$$

And the cross-flow fundamental frequency f_{0-cr} must fulfil:

$$\frac{f_{0-cr}}{\gamma_f} \geq \frac{U_{c,Xyr}+U_{w,1yr}}{V^{cf}_{R,onset}\cdot D}\cdot\gamma_{cf} \qquad \textbf{(4.16)}$$

where:

$U_{c,Xyr}$ is the 100 year current velocity at the pipeline level, $U_{c,100\,yr}$, in Operation case or is the 10 year current velocity at the pipe level, $U_{c,10\,yr}$, in Temporary Condition and System Pressure Test cases.

$U_{w,1\,yr}$ is 1 year wave induced velocity at the pipeline level.

$V^{in}_{R-onset}$ is the in-line onset value for reduced velocity.

$V^{cr}_{R-onset}$ is the cross-flow onset value for reduced velocity. **(4.17)**

$\overline{\alpha}=\frac{U_c}{U_c+U_w}$ is the current flow ratio.

L is the span length.

$\gamma_f=1.20$ is a safety factor on the fundamental frequency.

$\gamma_{il} = \begin{cases} 1.15 & DNV-RP-F105: March\ 2002 \\ 1.4 & DNV-RP-F105: February\ 2006 \end{cases}$ is a safety factor for the in-line screening criterion.

$\gamma_{il} = \begin{cases} 1.3 & DNV-RP-F105: March\ 2002 \\ 1.4 & DNV-RP-F105: February\ 2006 \end{cases}$ is a safety factor for the cross-flow screening criterion.

The water particle velocity induced by current and waves at the pipeline level are found through the same algorithm described in relation with the stability module.

The fundamental frequency is calculated from the following general formula:

$$f_0 = C_1 \cdot \sqrt{1+CSF} \cdot \sqrt{\frac{EI}{m_e \cdot L^4} \cdot \left(1 + C_2 \cdot \frac{S_{eff}}{P_E} + C_3 \cdot \left(\frac{\delta}{D_{po}}\right)^2\right)} \tag{4.18}$$

where

CSF represents the stiffening effect of concrete coating, here set to zero.

EI is the pipe's bending stiffness.

m_e is the pipe's effective mass per unit length $= m_p + \frac{\pi \cdot D_{po}^2}{4} \cdot C_a$

m_p is the dry weight of the pipe and content

C_a is the added mass coefficient = $\begin{cases} 0.68 + \frac{1.6}{1+5e/D} & \text{for } e/D < 0.8 \\ 1 & \text{for } e/D \geq 0.8 \end{cases}$

e is the gap between pipeline and seabed.

P_E is the Euler buckling load $= (1+CSF) \cdot \frac{\pi^2 EI}{L^2}$ **(4.19)**

S_{eff} is the effective axial force according to Eq. (4.8)

δ is the static deflection $= C_6 \cdot \frac{q \cdot L^4}{EI \cdot (1+CSF)} \cdot \frac{1}{\left(1 + C_2 \frac{S_{eff}}{P_E}\right)}$

C_1, C_2, C_3 and C_6 are boundary condition coefficients:

Boundary condition	Pinned-Pinned	Fixed-Fixed	RP-F105 Single Span
C_1	1.57	3.56	3.56
C_2	1.00	0.25	0.25
C_3	0.8	0.2	0.4
C_6	5/384	1/384	1/384

The onset reduced velocity for in-line motion is calculated as:

$$V_{R-onset}^{il} = \begin{cases} 1.0/\gamma_{on} & \text{for} \quad K_{sd} \le 0.4 \\ (0.6 + K_{sd})/\gamma_{on} & \text{for} \quad 0.4 < K_{sd} \le 1.6 \\ 2.2/\gamma_{on} & \text{for} \quad K_{sd} > 1.6 \end{cases} \quad \textbf{(4.20)}$$

$K_{sd} = \frac{4\pi \cdot m_e \cdot \zeta_T}{\rho_w \cdot D^2 \cdot \gamma_k}$ is the stability parameter in which the damping $\zeta_T = 1\%$ and

$\gamma_k = 1.30$ is a safety factor on the stability parameter.

$\gamma_{on} = 1.10$ is a safety factor on the onset velocity.

The onset reduced velocity for cross-flow motion is calculated as:

$$V_{R-onset}^{cr} = \frac{3 \cdot \psi_{proxi,onset} \cdot \psi_{mass,onset} \cdot \psi_{\alpha,onset} \cdot \psi_{trench,onset}}{\gamma_{on}}$$

$$\psi_{proxi,onset} = \begin{cases} \frac{1}{4} \cdot (3 + 1.25e/D) & \text{for} \quad e/D \le 0.8 \\ 1 & \text{else} \end{cases}$$

$$\psi_{mass,onset} = \begin{cases} \frac{1}{2} + \frac{1}{3} \cdot \frac{\rho_p}{\rho_w} & \text{for} \quad \frac{\rho_p}{\rho_w} \le 1.5 \\ 1 & \text{else} \end{cases} \quad \textbf{(4.21)}$$

$$\psi_{\alpha,onset} = \begin{cases} 1 + \overline{\alpha}/3 & \text{for} \quad \overline{\alpha} \le 0.5 \\ 1.167 & \text{else} \end{cases}$$

$$\psi_{trench,onset} = 1 + 0.5 \cdot \Delta/D, \ \Delta/D = (1.25 \cdot d - e)/D, \ 0 \le \Delta/D \le 1$$

where d is the trench depth relative to a point three diameters away from the pipe, an ρ_p is the specific mass density of the pipe, not including added mass.

The reduced velocities presented by the module are for the in-line and the cross-flow cases:

$$V_R^{il} = \frac{U_{c,Xyr}}{f_{0,il} \cdot D_{po}} \text{ and } V_R^{cf} = \frac{U_{c,Xyr} + U_{w,1yr}}{f_{0,cf} \cdot D_{po}} \quad \textbf{(4.22)}$$

respectively.

