



# **SMOOP**

## SMOOTHing Program for Survey Data of a Pipe Profile Release Report



Unrestricted

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**SMOOP**  
**SMOothing Program for Survey Data of a Pipe Profile Release Report**  
by  
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## **Executive summary**

Upheaval buckling assessments of high temperature and pressure (HPHT) pipelines is often based on a surveyed pipe elevation profile, which is used to determine the initial configuration of the pipeline as required for finite element analysis or other types of analysis to determine whether the pipeline can withstand the design temperature and pressure conditions without upheaval buckling.

Inevitably the survey data used to determine this initial profile suffer from some random errors, so that smoothing of the survey data is required. Various smoothing methods have been proposed and used in the industry. The one proposed here, and implemented in SMOOP, is one that can be described as fitting finite element analysis (FIFEA). The underlying assumption is that the downward force on the pipeline is known, and the upward reactions from the seabed or bottom of the trench are adjusted to provide an optimum fit to the survey data in the least squares sense. In other words SMOOP will provide the best possible fit to the survey data that is physically possible under certain assumptions.

This report provides these assumptions (see Chapter 2), source code (in FORTRAN), executables (for MS Windows), and basic documentation for SMOOP4 (the current version).

## **Disclaimer**

The use of SMOOP4 is entirely on the user's own risk. Shell provides no guarantee as to the accuracy of the results calculated with SMOOP4. Although certain opportunities for validation against other codes, methods of analysis, and/or experiments have been exploited, there has been no systematic checking of all the available options the program provides. Therefore there can be no guarantee of the accuracy of the results from SMOOP4. Further this report has only be reviewed for the contents of the report, and not for the attachments.

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## 1. Background

Pipelines may be buried by the trench and cover method, to protect them or for thermal insulation. This restrains expansion of the pipe due to temperature and pressure loads. Thus it can lead to large axial compressive forces in the pipeline under such loads, and associated upheaval buckling. Upheaval buckling is also strongly influenced by out-of-straightness (OOS) in the pipe elevation profile. For this reason a common practice is to survey the pipeline to determine the OOS, and to use this information for an upheaval buckling assessment by finite element analysis or other method. The survey data inevitably contains random errors, so some smoothing of those data is required to define the initial configuration for finite element analysis. However over smoothing could eliminate or reduce the very OOS features that the survey is intended to capture. SMOOP performs the smoothing in a physically realistic way, by considering only physically possible pipeline profiles, and finding which of these physically possible profiles best fits the survey data. A key underlying assumption is that the pipe is straight when stress-free. If at any point SMOOP fails to produce a good fit to the survey data, it means that either the survey data are incorrect, or an assumption has been violated, for instance because the pipe has been plastically deformed, e.g. during pipelay or trenching.<sup>1</sup>

SMOOP was initially developed as a weekend project<sup>2</sup> around the year 1999. The theory is relatively simple: The pipe is discretized into linear elastic beam elements. The sum of the squares of the survey errors then becomes a positive (semi)<sup>3</sup> definite quadratic form in the nodal displacements and rotations, which is minimized, subject to equality constraints (from moment equilibrium at each node) and inequality constraints (from the requirement that the soil can only exert an upward reaction force on the pipe). The algorithm is a heuristic one exploiting the sparsity of the matrices involved. Nevertheless at the time of the initial development (around 1999) an overnight run on a standard desktop PC would be required even with only moderate mesh refinement to 2m-long elements.

Although SMOOP4 performs finite analysis, it is intended as a survey data smoothing program only, and not for use in subsequent analysis, such as upheaval buckling analysis under internal pressure and thermal loads. Instead the outputs from SMOOP4 can be used as inputs to determine the initial state in a finite element analysis with a different program. Often the size and line-up of the elements for SMOOP4 and the subsequent FE analysis are the same, so that SMOOP4 nodal displacements and forces can be used directly. However SMOOP4 can also provide interpolated results, for the case that subsequent FE analysis is to be performed with a finer mesh than then SMOOP4 analysis. (See “TEXFLAG” options in Section 4.2).

