University of Southern Queensland

School of Engineering

Finite Element Modelling of Coal-Seam Gas Well Pumping Assembly for the Prediction and Prevention of Tubing Wear

A dissertation submitted by

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ENP4111 Professional Engineer Research Project

towards the degree of

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Abstract

The project identified that there is limited research on the behaviour of rod strings under operational load in the progressive cavity pumping systems employed in oil & gas wells. It seeks to conduct finite element modelling investigate the loadings on rod strings, particularly in the context of predicting where higher contact loads of the rod against the tubing lead to worn holes, for commercial utility.

Sophisticated modelling proved complex and difficult to achieve; accordingly, successively simpler modelling was conducted so that reliable insights could be determined. To this end, the static bending loads, and typical torsional loads were considered to determine their contribution to contact loads, and found to be minor. Subsequently, dynamic shaft balance loads were briefly explored and shown to be an avenue of future investigation.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Nomenclature

A mixture of SI and Imperial units are used in this dissertation, in a manner that best suits industry practice, readability and ease of technical communication. For instance, Oil Country Tubular Goods (Casing, Tubing, Sucker rods) are often defined by their size in inches: a 1in Rod, 7in Casing, etc. Imperial units will thus be used where sensible, but SI will otherwise be used by default. The manner aspires to be familiar to the veteran yet intuitive to the newcomer.

Chapter 1: Introduction

The pumping systems of coal-seam gas wells in western Queensland are predominantly progressive cavity pumping (PCP) systems, and have long tubing and rod strings to transmit torque from surface down to the pump, and the pumped liquid up to surface. The rod string sits concentrically inside the tubing string, and over time with many thousands of revolutions, can wear holes in the wall of the tubing. Such a hole requires a service rig to perform a workover to replace the worn tubing, incurring the costs of the job and of the lost production revenue. The basic configuration of a PCP system installed in a wellbore is shown in Figure 1,

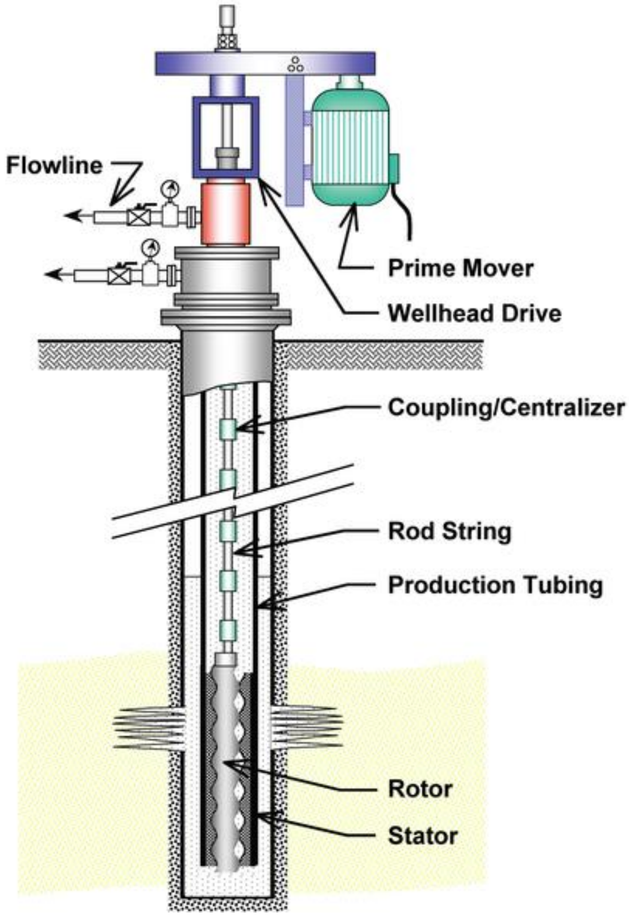

Figure 1- PCP System Overview (Petrowiki 2006)

Design options exist to mitigate the wear rate; but are expensive and thus are typically reserved for reactive installation. Deviation plots of wellbores (which are never perfectly vertical) have been used to predict the locations where the rodstring will press against the tubing, however results have been mixed; suggesting strongest sideloading may not coincide with the regions of greatest wellbore deviation.

It is proposed therefore to develop a Finite-Element model of a well identified as having a history multiple hole-in-tubing failures, or hole-in-tubing failures that do not coincide with deviation. There exists a body of research into the buckling behaviour of slender rods and tubing, but much of this has tended to examine axial loading of these strings, rather than the torsional loading associated with PCP systems.

It is desired to build upon the work of Zhang et al (2019) and (2021), which sought to use FEA methods to analyse the behaviour of the torsional behaviour of a slender column inside a cylinder (i.e.: a rod constrained by tubing), and the effects of rod guides on this buckling.

It is desired to build up this work: since rods buckle and apply loading onto the tubing wall, how significant are these loads in the range conditions experiences by PCP installations in the Surat Basin? What influence does the wellbore deviation have?

