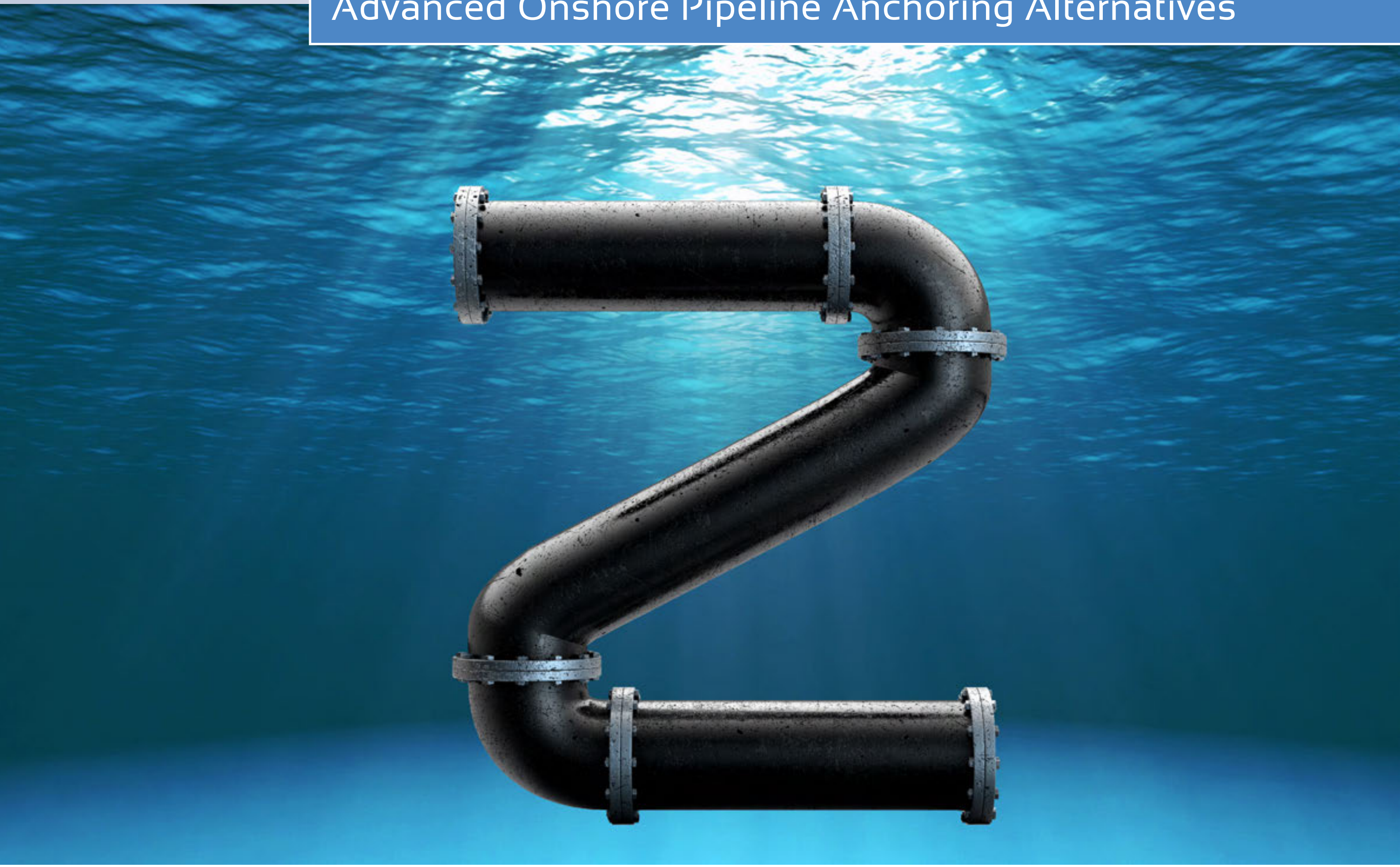
Advanced Onshore Pipeline Anchoring Alternatives



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Abstract

Pipelines may observe significant axial displacement or force at the ends that tie-in with connected equipment and/or facilities. These axial forces are mainly driven by pipe size, temperature, pressure, length and surrounding soils or supports, and can have devastating effects on connecting facilities if not properly accommodated in the design.

The most common approach to address this issue is deployment of concrete anchor blocks just before tie-in locations to achieve full isolation between pipelines and other connected systems. This leads to an increased cost of construction as well as handling and installation of massive concrete tonnage on a soil foundation of potentially high uncertainty, therefore proving to be economically unattractive. With the expansion of fields and processing facilities, including an anchor may also be physically challenging due to space restrictions.