The static free span criterion is the load controlled combined loading criteria (LC b) from DNV-OS-F101 Design Checks module. The bending moment included in calculation is obtained by

$$M_{static} = C_5 \cdot \frac{q \cdot L^2}{\left(1 + C_2 \dfrac{S_{eff}}{P_E}\right)} \qquad \textbf{(4.23)}$$

where

C_5 is boundary condition coefficient:

Boundary condition	Pinned-Pinned	Fixed-Fixed	RP-F105 Single Span
C_5	1/8	1/12	1/12

By pressing the "Additional Results" button, the following window appears showing essential parameters in the intermediate calculations:

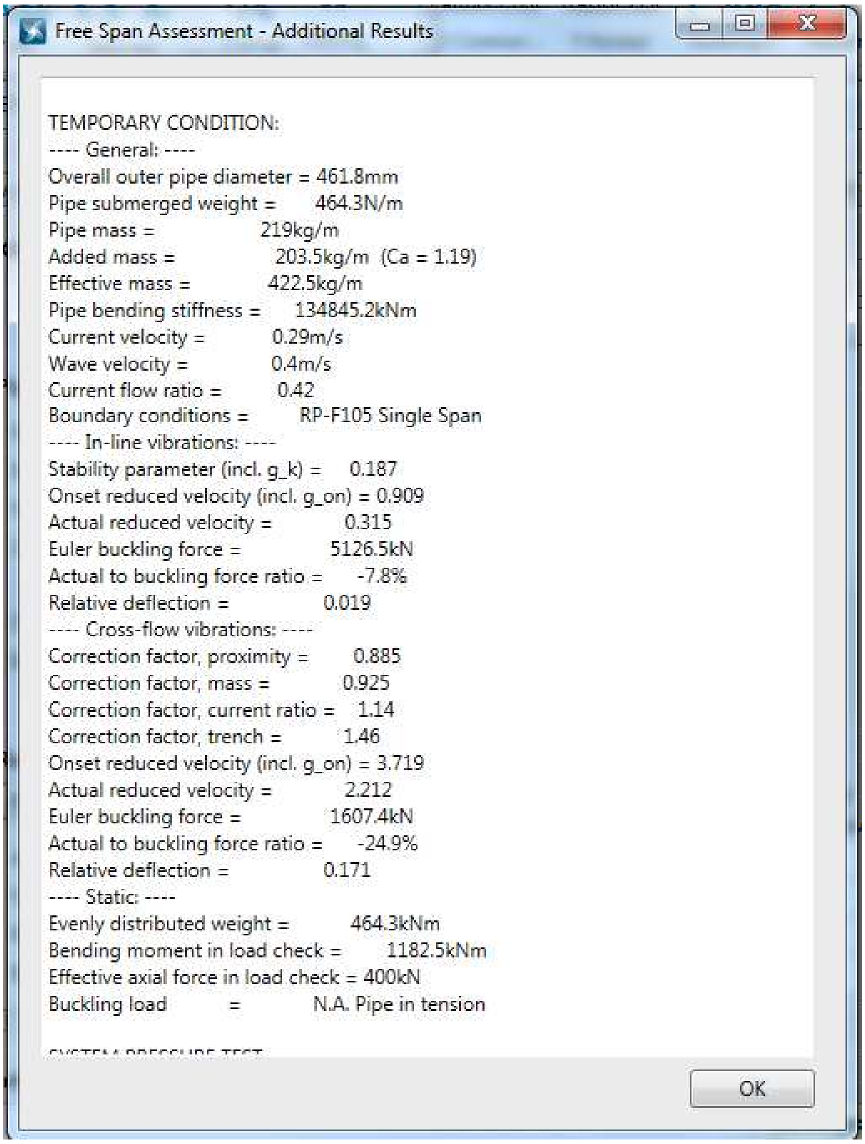


Figure 4-11 Free span module Additional Results window

4.7 Reel Straining

4.7.1 Introduction

This module calculates:

- Maximum bending strain on the reel including a code check according to DNVGL-ST-F101 and its older version DNV-OS-F101 (please ote that the code is selected in the DNV-OS-F101 Design Checks module),
- corresponding ovality and
- accumulated plastic strain during reeling, unreeling, aligning and straightening.

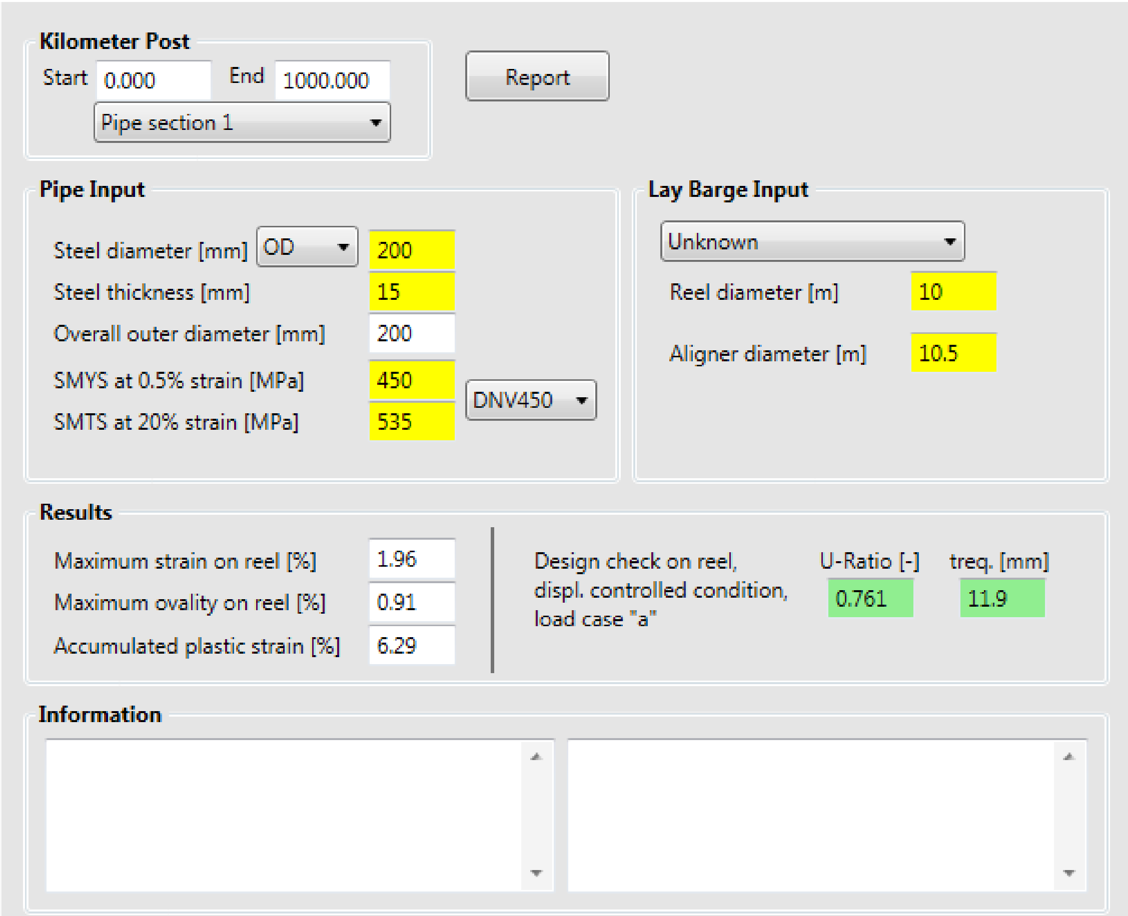
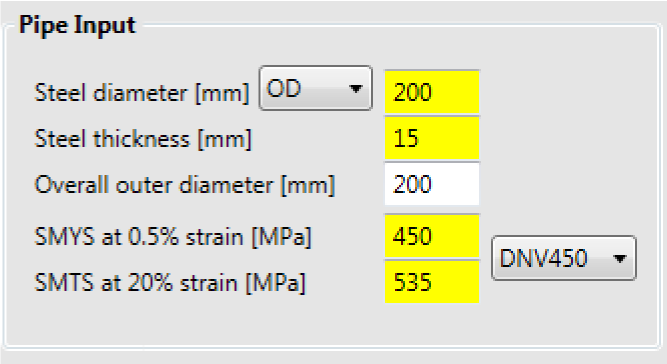