Chapter 2: Literature Review

There has been considerable study conducted into the buckling behaviour of slender tubulars in oil & gas wells. Gao and Huang (2015) conducted a comprehensive review of research of the topic: gathering together, and comparing and contrasting, various approaches and results across almost 70 different sources.

These studies have largely been conducted in two contexts: either buckling drill pipe during drilling operations, or buckled rod strings during reciprocating rod pump operations (the classic "nodding donkey" style of pumping operation). Some research has been scale-model experimental in nature, such as Li et al (2021), while others have conducted numerical simulation at either small or full-wellbore scale, such as Sun et al (2019).

In the case of drill pipe studies, the goal has been to understand the behaviour of drill pipe in order to optimise the well construction process. Drill pipe is relatively thick, robust steel pipe designed to handle the extra stress of the drilling process- with compressive axial forces and torsional forces (depending on the type of drilling). It is not sought to examine deeply the breadth of all research into drill pipe behaviour. Still, by way of example, Wang et al (2018) may be considered, providing experimental research into the whirl behaviour of the lower section of a drill pipe assembly.

Though the components and purpose may be different to our aims, the spirit of this research (and plenty like it) is nonetheless similar, since it seeks to understand the deforming behaviour of downhole tubulars. It may be said that drill pipe analysis is useful to us in so far as it considers a long, slender column subjected to buckling inside a cylindrical constraint. However, there are key differences to consider in examining sucker rods instead. Rods are thinner, less robust and (generally) not hollow as in drill pipe. In the Progressive cavity pump application, the load consideration is primarily torsional.

Meanwhile, in the case of reciprocating pumps applications, these studies have focused on investigating the behaviour of axially-loaded rod strings, where the study is examining buckling behaviour in order to ultimately mitigate the holes prematurely worn into the tubing wall (and the associated cost of downtime and repair) that this buckling loading of the rod string causes. Araujo and De-Souza (2021), for example, give insight to the behaviour of reciprocating rod strings inside of directionally-deviated (non-vertical) well bores.

This kind of research is nearer to the project's concern: the rods used in reciprocating applications are generally similar to those in PCP application, and the problem of worn tubing holes is of equal concern. However again, the primary concern in this project is not axial loading but torsional loading.

Both Wang and Araujo may be considered as singular examples to give a general indication only of recent research in the respective areas: there is a wide range of research examining various aspects of bucking problems for drill strings and reciprocating rod pump strings; Gao (2015) lists many. The problem is mathematically and operationally complex. Gao (2015) refers to Huang's (2015) helpful compilation of the no less than *twelve* different phases of possible buckling states. At one end of the loading scale, the string has no buckling and no contact to the outer tubular wall – at the other end, the string is in helical buckling and wrapped contact.

Figure 1 shows the progression of buckling along a wellbore: from support through to full helical buckling. Meanwhile, Figure 2 shows the grid of possible buckling states.

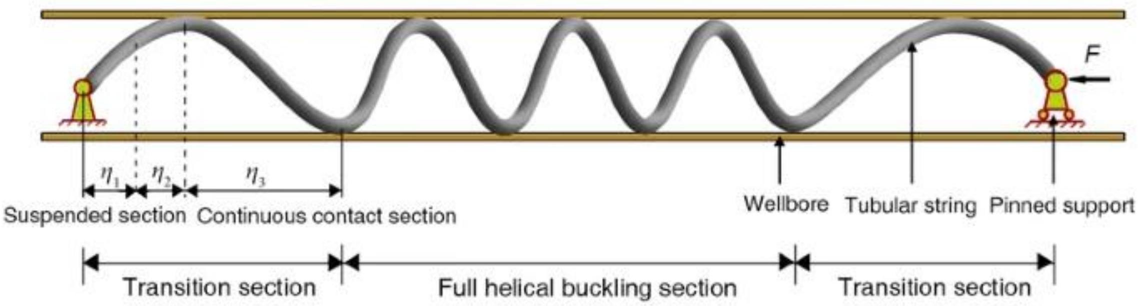

Figure 1- Diagram of progression of constrained tubular buckling, Gao and Huang (2015)