This paper covers assessments of several pipeline case studies that range from 6" to 18" Nominal Pipe Size (NPS) interacting with the major soil categories clay and sand for design temperatures up to 250°C. The assessments show that for a significant number of cases the presence of an anchor is an over-design of the pipeline system, leading to unnecessary costs and potentially more complicated logistics.

Studied cases were analysed using the non-linear Finite Element Analysis (FEA) algorithm of the Abaqus software suite with controlled end displacements.

The work also establishes a case envelope to which the outcomes of this study will be applicable where pipeline conditions lie within the boundaries of the studied cases.

1. INTRODUCTION

Pipelines, particularly steel ones, can observe significant axial displacement or force at straight ends that tie-in with connected equipment and facilities. This is mainly driven by temperature, pipe size, straight length, surrounding soils, supports, and pressure.

Depending on the pipeline configuration, the axial effect is conventionally quantified by either calculating the fully restrained theoretical force at the pipeline end, or fully converting the force to end movements in a theoretically unrestrained pipe.

Depending on functional requirements and operator specifications, the generated axial forces and movements need to be within the allowable limits of connecting utilities, such as piping, or isolated using an engineered solution.

Recent advances in seismic imaging and reservoir mapping technologies (Halsey, 2016) have enabled production from deeper reservoirs at higher pressures and temperatures. This poses new challenges to production and transport infrastructure design, which are sometimes technically prohibitive using conventional engineering.

This paper discusses the current issues facing pipeline end interface design under elevated operating conditions and presents a Finite Element (FE) based approach to optimize, or eliminate, pipeline anchoring requirements.

2. TECHNICAL CHALLENGE

The search for new, production feasible, hydrocarbon reservoirs is driving drilling deeper wells (DeBruijn, et al., 2008), and with temperatures increasing proportionately with depth in the order of 15 to 30 degC per 1km of depth (Satter & Iqbal, 2016) this translates to more challenging design conditions.

Concurrently, pipeline technologies have developed and enabled an increase in operating pressures from 2 to 120 bar between the years 1910 and 2000 (Hopkins, 2007). More recently, the use of thermal recovery techniques, even in shallower layers, has dramatically increased production temperatures (Belani & Orr, 2008).

It follows that requests for pipelines designed to temperatures in the order of 70 to 100 degC for production from high-temperature wells (Mahmoud, 2017), are becoming more common. Pipelines designed to such conditions could generate sufficient axial force to cause damage to connecting infrastructure if left unrestrained or not considered in the design.

The conventional approach to resist axial forces is by utilizing anchors at the interface (Bahadori, 2017). Some Engineering Standards for designing concrete blocks also define the allowable limits for pipeline end displacements (Saudi Aramco, 2005).

For lower flowing temperatures the required anchor capacities are in the order of 2000 to 3000 kN, typically yielding an anchorage footprint of 5x5m, with typical depths of between 4 and 5 m. However, anchor capacities for larger pipes with challenging design conditions can reach 5000 to 9000 kN, with much larger footprints (16x16m) (SA_Water, 2007), which is demonstrated in Section 4.

The construction of such anchors, particularly in mature fields with safety and access complexities, leads to excessive soil resistance requirements and becomes near prohibitive. Moreover, supporting sheet piles may be required if many anchors are required within a congested field (Thorley & Atkinson, 1994).

Notably, (Ghdaib, et al., 2011) conducted a field monitoring study on a pipeline anchor block system indicated that the installed anchor block sizes could be reduced based on the obtained strain and stress response data.

3. AVAILABLE SOLUTIONS

An investigation of available alternatives to mitigate the large expansions and forces encountered at pipeline ends was driven by the challenges outlined in Section 2 with the aim of reducing anchor size or eliminating the anchor requirement.
One of the options to reduce the end forces and the anchor block footprint is combining gravity based anchors with a form of piling, such as sheet piling as shown in Figure 1.

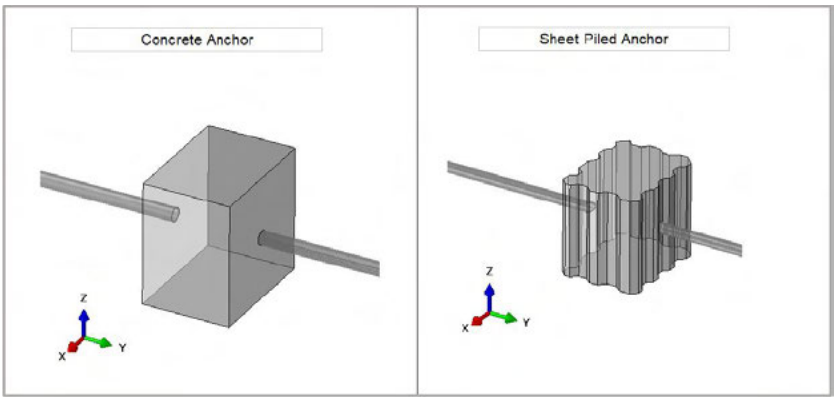


Figure 1: Pipeline Ends - Anchor Blocks

Route optimization is also a common option, and although primarily utilizing in-line bends to minimize route obstructions and rough terrain, it is sometimes aimed at minimizing straight pipe lengths to reduce high load and stress concentration areas as indicated in Figure 2.