There was no disclosure, further use or development of SMOOP until 2013, when some minor improvements were made, not changing the basic algorithm, but enabling a multi-grid approach,

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- 1 A certain amount of stress-free OOS is also allowed according to typical line-pipe specifications, and also as part of the mitring misalignment tolerance for the girth welds. This is often disregarded in upheaval buckling assessments, though worst conceivable stress-free OOS that is allowable according the linepipe and welding specifications could be quite significant compared to other OOS, especially for larger diameter pipelines that are so stiff that they tend to remain rather straight.
  - 2 This there were already adequate algorithms for the smoothing of survey data such as Lloyd Register's LR-STAR [1], there was not a sufficiently strong business driver at the time to develop an improved algorithm, and this therefore became a weekend project.
  - 3 If there are enough survey data the quadratic form is positive definite. Gaps in the survey data (e.g. no survey data over a length of 2 elements) can make it positive semi-definite. The implications of this on the algorithm have not been investigated by the author, but it is noted that by using the equality constraints to eliminate the rotational degrees of freedom the quadratic form becomes positive definite.

so that the problem could first be run with a coarse mesh, which is generally found to converge quite rapidly, and then the interpolated coarse-mesh solution used as an initial guess in re-solving the problem with a finer mesh. Also a few more output and ease of use options were added, resulting in the current (SMOOP4) version. With the much faster computers currently available compared to those at the time of the initial development, run times are also much reduced.

## 2. Assumptions

SMOOP provides the best possible fit to the survey data that is physically possible under the following assumptions:

1. The pipe remains linearly elastic and is perfectly straight when stress-free, so that the standard relation  $M = EI \kappa$  applies between bending moment  $M$  and curvature of the pipe  $\kappa$ , where  $EI$  denotes the flexural rigidity.
2. Shear deformations are neglected.
3. Geometrically nonlinear effects, and the effect of the axial force are neglected.
4. The pipe is subject to a constant uniformly distributed downward load  $q$  that is typically taken to be equal to the submerged weight of the pipe.<sup>4</sup>
5. The seabed or bottom of trench exerts only upward reaction forces on the pipe, which are calculated to give an optimum fit to the survey data, with no upper bound imposed on the upward force per unit length. (Indeed, as might be expected, the optimum solution seems to consist of concentrated upward forces at locations determined by the optimization.)
6. The error measure that is minimized for an optimal fit is the sum of the squares of the difference between the  $(x,z)$  survey data points and the calculated physically admissible pipe profile.
7. In the current implementation the pipe properties (flexural rigidity and downward load) are assumed to be constant along the entire length modelled.

Even where not all these assumptions are satisfied exactly, SMOOP can be used as an approximation with a clear physical basis. Any inability to match the survey data means that either the survey data is wrong or one or more of these assumptions are violated.

On the other hand if the survey data are very good, then using an unrealistically high value of the maximum net downward force  $q$  on the pipe will give much the same results as using a realistic value. The optimization algorithm will simply compensate the excess downward load with upward forces.

When the pipeline is placed on a soft seabed there is of course also a limit to the upward force per unit length which the seabed (or bottom of trench) can exert on the pipeline that is not considered according to Assumption 5. This could lead to overestimation of the bending moments at the supported points. However again, if survey data were sufficiently accurate and dense, the optimization algorithm should converge to the correct upward forces, even when no upper limit is set on them.

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<sup>4</sup> Once buried the pipe could also experience downward loads from the soil above, and one can certainly increase the downward load  $q$  provided as input to SMOOP to account for this. Indeed  $q$  is to be interpreted as the maximum feasible net downward load. However the preferred way to place backfill is to place it under the pipe to fill any gaps under the pipe and support the pipe, before backfill is added over the pipe. Under such circumstances  $q$  can reasonably be taken as the submerged weight of the pipe, even when the pipe is buried. Of course this only applies for an as-laid and backfilled condition. Circumstances are also conceivable when the effective value of  $q$  is even lower than the submerged weight: for instance if the trench is backfilled by clay slurry the backfill essentially only exerts an increased buoyancy load on the pipe, but settlement involved in solidification and consolidation of the clay could change the downward load on the pipe.