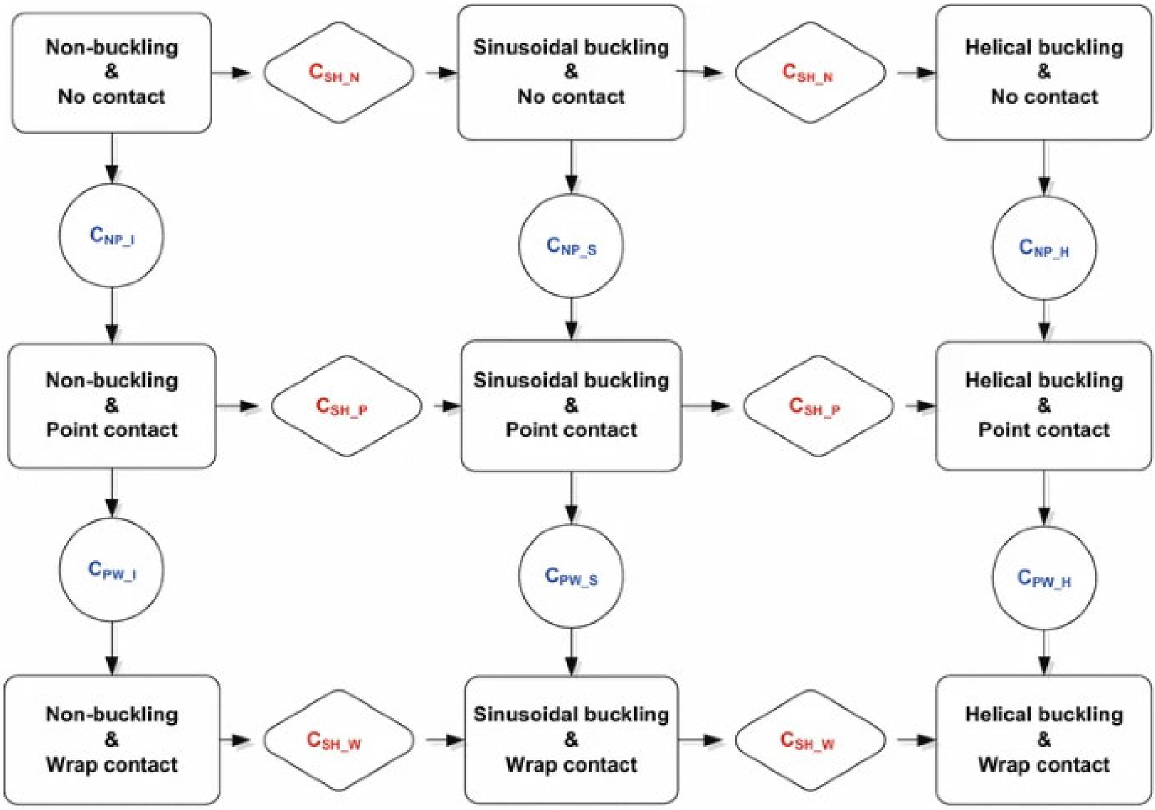

Figure 2- Diagram of buckling modes, Gao and Huang (2015)

In this context then, insight is sought into the rod behaviour under torsional load in progressive cavity pumping systems. While reciprocating rod pumps are commonplace worldwide as an artificial lift system for oil & gas wells, more common in the context of the Surat and Bowen basins of Queensland is the progressive cavity pump (PCP), where the rod string undergoes torsional loading rather than axial. Worn hole in tubing failures remains an issue, but unlike drill pipe or reciprocating strings, the behaviour of rod strings in the PCP application has relatively little research.

Zhang et al (2019) and (2021) provide the main studies to build further upon. Their 2019 study sought to examine and model the torsional buckling behaviour of a slender, round column constrained inside a cylinder: i.e., the buckling of a sucker rod inside production tubing, being deformed under torsional load as would be experienced by the rod string of a PCP system. Finite Element modelling was conducted to understand the behaviour of a range of sucker rod and drill pipe diameters under various loadings. The study focused heavily on identifying the modes of contact of the column against the constraint of the cylinder wall as the column buckles in a helical fashion, and shows the development of single, double, and three-point contact of column against the cylinder, and beyond as the deformation progresses.

Their 2021 research builds on this; with assessment of the effects of adding centralising guides to the sucker rods, so that contact loads of rod against tubing from buckling may be minimised. This gives practical application for the elongation of tubing and rod lifespan. The research showed that addition of centralisers improves the critical buckling torque values, and gives formulae for spacing of centralisers. Figure 3 shows the development of the centralised model: it may be compared to the buckling behaviour in Figure 1.