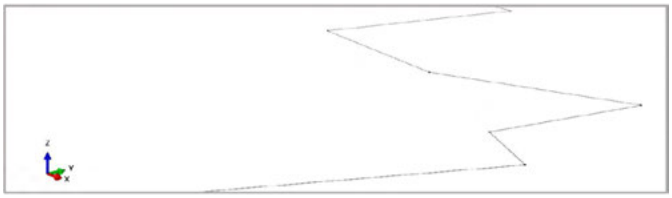


Figure 2: Pipeline Route - Minimizing Straights

Another alternative is introducing L, Z or U bends at the pipeline end to accommodate the incoming forces and expansions as shown in Figure 3.

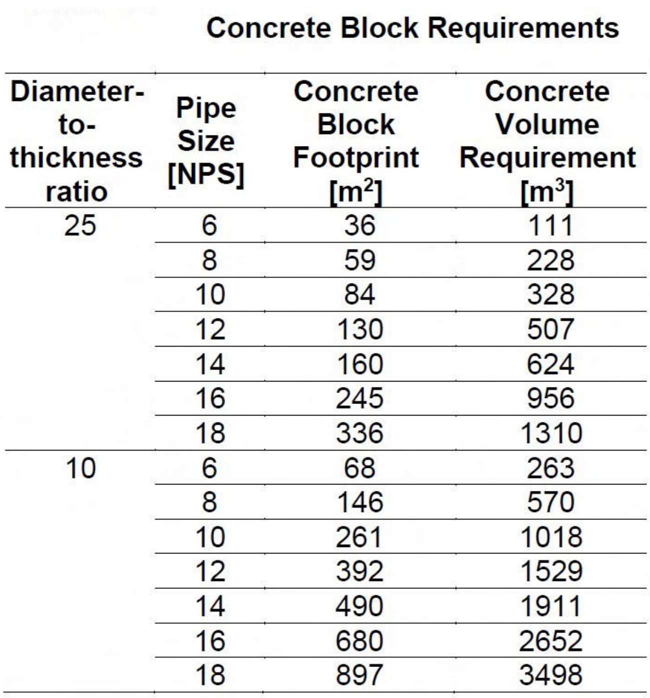
4. CONVENTIONAL APPROACH

The typical approach to designing tie-in interfaces is obtaining analytical estimates for end forces and displacements using principal equations. This is widely considered a quick method providing conservative results.

This was performed for the investigated cases and ASME B31.8 (ASME, 2016) equations for calculating restrained pipe axial forces were consulted.

End displacements were calculated using the difference between the driving pipeline strain due to temperature and pressure in the face of resisting soil friction to arrive at the resulting pipeline end expansion.

That formed the basis for concrete block sizing based on lateral earth pressure theory (Das, 2014), which covers stability, sliding, overturning and base load checks on anchor design. Below is a summary of the concrete block sizes required.



Concrete Block Requirements

Diameter-to-thickness ratio	Pipe Size [NPS]	Concrete Block Footprint [m^2]	Concrete Volume Requirement [m^3]
25	6	36	111
	8	59	228
	10	84	328
	12	130	507
	14	160	624
	16	245	956
	18	336	1310
10	6	68	263
	8	146	570
	10	261	1018
	12	392	1529
	14	490	1911
	16	680	2652
	18	897	3498