Figure 4-12 Reel Straining calculation module

4.7.2 Input

The input parameters are separated in two groups:

1: Input related to the steel cross section:



D Steel pipe diameter. Note that the user may specify inner or outer diameter depending on the selection of the combo box.

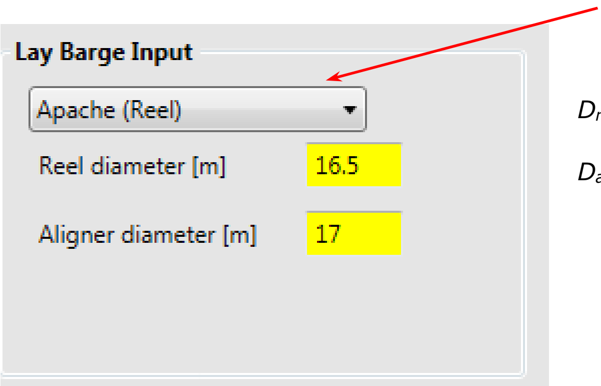
t Steel wall thickness.

D_{po} Overall outer diameter including coating is calculated, not specified by the user. Reference is made to the Weight and Volume Module.

SMYS Specified minimum yield stress.

SMTS Specified minimum tensile strength.

2: Input related to the reel/carousel:



A specific barge may be selected, and values below are inserted automatically.

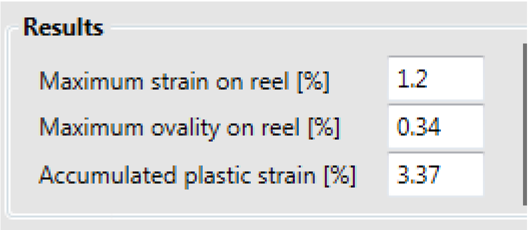
D_{reel} Reel diameter.

D_{align} Bending diameter on the aligner. When a barge is selected, this is taken as a half metre larger than the reel diameter.

Additionally, the minimum bending diameter between reel and aligner (determining an un-loading cycle in the accumulated plastic strain calculations) is accounted for. This is taken as 1500 m.

4.7.3 Results

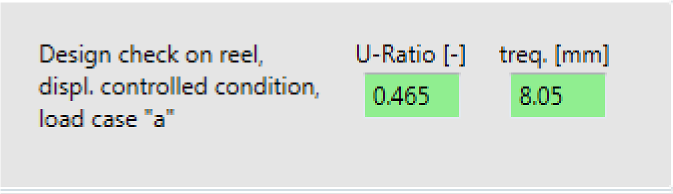
The results produced by this module are:



Maximum strain on the reel

Maximum ovality on the reel.

Accumulated plastic strain during reeling, unreeling, aligning and straightening.



Utilisation and minimum required nominal wall thickness with respect to DNV-OS-F101 version selected in DNV-OS-F101 Design Checks module.

Maximum strain in the pipe on the reel is calculated as:

$$\varepsilon_{reel} = \frac{D}{D_{reel} + D_{po}} \qquad \textbf{(4.24)}$$

The code check is made according to the displacement controlled criterion with the following assumptions:

- Corrosion allowance t_{corr} = 0 mm
- No material derating due to elevated temperature.
- No internal nor external pressure.
- Functional compressive strain ε_f = ε_{reel}
- Environmental compressive strain ε_e = 0.0
- Load condition factor γ_C = 0.82
- Safety Class = LOW

Ovality on reel:

$$f_{reel} = 0.03 \cdot \left(1 + \frac{D}{120 \cdot t}\right) \cdot \left(2 \cdot \varepsilon_{reel} \cdot \frac{D}{t}\right)^2 \qquad \textbf{(4.25)}$$

The accumulated plastic strain is calculated cumulatively through the reeling/unreeling process as:

$$\varepsilon_{acc}^{i+1} = \varepsilon_{acc}^{i} + \left| \varepsilon_{tot}^{i+1} - \frac{\sigma^{i+1}}{E} \right| \qquad \textbf{(4.26)}$$

Where:

ε^{i}_{tot} is the the strain at a point *i* in the reeling- straightening cycle. It is defined by four points: origin, reel, arc between reel and aligner, and aligner. The total strain in the origin is taken as 0%, while at the other points it is calculated following (4.24) with the appropriate point diameter;

ε^{i}_{acc} is the accumulated plastic strain at a point *i* in the reeling- straightening cycle;

and σ^{i} is the stress at a point *i* in the reeling- straightening cycle.

It is assumed zero stress after the straightening process.

4.8 Reel Packing

4.8.1 Introduction

This module calculates:

The amount of pipe that can be packed on a reel/carousel. The calculations are performed with the assumption that the top of the stacked pipes should not exceed the flange height.