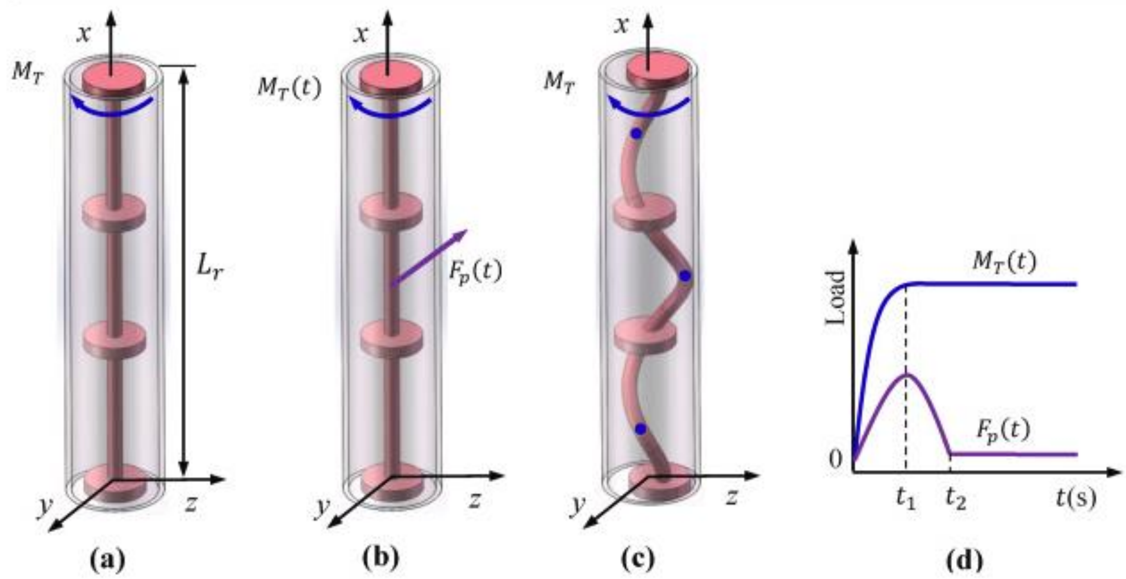

Figure 3- Progression of torsional buckling of rods with centralisers. By Zhang et al (2021)

Building on these foundations, it is desired to push towards further analysis of the behaviour of rod-in-tubing, and address knowledge gaps as follows: knowing that rod strings buckle and generate outwards loading onto the tubing string which leads to wear, how significant are these loads at a range of conditions experienced in the Surat Basin? What degree of influence does the deviation of the wellbore have? How do modelled results compare to field experience of the locations of worn tubing holes in specific operational wells? What effect does various different tubing and rod strings have? Most critically of all: can high-wear locations be accurately predicted, such that design mitigations can be pre-emptively installed?

It is also hoped to build upon the work of Cheng et al (2021), which considered the buckling behaviour of concentric tubular strings. Note that the rod-and-tubing combination considered by Zhang et al, in actuality is always encased in a further, larger cylinder: the wellbore casing, such that rod sits inside tubing sits inside casing. The scope of Zhang's work considers tubing as assumed fixed, whereas Cheng seeks to understand bucking not only of the rod string, but also of subsequent buckling of the tubing against the casing wall by the lateral force exerted by the buckled rods. Figure 4 shows this concentric arrangement: the rods ("inner tube") lie inside the tubing ("middle tube"), which in turn lies inside the casing ("Outer tube").

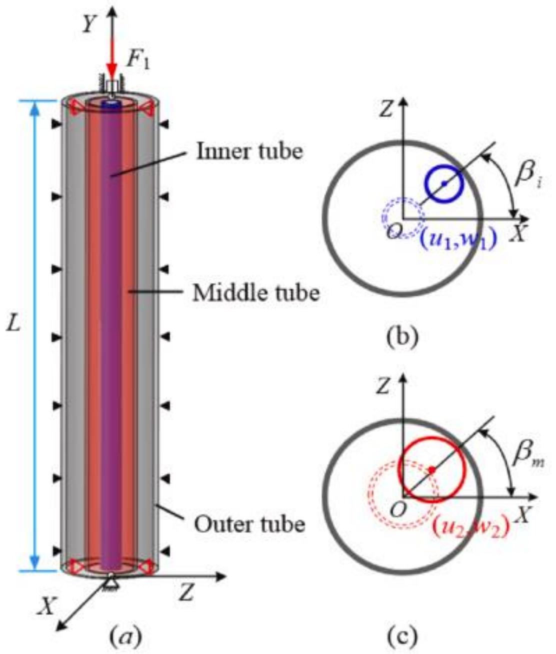

Figure 4- Layout of concentric tubulars in a wellbore, by Cheng et al (2021)

Zhang considers torsional buckling of rods only at full-wellbore scale; meanwhile Cheng considers Axial buckling of both rod and tubing at a shorter scale. It is hoped therefore to examine knowledge gap of considering the torsional buckling, at wellbore scale of both rod and tubing.

To summarise then: buckling of slender tubular columns in oil & gas applications remains a complex problem, and in the field of drill pipe has undergone plentiful and ongoing research, likewise the buckling of reciprocating rod strings. Less prolific is expansion of this research into the behaviour of rod strings in progressive cavity pump applications, and it is here the project's efforts will be targeted; with a focus less on a purely mathematical investigation, but to examine behaviour of buckling rods and their relationship to worn hole-in-tubing, especially in the context of lightly deviated wells.

Chapter 3: Methodology

The research aims to provide answers the following four principal questions:

1. Do the regions of highest side-loading align to the regions of highest deviation in the well?
2. Do the regions of experienced hole in tubing align to the regions of highest side loading and/or highest deviation?
3. Do different sized tubing strings induce or alleviate sideloading in a given well?
4. Do different sized rod strings induce or alleviate sideloading in a given well?

To investigate these, a finite element model of a wellbore and the relevant tubulars therein shall be constructed, to mimic the operational conditions as best as can be practically achieved. From this model, it is envisaged that the material behaviour (stresses and strains) will give insights to the research questions.