### 3. Iterative Solution Scheme

SMOOP4 uses an iterative scheme to solve the very sparse quadratic programming problem, essentially by solving in a “Region of Significant Influence” (“ROSI”) and then moving to the next ROSI. It does this for each currently supported point (i.e. where there is a non-zero upward force from the foundation), finding the optimal location of that support or whether then support should be removed before moving to the next currently supported point. Thus the ROSIs overlap. The extent of the ROSI is controlled by the user by the variable NROSI, which is the number of currently supported points to each side included in the ROSI.

Convergence criteria are based on the change in vertical displacement (“TOL\_VV”), and the change in vertical reaction force (“TOL\_PP”) from one iteration to the next. If both are below the user-specified tolerance the system is deemed to have converged, and iterations stop. Iterations also stop if the user-specified maximum number of iterations (“NITMAX”) has been exceeded without convergence being achieved.

An “iteration” is a sweep of all currently supported points. Normally SMOOP sweeps from one side to the other, and then returns back to the start. However there is an option (see “IEXFLAG” below) to iterate in alternating directions, i.e. start to end, then end to start, and so on. Sometimes this can help if iterations get stuck and stop delivering further reductions in errors.



## 4. User Manual

### 4.1. General

To use Smoop4, all files in the zip file included in Appendix 1 should be extracted to the same directory (or “folder”), which will be referred to as the Smoop directory.

Input is provided in a text-based question and answer session. Creating plots of the results is something that needs to be done by the user of SMOOP4, e.g. by importing the results into MS excel and plotting them.

All operations are carried out in the same directory which also contains the executable file. There are 32-bit and 64-bit versions of the executable file, Smoop4\_32.exe, and Smoop4\_64.exe, respectively. The 32-bit version can also work on a 64-bit machine, but not the other way around. SMOOP4 first looks for input in the Smoop4.u9 file, if this is absent it prompts the user for inputs. If the Smoop4.u9 file ends before all input has been provided, SMOOP4 prompts the user for the missing input. To start a new problem the Smoop4.u9 file should be first renamed or removed, so that SMOOP4 will prompt the user for input from the start.

The console output can be routed to a file, with a command line such as

```
Smoop4_32.exe >Smoop4.u6
```

This will work if the file Smoop4.u9 is present and contains all the required inputs. The file Smoop4.u6 will then be created containing the console output, which includes the prompts generated by SMOOP4 for the inputs. The main output is written to a file named in the user input.

### 4.2. Input

SMOOP4 will not just do one run at a time, but as many as desired. This can include completely different runs with different pipe properties and different survey data, or it can include a re-run, for the same pipeline and survey data, which is useful in applying a multi-grid approach: in this case a run with a coarse mesh (large value of the element length “CL”) is followed by a re-run with a finer mesh (smaller “CL”), which interpolates the results from the previous run to obtain an initial guess for solution, from which to start iterating to the refined solution for the finer mesh. SMOOP4 will only stop when it encounters “quit” or “QUIT” as the name of file containing the survey data.

In practice it is best, at least initially, to perform just one run at the time, and look at the results before doing the next run. If a run has not converged fully, it is also possible to restart can perform more iterations from where it stopped. (In some cases it converges quite slowly even though it appears to be quite close to the solution for some reason.) Nevertheless, the multiple runs capability is useful, to create a clear, reproducible record of the runs performed, and also in parametric studies.

The prompts for the inputs in the interactive question and answer session are self-explanatory for the most part, and will not be repeated here. Each input parameter is identified by the variable name that is used in the source code. The notes below give some further explanation of these inputs, arranged alphabetically according to the input parameter name:

#### IEXFLAG

Is calculated as a sum of the values appearing in the input prompt; further explanation of the options follows:

IEXFLAG sum includes 2

This is the option for re-running a previous run with a finer mesh.

IEXFLAG sum includes 4

Use this option if a finite element analysis to be performed subsequently with a different program is to use a finer or different mesh than the SMOOP4 analysis. This applies for instance if an upheaval buckling analysis under increasing temperature is to be performed. SMOOP4 does not perform this upheaval buckling analysis. It is only used to obtain the initial seabed profile. For various reasons<sup>5</sup> it may be advisable to use a finer mesh in the upheaval buckling analysis than in the SMOOP4 analysis. In that case this option can make SMOOP print the results at the nodal points for the finer mesh used in the upheaval buckling analysis. For this purpose it interpolates using the shape functions for the Hermitian beam elements used in SMOOP4.