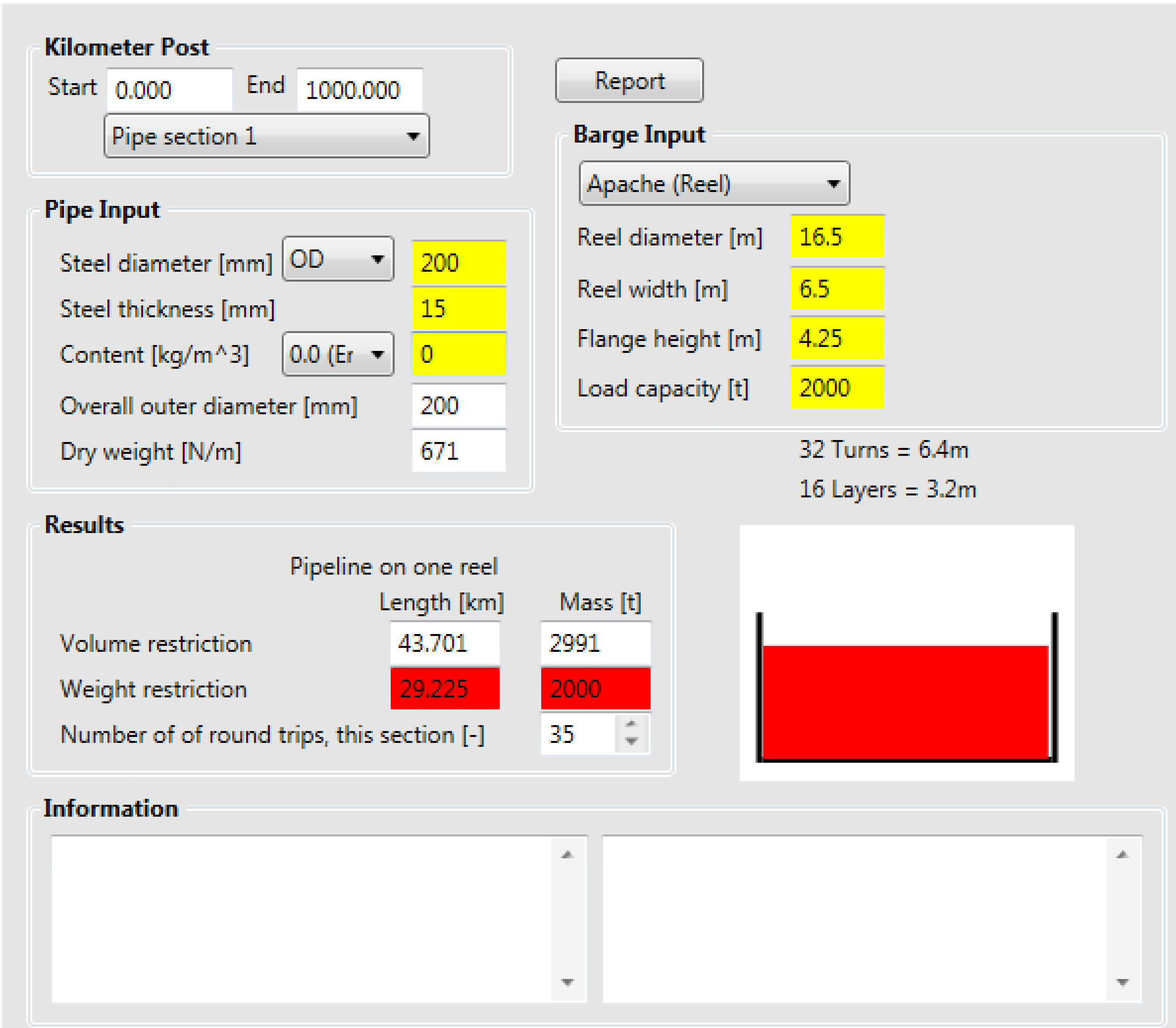
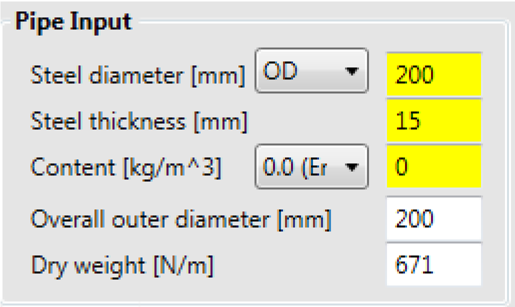


Figure 4-13 Reel Packing calculation module

4.8.2 Input

The input parameters are separated in two groups:

1: Input related to the pipe:



D Steel pipe diameter. Note that the user may specify inner or outer diameter depending on the selection of the combo box. Does not directly enter the calculations.

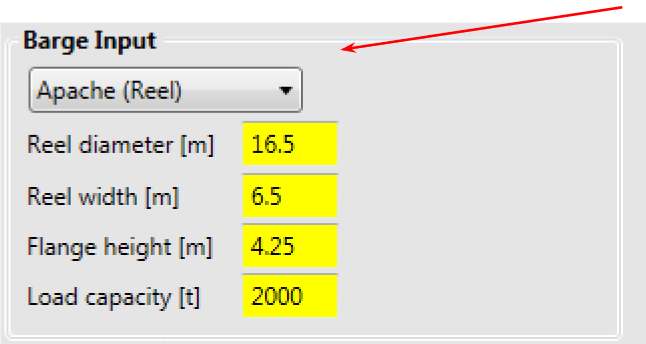
t Steel wall thickness. Does not directly enter the calculations.

Content mass density that reduces the allowable amount of pipe if weight restriction is governing.

Overall outer diameter D_{op} including coating is calculated, not specified by the user. Reference is made to the Weight and Volume Module.

Dry weight of pipe w_d (including content) is calculated, not specified by the user. Reference is made to the Weight and Volume Module.

2: Input related to the lay barge:



A specific barge may be selected, and values below are inserted automatically.

D_{reel} Reel diameter determines length of circumference.

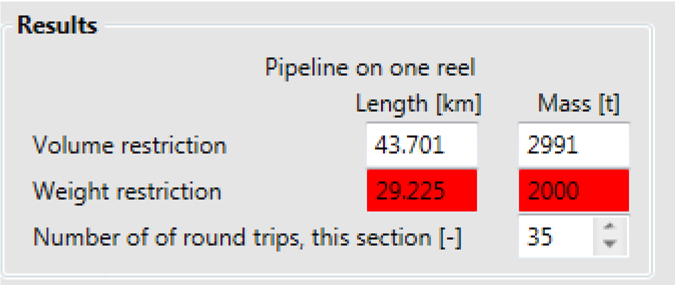
b_r Width between flanges determines number of turns.

h_f Flange height determines the number of layers (radially).

l_{cap} Barge load capacity sets weight restriction.

4.8.3 Results

The results produced by this module are for both volume and mass/weight restrictions:

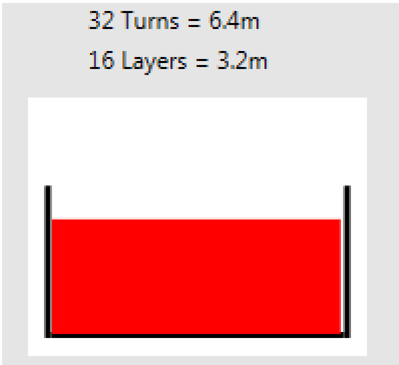


Results

	Pipeline on one reel Length [km]	Mass [t]
Volume restriction	43.701	2991
Weight restriction	29.225	2000
Number of of round trips, this section [-]		35

Length of pipe.
Corresponding mass.