To construct the finite element model, the deviation survey data from an example well shall be used. During well construction, after the production hole is bored out, a tool is run into the wellbore and measurements are taken: namely, the inclination and the azimuth. If one imagines to be looking directly down the wellbore from the surface: the azimuth indicates a compass direction in degrees (0 to 360) indicating the direction of the inclination. Meanwhile, the inclination indicates the angle in degrees that the borehole deviates from vertical. A zero-degree inclination would indicate a perfectly vertical section of wellbore, and a 90-degree reading would indicate a horizontal wellbore. In an intentionally vertical well then, inclination is thus typically a few degrees.

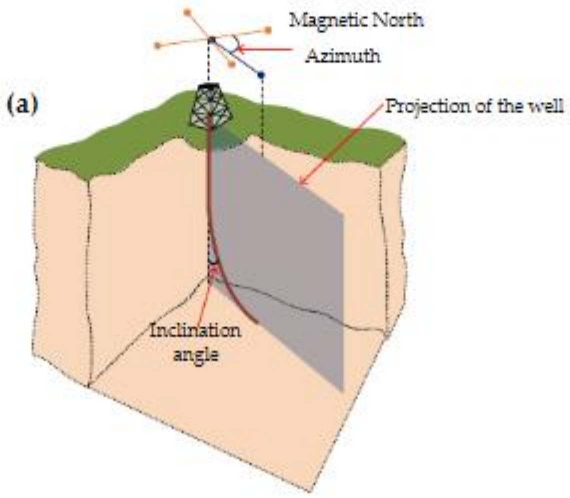

Figure 5- Wellbore Path - Gooneratne, C et al, (2017)

Deviation surveys therefore provide a discretised representation of the path of a wellbore. The example well has measurements that were taken approximately every 10 metres of depth.

Since the measurements in this case are taken in the 9-5/8" surface casing and the 8-3/4" openhole, it will be assumed that the 7" casing follows the pathing directly. Though an imperfect approach, more accurate data cannot be gained without extreme expense, and it should be noted that the 7" casing does have centralisers installed as part of the well construction- centralisers intended to ensure the casing holds to the centre of the wellbore at least enough to ensure that cement can be placed between the casing and wellbore wall with sufficient uniformity as to ensure wellbore integrity from pressure migration.

By contrast, the tubing is not centralised in the casing except at the torque anchor at the bottom of the tubing string. So, the casing shall be treated as following the DLS precisely, and allowing the tubing to displace freely inside the casing annulus.