IEXFLAG sum includes 8

Use this option if not only pipe elevations, but additional data are to be smoothed. For instance the survey data may also contain cover depths, and one would like to obtain smoothed values of these cover depths at the same nodal points used in the SMOOP4 analysis. (Even if the cover depths are already smoothed, they may not be given at the same nodal points at which they are wanted, and this option can also be used for that case.) With this option SMOOP4 will fit a parabola to the survey data points within a distance "HR" of the nodal point where the smoothed value is to be determined. It will do this for each nodal point. The output contains only the smoothed value at the nodal point, obtained from the fitted parabola. For the next nodal point a new parabola is used to determine the smoothed value at the nodal point. To define the parabola, one must make sure that "HR" is large enough to include at least 3 data points.

IEXFLAG sum includes 16

This option should always be used. Exceptions might include instances where one only wants to interpolate existing results, or one only wants to smooth data other than pipe elevations using the parabolic fits.

IEXFLAG sum includes 32

When the iterative scheme gets stuck (i.e. no reduction in the errors from one iteration to the next), applying this option can help get it unstuck. In general it is not the preferred option, however.

NITMAX, NROSI

These parameters control the iterative solution scheme, as described in Chapter 3. Specifically NITMAX is the maximum number of iterations (after which the program will stop even if does not reach convergence), and  $2*NROSI+1$  is the number of supported points in the "region of significant influence" (ROSI) considered in the iterative solution scheme. Reasonable default values are NROSI=15, and NITMAX=1000. With higher values of NROSI the iterations may achieve greater convergence per iteration, but also require more computation per iteration.

TOL\_VV, TOL\_PP

These define the convergence criteria. They represent changes in vertical displacement, and vertical force, respectively. When the changes from one iteration to the next are less than these tolerances, the iterations are deemed to have converged, see Chapter 3.

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<sup>5</sup> Reasons might include: (a) Elements used in upheaval buckling analysis are less accurate, e.g. including linear interpolation of displacements and rotations, rather than cubic interpolation of displacements and rotations by differentiation of the displacements. (b) Upheaval buckling analysis involves plasticity which typically involves more localized deformations, requiring a finer mesh to resolve them. (c) The upheaval buckling analysis is computationally less demanding than the SMOOP4 analysis, so one can easily afford a much finer mesh, which then also provides a good way of checking the consistency of the SMOOP4 and subsequent FE analysis, by verifying that the initial state in the subsequent FE analysis with a different program agrees with that of the SMOOP4 analysis.

### 4.3. Output

The output files are in text format. A convenient way of looking at them is to import them into MS excel as “space delimited”. This will make the proper headings appear on top of columns of numbers with the results. (They are not lined up in the text file because “free format” is used).

Search for “XX” in the output file, to find a list of outputs in which lead output variable is identified in a text message above the data.

## **5. Examples**

This report contains no examples, since the only available examples involve restricted or confidential survey data which could not be disclosed without approval of the 3<sup>rd</sup> parties involved.

## References

- [1] LR-STAR: Seabed Topography Analysis Routine, Lloyd's Register, London 1989
- [2] R. Bruschi, L. Vitali, M. Spinazzè, L. M. Bartolini, L. Marchionni, C. Crea, R. Vichi, A. Battistini, (2013), "Out-Of Straightness Survey As An Engineering Tool For Integrity Management Of Offshore Pipelines Subject To In Service Buckling," Rio Pipeline 2013 Conference and Exhibition, 24-26 Sept. 2013, Brazilian Petroleum, Gas and Biofuels Institute - IBP, Paper No. IBP1474\_13
- [3] DNV-RP-F110, "Global Buckling of Submarine Pipelines Structural Design Due to High Temperature/High Pressure", Recommended Practice, DNV-RP-F110, Det Norske Veritas, Høvik, Norway, October 2007

## Appendix 1. Embedded Attachment

This report contains attachments that are embedded in the Word file.



appendix 1.docx

Word file containing a zip file containing npex source, executables, and documentation. This has been encrypted to enable it to be sent by email. Password is 2\_Evade\_Filter.

**Bibliographic information**

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