The text boxes with red back colour indicates what governs the load capacity, volume or weight/mass.



Layers and turns, (layers in the radial direction and turns in the width direction).

The results are presented graphically. The thick black lines represent the two flanges and the reel drum surface, and the red rectangle represents the packed pipe volume.

Number of turns and layers is calculated as:

$$n_{turns} = Int\left[\frac{b_r}{D_{op}}\right] \quad \text{and} \quad n_{layer} = Int\left[\frac{h_f}{D_{op}}\right] \qquad \textbf{(4.27)}$$

Int[] denotes integer division, i.e. always rounding down to nearest integer. Pipe length on one reel based on the volume restriction is thus:

$$L_{vol} = \sum_{i=1}^{n_{layr}} \pi \cdot D_{r,i} \cdot n_{tunr} \qquad \textbf{(4.28)}$$

where $D_{r,i}$ is the diameter (to centre of pipe) for layer no. *i*.

Pipe length on one reel based on the weight restriction is:

$$L_{wgt} = \frac{l_{cap}}{w_d} \text{ (with proper unit conversion (Tonne vs. Newton))} \qquad \textbf{(4.29)}$$

Pipe mass is then:

$$m_{vol} = \frac{w_d \cdot L_{vol}}{g} \quad \text{and} \quad m_{wgt} = \frac{w_d \cdot L_{wgt}}{g} \qquad \textbf{(4.30)}$$

4.9 J-Lay

4.9.1 Introduction

This module calculates the following during pipe J-lay:

- the actual top tension (axial force in pipeline) during laying,
- horizontal top tension,
- maximum curvature and moment in the sag bend including utilisation ratio according to DNVGL-ST-F101 and its older version DNV-OS-F101 (please ote that the code is selected in the DNV-OS-F101 Design Checks module),
- horizontal distance from touch down to barge,
- length of pipe in the free span, and
- minimum horizontal lay radius.

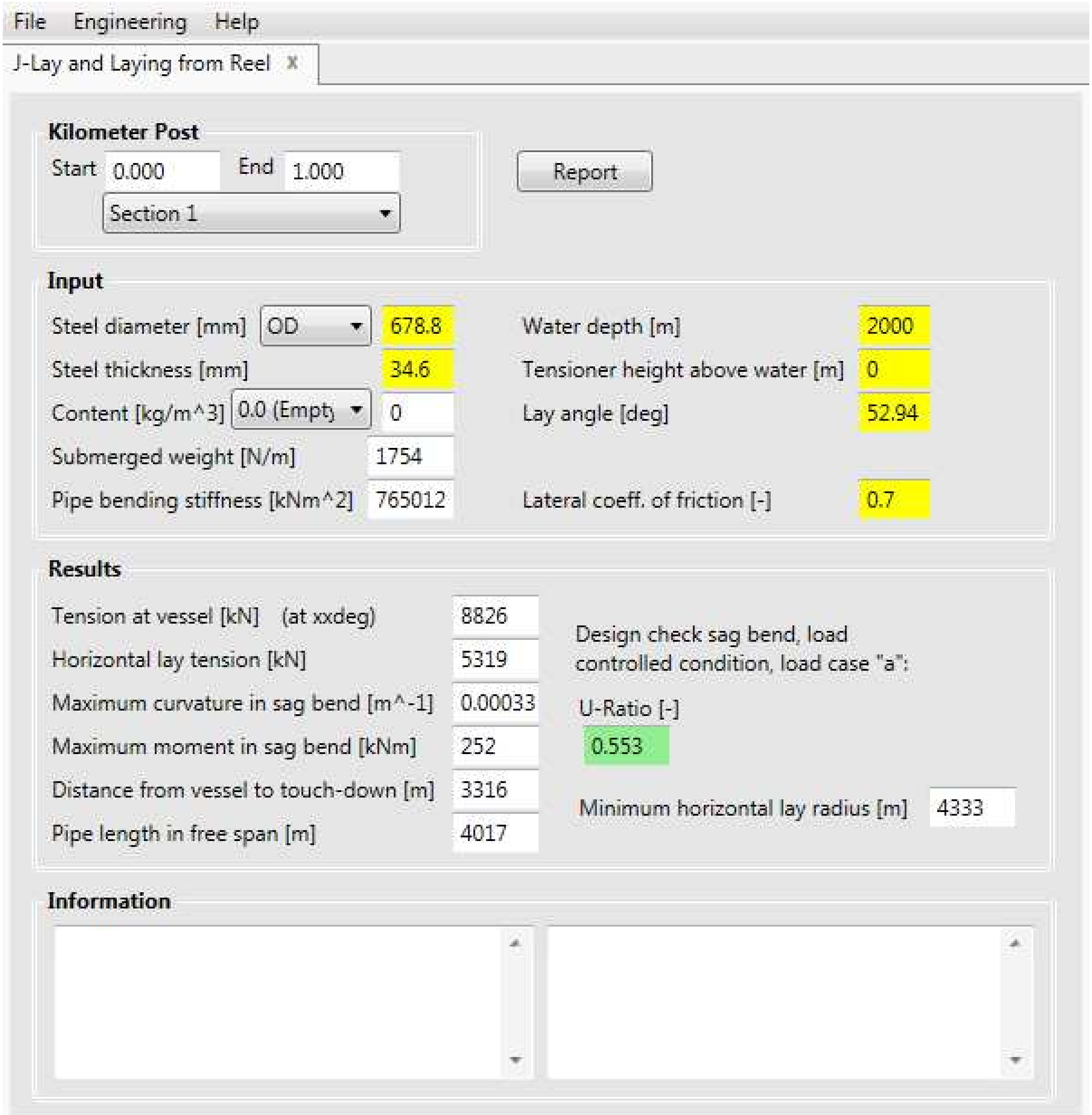
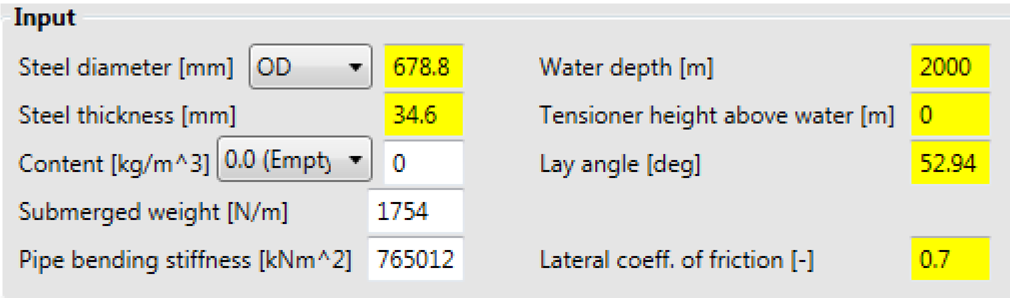


Figure 4-14 J-lay calculation module

4.9.2 Input

The input of the J-lay calculation module is shown below.