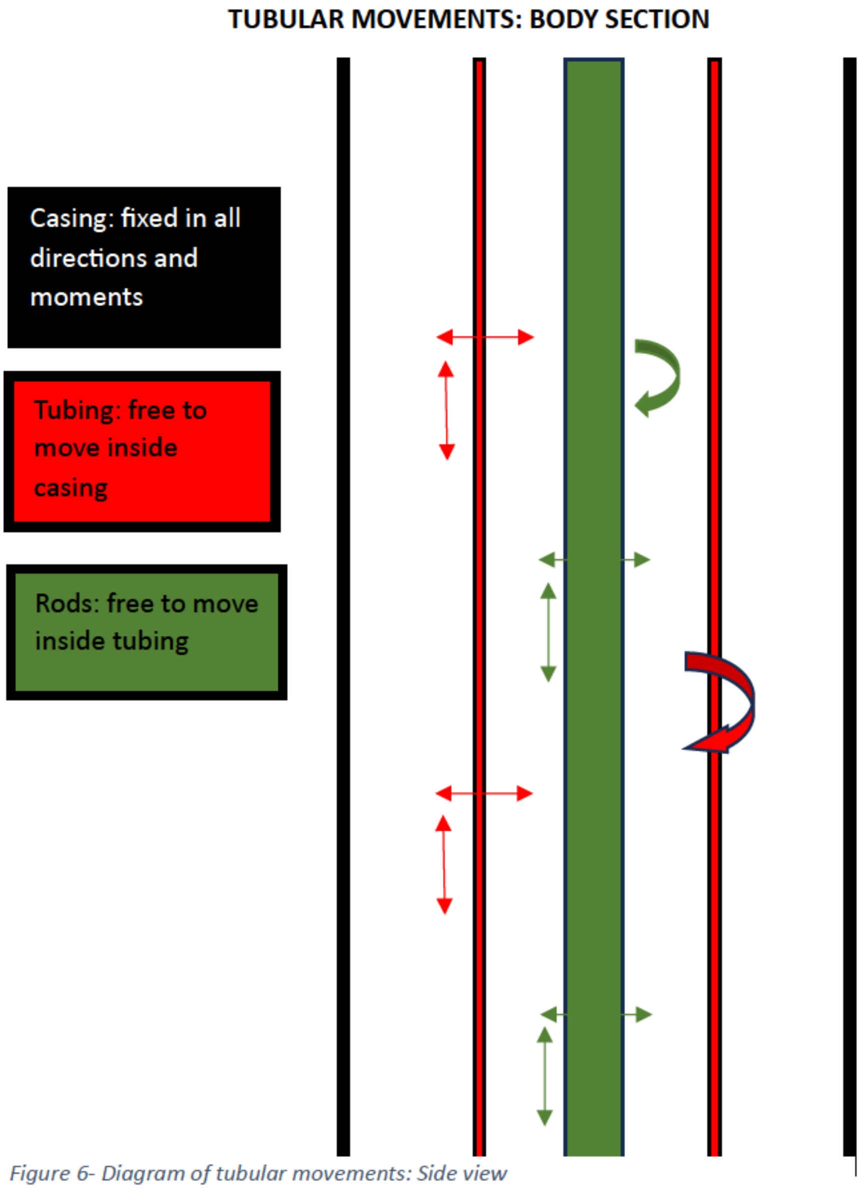

Figure 6- Diagram of tubular movements: Side view

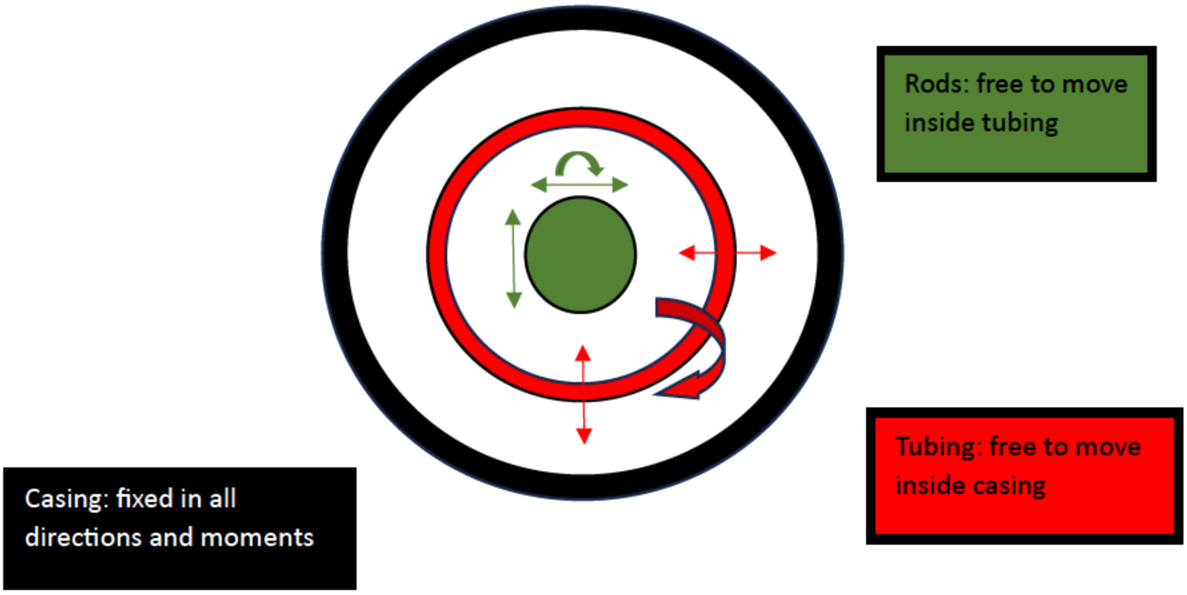

Figure 7- Diagram of tubular movements: Top view

CASING	X-Translation	Y-Translation	Z-Translation	Z-Moment
Top	Fixed	Fixed	Fixed	Fixed
Body	Fixed	Fixed	Fixed	Fixed
Bottom	Fixed	Fixed	Fixed	Fixed

Table 1- Casing Movement Constraints

TUBING	X-Translation	Y-Translation	Z-Translation	Z-Moment
Top	Fixed	Fixed	Fixed	Fixed
Body	Free	Free	Free	Free
Bottom	Fixed	Fixed	Free	Fixed

Table 2- Tubing Movement Constraints

RODS	X-Translation	Y-Translation	Z-Translation	Z-Moment
Top	Fixed	Fixed	Fixed	Applied Torque
Body	Free	Free	Free	Free
Bottom	Free	Free	Free	Fixed

Table 3- Rod Movement Constraints

To create the wellbore model, the casing will first be generated, using the deviation survey measurements to string together the wellbore path. The effect of any collars (couplings) will be ignored and assume a perfectly smooth wellbore at the 7" nominal diameter. The casing will be fixed in the model and not permitted to displace in any manner.

Inside this, the tubing will be placed. 2-3/8" OD tubing will be used as a baseline, with collars at 9m intervals (the typical length of a joint); but only the external size of these will be realised, internally the tubing shall be a smooth bore of 1.995" diameter, ignoring any effects by the collars. The OD of the collars is relevant however, since these will contact the casing before the thinner tubing body.

The top edge of the tubing string will be fixed in the centre of the wellbore, and unable to displace in any direction. This reflects the reality where the top connection of the tubing is fixed to the tubing hanger inside the wellhead, and is thus centred and unable to move vertically, laterally or in torsion.

Beneath this top edge, however, the tubing is free to move inside the casing; it can bend along the wellbore path, can move side to side, or twist. While it is possible for connections between tubing joints to be come undone, it will be assumed that all connections are properly torqued and not prone to loosening.