Figure 4: Concrete Block Requirements

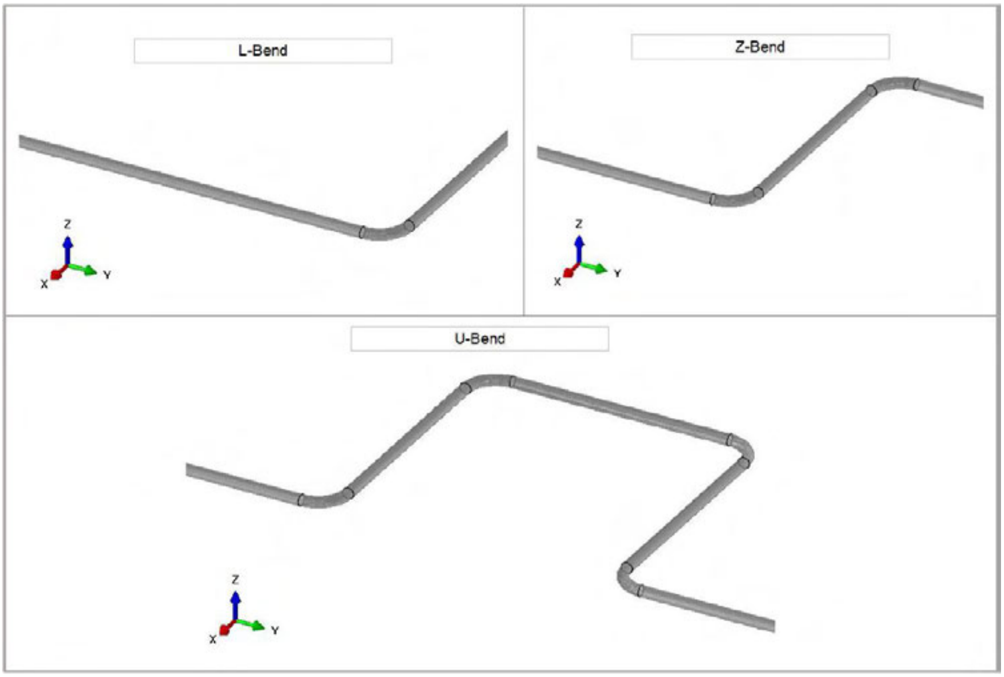


Figure 3: Pipeline Ends - Bend Configurations

5. ADVANCED APPROACH

In recent years the increased availability and efficiency of FE based Analysis and computational power have enabled detailed capture of previously over-estimated loads by considering geometrical, soil and material non-linearities.

The advanced approach is based on utilizing FE tools to capture the property and geometry variations not captured in the conventional approach presented in Section 5.

Additionally, incremental FE analysis is useful in defining the workable limits of a proposed configuration, including the maximum acceptable temperature or pressure.

5.1. NON-LINEAR SOLUTION

The FE based Abaqus solver efficiently estimates forces and displacements of buried pipelines approaching above ground tie-ins and simulates pipe and soil 3D behaviour.

Contrary to the conventional single system linear solution, the non-linear Abaqus solver is based on incremental loading and equilibrium, this enables the simulation of true loading scenarios as they would occur in real-life.

5.2. COUPLED MODELLING

A key input for anchor block force balance is the incoming loads on both sides, the above ground and the buried side of the anchor location. Conventionally, this would be independently calculated for each side and conservatively approximated, resulting in over-estimated above ground displacements and exaggerated the interface loads.

This can be optimized through coupled modelling, which incorporates the stiffness of connected piping/utilities into the modelled system as indicated in Figure 5.
The established model continuity develops a global understanding of the integrated system during design and ultimately helps reduce, or eliminate, approximations at interfaces and achieve maximum design optimization with minimum construction spreads.

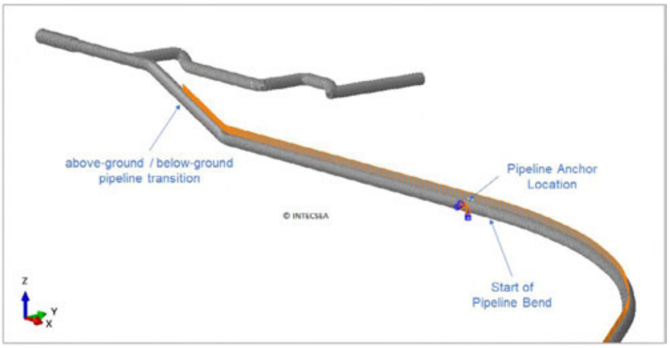


Figure 5: Coupled Pipeline/Piping Model

5.3. SAMPLE CASE STUDY

To demonstrate the benefits of advanced analysis capturing realistic interface loads when utilized alongside simple geometry, the simplified Z-bend pipeline end configuration Figure 6 was selected as a representative sample case. The analysed cases covered buried pipe sizes between 6” and 18” covering 2000m of straight length for diameter-to-thickness ratios 10 and 25.

Optimization outcomes were measured by comparing the resulting forces and displacements to the analytical estimates as detailed in Section 6.