D Steel pipe diameter. Note that the user may specify inner or outer diameter depending on the selection of the combo box.

t Steel wall thickness.

ρ Density

w_s Submerged weight of pipe is calculated, not specified by the user. Reference is made to the Weight and Volume Module.

EI Pipe elastic bending stiffness.

h Tensioned height above seawater

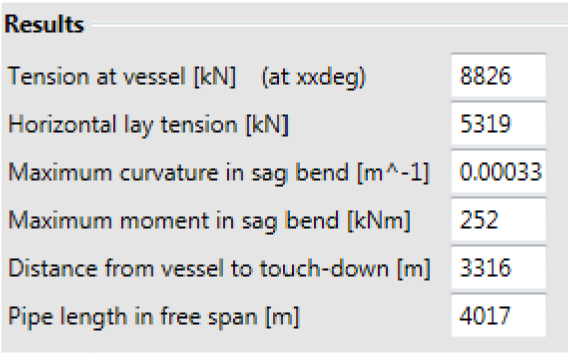
d Water depth.

α_{lay} Lay angle.

μ_{lat} Lateral coefficient of friction.

4.9.3 Results

The results produced by this module are for both volume and mass/weight restrictions:



Tension at barge (parallel to pipeline).

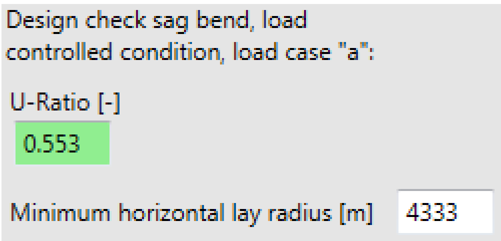
Horizontal component of barge tenion.

Maximum curvature in sag bend.

Maximum moment in sag bend.

Distance between touch down point and barge.

Pipe length in free span



Utilisation ratio according to the load combination criterion in DNV-OS-F101 version selected in DNV-OS-F101 Design Checks module.

Minimum horizontal lay radius.

Warning: The calculations in this module are based on catenary behaviour and will be increasingly inaccurate for shallower depths.

The pipeline is assumed to follow a catenary shape from the tensioner to the seabed. The effect of the dry pipe weight between the tensioner and sea level is included by using equivalent values for depth and submerged weight. The depth used in the calculations is simply increased by the height between sea level and tensioner whereas the dry weight is smeared out over the whole free spanning pipeline.

$$d' = d + h$$

$$w_s' = \frac{w_s \cdot d \cdot \sin^2 \alpha_{lay} + w_d \cdot h \cdot (1 - \cos \alpha_{lay})}{d \cdot \sin^2 \alpha_{lay} + h \cdot (1 - \cos \alpha_{lay})} \qquad \textbf{(4.31)}$$

Furthermore, the pipeline is assumed to exit the tensioner at the lay angle and enter horizontally onto the seabed. When a coordinate system is established with $x = z = 0$ at the touch down point, x is positive forward towards the lay barge, and z is positive upward towards the sea surface, the shape of the pipeline is described by the equation:

$$z = a \cdot \left(\cosh \frac{x}{a} - 1 \right), \qquad a = \frac{H}{w_s'} \qquad \textbf{(4.32)}$$

where H is the horizontal component of the lay tension.

The tension (parallel to the pipeline) at the barge is given by:

$$T = w_s' \cdot (d' + a) = \frac{w_s' \cdot d'}{1 - \cos\alpha_{lay}} \qquad \textbf{(4.33)}$$

The horizontal component of the axial force is:

$$H = T \cdot \cos\alpha_{lay} \qquad \textbf{(4.34)}$$

Maximum curvature in the sag bend is found by differentiating the catenary equation twice and insert x = 0:

$$\kappa_{sb} = \frac{w_s'}{H} = \frac{1}{a} \qquad \textbf{(4.35)}$$

Maximum moment in the sag bend is found by multiplying the corresponding curvature by the bending stiffness of the pipeline:

$$M_{sb} = \kappa_{sb} \cdot EI \qquad \textbf{(4.36)}$$

The code check for the load combination in the sag bend is performed according to the load controlled condition, load case a in DNVGL-ST-F101 with the following set of input parameters:

− Corrosion allowance	t_{corr}	= 0mm.
− No material derating due to elevated temperature.		
− Internal pressure	p_i	= 0
− External pressure	p_e	= $\rho \cdot g \cdot d$
− Functional bending moment	M_f	= M_{sb}
− Environmental bending moment	M_e	= 0.0.
− Functional effective axial force	S_f	= H
− Environmental effective axial force	S_e	= 0.0.
− Load condition factor	γ_C	= 1.0.
− Safety Class		= LOW.

The distance between touch down point and tensioner is found by inserting $z = d'$ in Eq. (4.32) and solve for x:

$$x_{td} = a \cdot \cosh^{-1}\left(\frac{d' + a}{a}\right) \qquad \textbf{(4.37)}$$

Pipe length in free span is:

$$s_{span} = a \cdot \sinh\left(\frac{x_{td}}{a}\right) \qquad \textbf{(4.38)}$$

Minimum horizontal lay radius is calculated as:

$$R_{lay} = \frac{H}{\mu_{lat} \cdot w_s'} \qquad \textbf{(4.39)}$$

4.10 S-Lay

4.10.1 Introduction

This module calculates the following during pipe S-lay:

- the actual top tension (axial force in pipeline) during laying,
- horizontal effective axial tension,
- maximum strain on the stinger including utilisation ration according to DNVGL-ST-F101 and its older version DNV-OS-F101 (please ote that the code is selected in the DNV-OS-F101 Design Checks module),
- maximum curvature and moment in the sag bend including utilisation according to DNVGL-ST-F101 and its older version DNV-OS-F101 (please ote that the code is selected in the DNV-OS-F101 Design Checks module),
- horizontal distance from touch down to barge,
- length of pipe in the free span and
- minimum horizontal lay radius.