The very bottom of the tubing string shall be constrained from lateral displacement and torsion, but be able to displace vertically; replicating the effect of the torque anchor, which resists the torque applied by the pump's operation and holds the string to the centre.

Inside the tubing shall be installed the rod string: 1" in diameter, with couplings every 7.62m that bell out to 1.625" diameter. Like the tubing, the rod string shall be constrained to the centre of the tubing annulus at surface; unable to move laterally or vertically. A torque shall be applied to the string at the top, replicative of the torque applied by the drivehead in reality. The rodstring will be free to displace inside the tubing string: laterally, vertically and in torsion. At its bottom, the rodstring will be constrained laterally to the centre of the wellbore, and be fixed in respect of torsion. In this way, the model should capture a "pause in time" of the pumping system in operation. Torque will be applied to the rodstring to simulate the loading of an operation PCP, ranging from 100Nm to 1400Nm in 100Nm increments. It shall also be examined without the torque applied, with a view to understanding any differences in side loading created by the helical deformation of the rodstring under torsional load.

Force of gravity will be applied to the tubing and rods; each are several hundred metres long and made of steel, and hang in tension in the wellbore. As well, the tubing shall be treated as full with water (and thus exerting a pressure gradient from the bottom to top of the string). Meanwhile, the casing annulus shall be treated as dry, and exerting a relatively light pressure (250 kPag) onto the tubing exterior, and so resembling a steady-state producing well where the fluid level has been drawn down to the pump intake.

From this, the regions of greatest stresses and deformation can be observed; and conduct comparison to the regions of greatest deviation, along with the regions of observed historical hole-in-tubing, and in doing so begin to examine questions one and two.

A nominal example well shall be used:

The well exhibits apparent high side-loads at various depths down the well bore: yet experienced a worn hole-in-tubing at 528mRT; a point of lesser magnitude than most others.

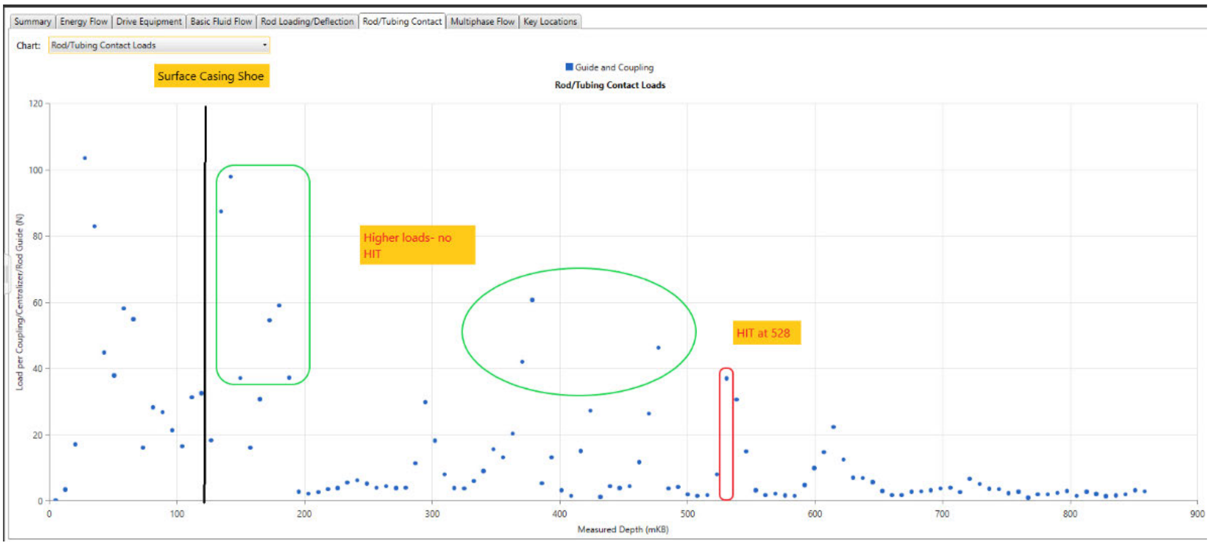

Figure 8- Sideloading as calculated by an Industry Design Software

The side loading is calculated in a typical industry design software suit, which assumes the tubing follows a perfect central path as described by the DLS.

Of course, for the purpose of this analysis, it shall be taken for granted that the directional survey is sufficiently accurate and of sufficiently fine resolution; and that side loading is a significant enough causal factor to warrant this focus.

By constructing the wellbore with a finite element tool, it is hoped to gain a greater insight to the actual behaviour of the strings, and examine their behaviour compared to a plain deviation survey.

If time permits then models can also be constructed models for, more complex wellbore geometries.