For this study, soil springs used in the analysis represented cases of typical sand and typical clay to cover both cohesionless and cohesive soil types. On a typical assessment, soil properties are obtained from geotechnical survey interpretations transformed into workable analysis inputs

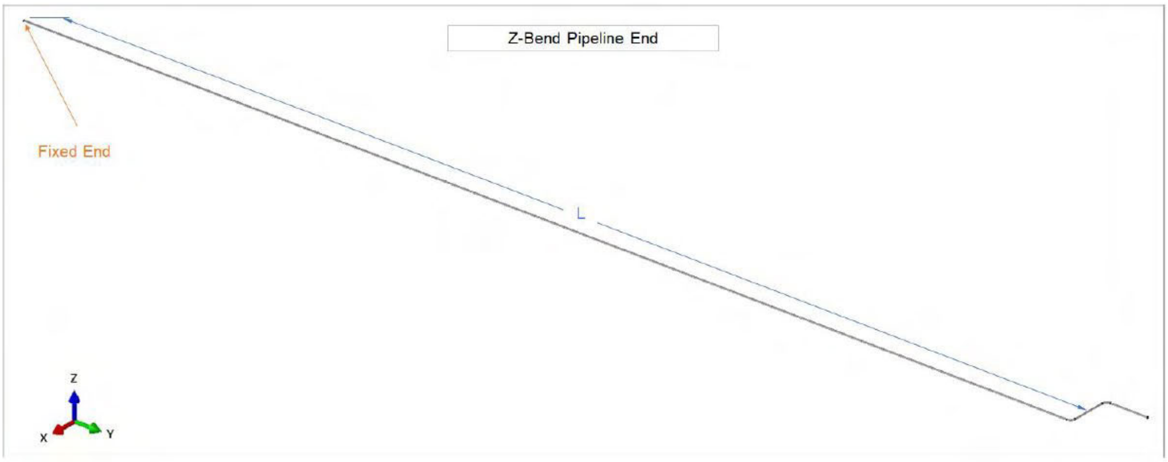


Figure 6: Selected Z-Bend Configuration

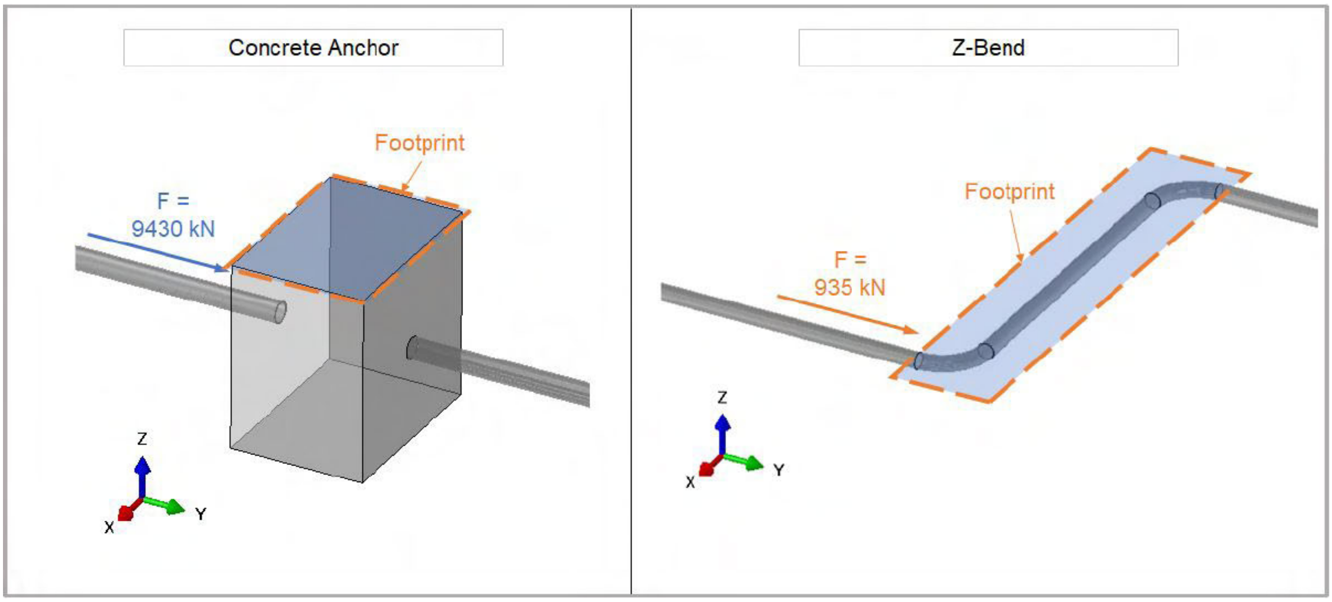


Figure 7: Sample End Force Comparison - 14" Pipe

based on PRCI (Douglas G. Honegger, 2004) soil models for axial, lateral, vertical bearing and vertical uplift resistances.

6. COMPARATIVE ASSESSMENT

6.1. RESULTS

The investigation included a comparative study of the resulting forces and displacements from the conventional approach and the advanced approach. The following outputs comprise the values used in the comparison for the studied load cases:

- Full force feed-in – This is the fully restrained axial force based on standard (ASME, 2016) calculations. It is the highest axial force possible for each considered case.
- Optimized force feed-in – This is the FE based axial force at the end of the straight pipeline segment, immediately before the Z-bend. This represents the axial force observed at the pipeline end with the introduced end optimization.
- Figure 7 indicates the forces when compared for a sample case.
- A sample force profile indicating the fully restrained force feed-in and the optimized force feed-in is shown in Figure 8.
- Full movement feed-in – This is the FE based displacement at the end of the straight pipeline segment, immediately before the Z-bend. It is the largest achieved end displacement for each modelled case
- Optimized movement feed-in – These are the conditions at the end of the Z- bend investigated in this study, they represent the partially restrained conditions only accurately captured using FE based analysis.