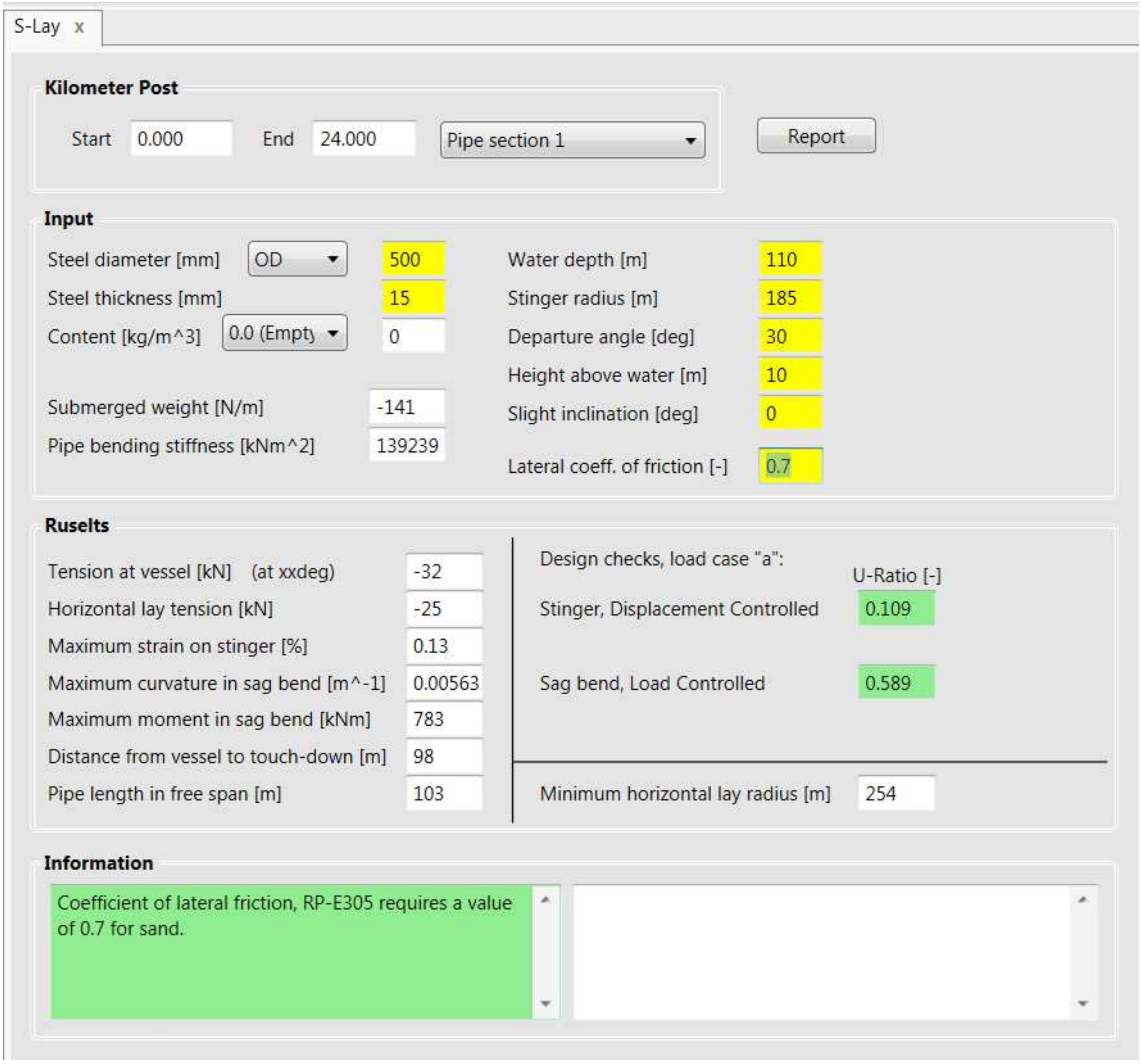
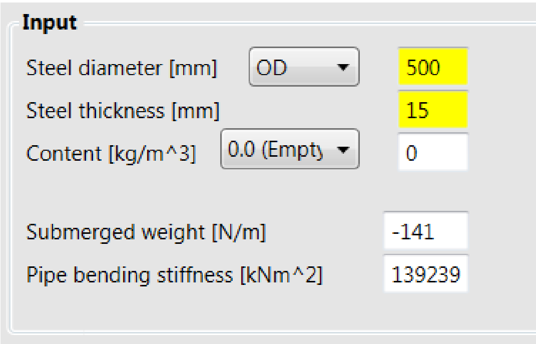
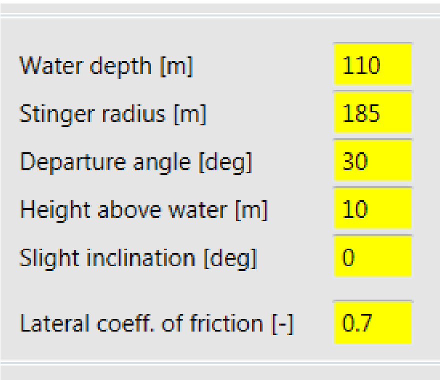


Figure 4-15 S-lay calculation module

4.10.2 Input

The input parameters are:





D Steel pipe diameter. Note that the user may specify inner or outer diameter depending on the selection of the combo box.

t Steel wall thickness.

w_s Submerged weight of pipe is calculated, not specified by the user. Reference is made to the Weight and Volume Module.
Note that content during laying can be specified by the user.

d Water depth.

R_s Stinger radius

α_{lay} Lay angle.

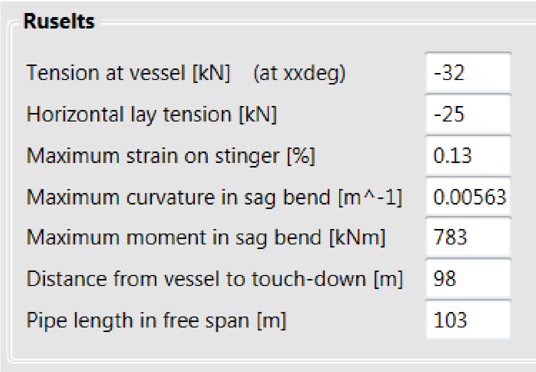
α_s Pipe angle when entering the stinger.

h Pipeline height above sea level when entering the stinger

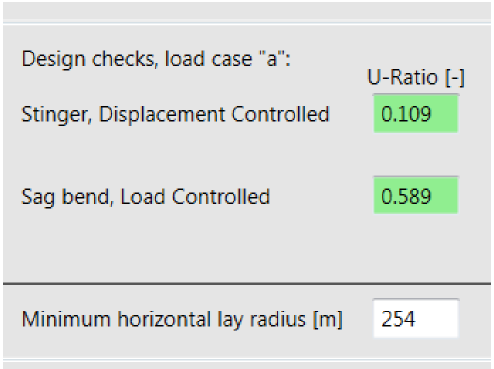
μ_{lat} Lateral coefficient of friction between pipe and seabed.