Figure 9 indicates the displacements when compared for a sample case. A summary of the results for non-cohesive soils indicating reduction is shown in Figure 10.

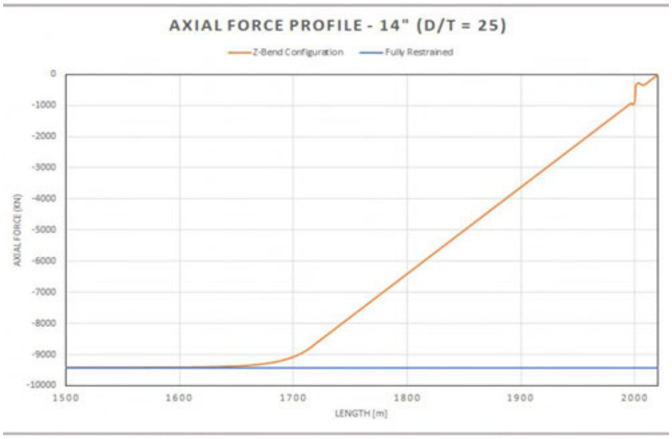


Figure 8: Sample Force Profile

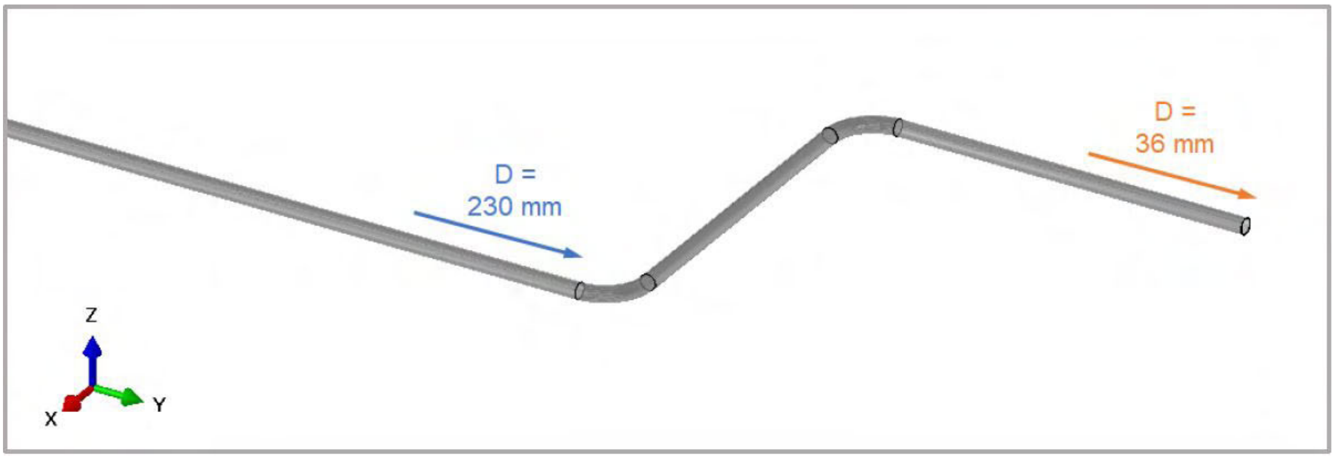
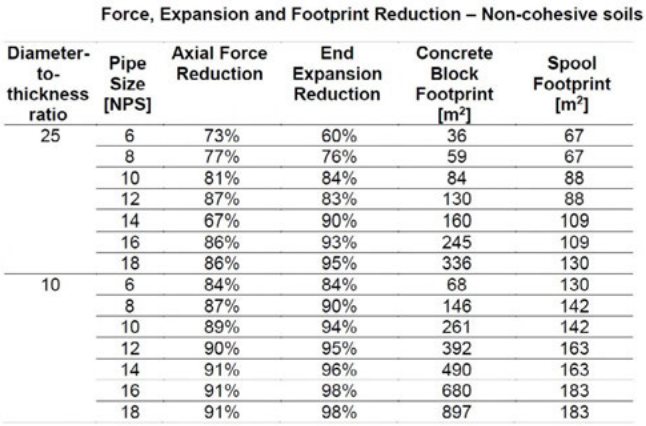


Figure 9: Sample End Movement Comparison - 14" Pipe



Force, Expansion and Footprint Reduction – Non-cohesive soils

Diameter-to-thickness ratio	Pipe Size [NPS]	Axial Force Reduction	End Expansion Reduction	Concrete Block Footprint [m²]	Spool Footprint [m²]
25	6	73%	60%	36	67
	8	77%	76%	59	67
	10	81%	84%	84	88
	12	87%	83%	130	88
	14	67%	90%	160	109
	16	86%	93%	245	109
	18	86%	95%	336	130
10	6	84%	84%	68	130
	8	87%	90%	146	142
	10	89%	94%	261	142
	12	90%	95%	392	163
	14	91%	96%	490	163
	16	91%	98%	680	183
	18	91%	98%	897	183

Figure 10: Force, Expansion and Footprint Reduction - Non-cohesive soils

6.2. DISCUSSION

6.2.1. END FORCE AND DISPLACEMENT

Upon reviewing the resulting forces and displacements, the assessment indicates effective axial force values of 30% or less of the conventional fully restrained axial force and 60% or more reduction in end displacements for the analysed cases.

It is clear from the results that the fully restrained axial loading is significantly higher than the partially restrained force at the anchor location. This is demonstrated in the presented force reduction in Figure 11.

The conventional approach of conservative analytical estimates of pipeline end force and displacement offers a clear split of scope between different engineering disciplines utilizing interface loads in their design, it also facilitates independent discipline variations and progress measurement.

However, based on the technical challenges presented in Section 2 and the results presented in this Section, this approach sometimes becomes uneconomic and unrealistic due to the pipeline anchoring occupying too much large real estate and sometimes introducing pipe misalignments.

The advanced approach, on the other hand, offers a versatile approach to addressing the loads at pipeline end connections, which depends on accurately capturing the interface loads and stiffnesses.

Although it does not offer complete isolation, advanced computation of interface loads enables the design to match the exact loading requirements.

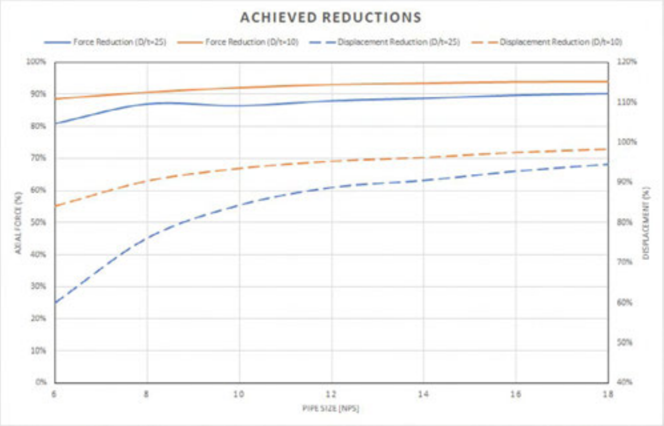


Figure 11: End Force and Displacement

6.2.2. SOLUTION FOOTPRINT

Using the conventional approach, isolation is achieved using the anchor footprint, explained in Figure 7, which incrementally increases with the increase in pipe size and diameter-to-thickness ratio.

Using the advanced approach shows the investigated Z-bend configuration offers minimal footprint increase with pipe size to achieve the desired reduction in forces and displacements. This results in optimized solution footprint for all investigated pipe sizes with diameter-to-thickness ratio of 10, and an optimized footprint for 12” and larger pipe sizes for diameter-to-thickness ratio of 25 as shown in Figure 12.

6.2.3. COUPLED MODELLING

The concept of coupled modelling discussed in Section 5.2 was applied by the author extensively on project specific configurations, using both linear and non-linear solvers.

A pilot comparison with the conventional independent approach showed that coupled modelling reduced the translated forces by more 90%. Moreover, the stress utilizations on the connected piping dropped by a full order of magnitude for thick wall pipes with diameter-to-thickness ratio of 9.5. This indicates significant technical and economic advantages of utilizing model continuity for pipeline ends design.

7. CONCLUSIONS

This paper demonstrates a simple, technically feasible engineering approach to optimizing pipeline end configurations, end expansions and forces for the investigated cases.

A sample case of Z-bend at the pipeline end is shown to reduce the axial force by 85% on average when compared to complete fixation achieved using anchor blocks, while maintaining axial displacement at less than 20% of the unrestrained pipeline configuration on average.

The results show that the Z-bend can be an efficient and less environmentally invasive alternative than conventional anchor blocks for buried pipelines, with established reduction in footprint for thick pipe sizes between 6” and 18”, and thin pipe sizes between 12” and 18”.

Moreover, if anchoring is unavoidable, significant reductions can be achieved in anchor capacity requirements while still maintaining the purpose of the anchor by adopting the advanced modelling approach discussed in this paper.