4.10.3 Results

The results produced by this module are for both volume and mass/weight restrictions:



Tension at barge (parallel to pipeline).
Horizontal component of barge tension.
Maximum strain on the stinger.
Maximum curvature in the sag bend.
Maximum moment in the sag bend.
Distance between touch down point and barge.
Total pipe length on the stinger and in the free span.



Utilisation ratio on the stinger according to the displacement controlled load combination criterion in DNVGL-ST-F101 version selected in DNV-OS-F101 Design Checks module.

Utilisation ratio in the sag bend according to the load controlled load combination criterion in DNVGL-ST-F101 version selected in DNV-OS-F101 Design Checks module.

Minimum horizontal lay radius on the seabed.

Warning: Inflection point is taken at the point where the pipeline departs from the stinger. This is an approximate simplification.

Warning: The calculations in this module are based on catenary behaviour between the inflection point and the touch down point and will be increasingly inaccurate for shallower depths.

The pipe is considered from where it leaves the barge and enters the stinger at a height *h* above the sea surface and with a slight inclination angle of α_S. On the stinger the pipeline is assumed to follow the stinger curvature until it departs this at the angle α_{lay}. From here on the pipe is assumed to follow a catenary shape to the touch down point on the seabed. The effect of the dry pipe weight above the sea level is not included in the calculations.

The bending strain on the stinger is

$$\varepsilon_s = \frac{D}{2R_s + D} \qquad \textbf{(4.40)}$$

The axial tensile strain on the stinger may be significant in deep waters, say 10% of the bending strain above, but is for the sake of conservatism neglected.

The code check for the load combination on the stinger is performed according to the displacement controlled condition, load case a in DNVGL-ST-F101 with the following set of input parameters:

− Corrosion allowance t_{corr} = 0mm
− No material derating due to elevated temperature
− No internal nor external pressure
− Functional compressive strain ε_f = ε_s
− Environmental compressive strain ε_e = 0.0
− Load condition factor γ_C = 1.00
− Safety Class = LOW

The pipeline is assumed to exit the stinger at the lay, or departure, angle and enter horizontally onto the seabed. The catenary solution is assumed to be valid from this inflection point (where the pipe departs from the stinger) to the touch down point such that the modified depth *d'* to be used for this part of the pipeline is:

$$d' = d + h - R_s \cdot (\sin \alpha_{lay} - \sin \alpha_s) \quad (4.41)$$

When a coordinate system is established with $x = z = 0$ at the touch down point, x is positive forward towards the lay barge, and z is positive upward towards the sea surface, the shape of the pipeline is described by the equation:

$$z = a \cdot \left(\cosh \frac{x}{a} - 1 \right), \qquad a = \frac{H}{w_s} \quad (4.42)$$

where H is the constant horizontal component of the tension in the pipeline.

The tension (parallel to the pipeline) in the pipeline on the barge is thus found by adding the tension at the inflection point, given by the catenary solution, and the weight component, parallel to the stinger, of the pipe on the stinger (friction against rollers is neglected):

$$\begin{aligned} T &= w_s \cdot (d' + a) + w_s \cdot R_s \cdot (\cos \alpha_s - \cos \alpha_{lay}) \\ &= \frac{w_s \cdot d'}{1 - \cos \alpha_{lay}} + w_s \cdot R_s \cdot (\cos \alpha_s - \cos \alpha_{lay}) \end{aligned} \quad (4.43)$$

The constant horizontal tension component in the catenary solution is calculated at the inflection point as:

$$H = \frac{w_s \cdot d' \cdot \cos \alpha_{lay}}{1 - \cos \alpha_{lay}} \quad (4.44)$$

Note that this horizontal component is not valid in the pipe on the stinger where the rollers put loads on the pipe.

Maximum curvature in the sag bend may be found by differentiating the catenary equation twice and insert $x = 0$:

$$\kappa_{sb} = a \quad (4.45)$$

Maximum moment in the sag bend is found by multiplying the corresponding curvature by the bending stiffness of the pipeline:

$$M_{sb} = \kappa_{sb} \cdot EI \qquad \textbf{(4.46)}$$

The code check for the load combination in the sag bend is performed according to the load controlled condition, load case a in DNVGL-ST-F101 with the following set of input parameters:

− Corrosion allowance	t_{corr}	= 0mm.
− No material derating due to elevated temperature.		
− Internal pressure	p_i	= 0
− External pressure	p_e	= $\rho \cdot g \cdot d$
− Functional bending moment	M_f	= M_{sb}
− Environmental bending moment	M_e	= 0.0
− Functional effective axial force	S_f	= H
− Environmental effective axial force	S_e	= 0.0
− Load effect factor	γ_C	= 1.0
− Safety Class		= LOW

The distance between touch down point and the stinger departure point is found by inserting $z = d'$ in Eq. (4.32) and solve for x:

$$x_{td} = a \cdot \cosh^{-1}\left(\frac{d' + a}{a}\right) \qquad \textbf{(4.47)}$$

Pipe length in free span, including pipe on stinger is:

$$s_{span} = a \cdot \sinh\left(\frac{x_{td}}{a}\right) + R_s \cdot (\alpha_{lay} - \alpha_s) \qquad \textbf{(4.48)}$$

Minimum horizontal lay radius is calculated as:

$$R_{lay} = \frac{H}{\mu_{lat} \cdot w'_s} \qquad \textbf{(4.49)}$$

5 REFERENCES

/1/ DNV GL: *Offshore Standard DNV-OS-F101 Submarine Pipeline Systems*, Høvik, Norway, 2000.

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/6/ Andrew C. Palmer et. al.: *Design of Pipelines Against Upheaval Buckling*, OTC 6335, Huston, Texas 1990.

/7/ P.E.L. Schaminée et. al.: *Soil Response for Pipeline Upheaval Buckøling Analyses : Full-Scale Laboratory Tests and Modelling,* OTC 6486, Huston, Texas 1990.

/8/ DNV GL: *Cathodic Protection of Submarine Pipelines by Galvanic Anodes*, Høvik, 2010

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