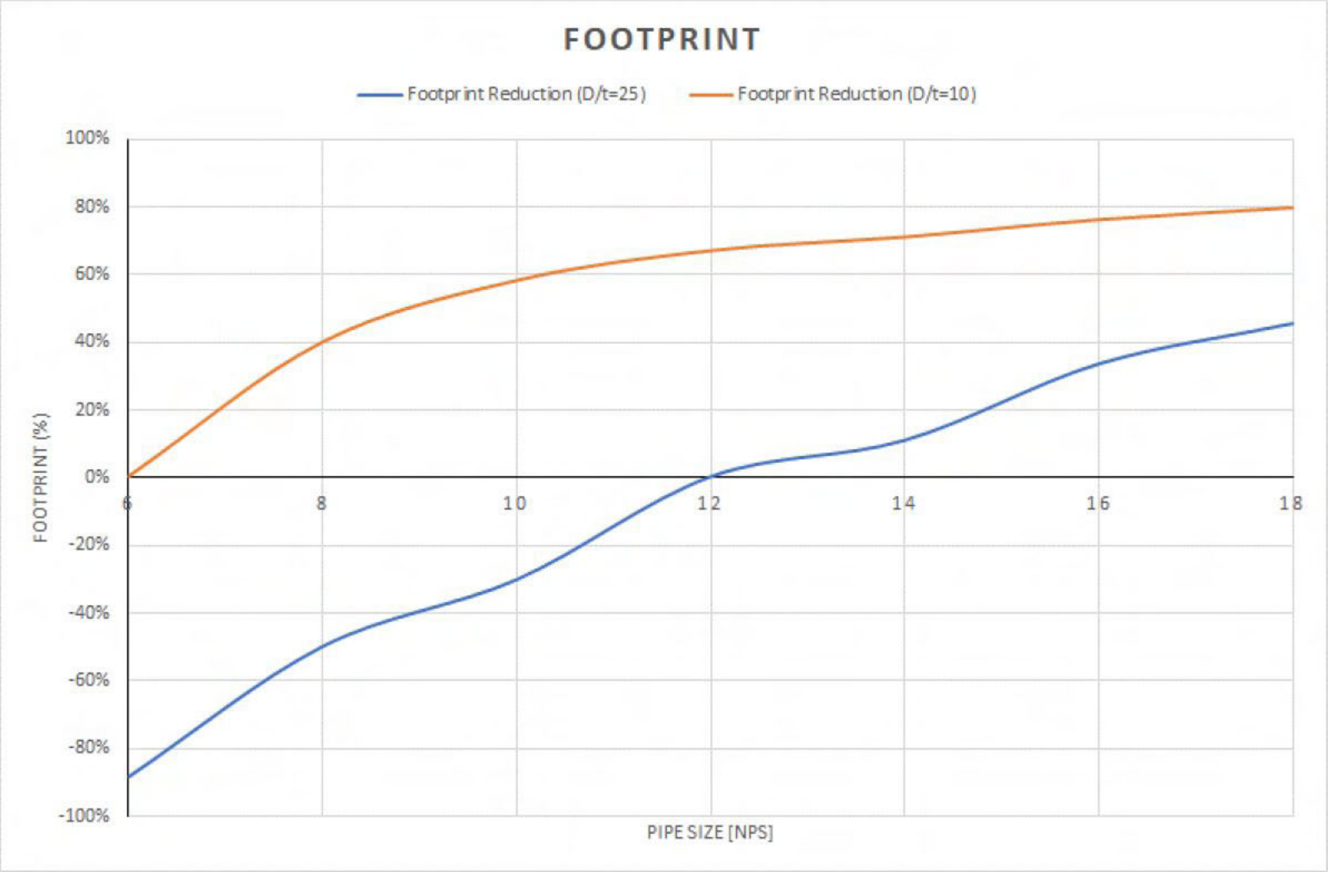


Figure 12: Solution Footprint

Introducing connected piping/utilities for project specific configurations further added to the presented optimization as discussed in Section 6.2.3. It is therefore also concluded that coupled modelling of pipelines and connected piping/utilities enables the design to accurately capture the forces and displacements from all system components.

This optimization of the interaction loads between underground pipelines and the connected above-ground facilities realizes significant technical and economic benefits.

8. RECOMMENDATIONS AND FUTURE WORK

Based on the results presented in this study, it is recommended that detailed investigation of engineered alternatives to concrete anchor blocks is adopted as common practice within the pipe size envelope of 6in to 18in, with diameters ranging 10 to 25 times the thickness.

Additionally, a risk assessment of the assumptions is also recommended to complement this work with quantifiable probabilities and scenarios of failure to drive further reduction in required sizes and, where feasible, eliminate the need for pipeline anchor blocks.

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