Further, investigation can be undertaken with alternative rodstring sizes, which match to particular tubing sizes:

Tubing Size	2-3/8"	2-7/8"		3-1/2
Rod Size	7/8"	7/8"	1-1/4"	1-1/4"

Table 4- Tubing and Rod Configurations

Chapter 4: Model Development

Creo Parametric 8 was utilised to begin construction of a model. Based on the deviation survey, a path was plotted in 3D space of points along the wellbore path. 104 total points are placed, spaced approximately 9m apart in terms of depths and at their respective lateral distances.

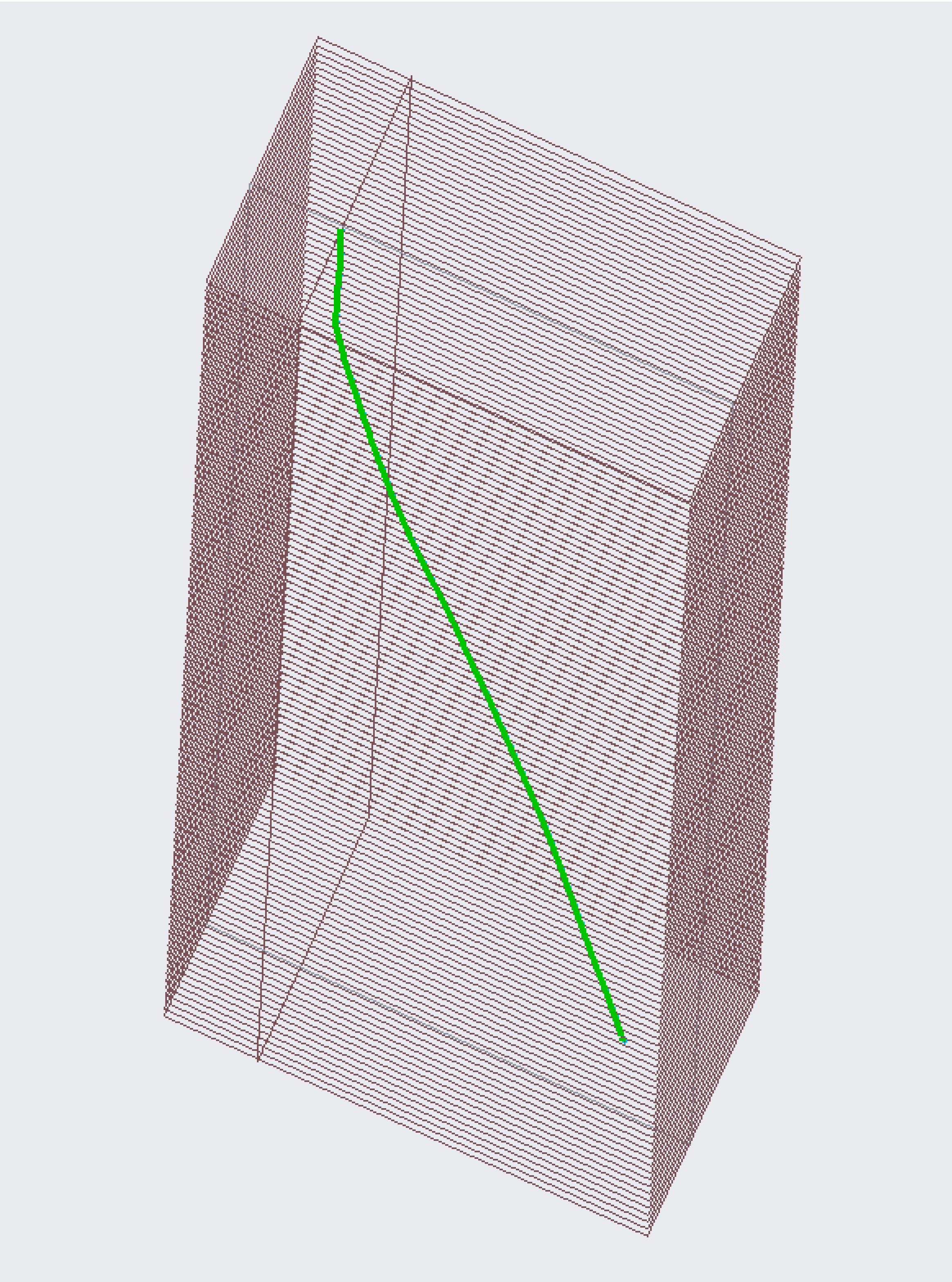

Figure 9- Wellbore Path

Along this path, the sweep function was used to create the cylindrical shapes of the Casing, tubing and rods. The process proved both time consuming and prone to error: especially plotting the trajectory, where manually entry of a large number of values in an extremely slender shape that is difficult to view clearly (so as to give a fast visual indication of error) was difficult.

Eventually the process was completed; nevertheless, several issues emerged with the geometry. In an effort to match the smooth geometry of a real wellbore, a smoothing mode was used on the sweeps; however, this created unrealistic shapes through the curvature of the wellbore: frequently the geometry would stretch laterally to compensate for the direction changes elsewhere in the strings. This stretching would cause collision between the strings, and proved difficult to rectify. A satisfactory solution could not be determined in Creo or in Ansys software.

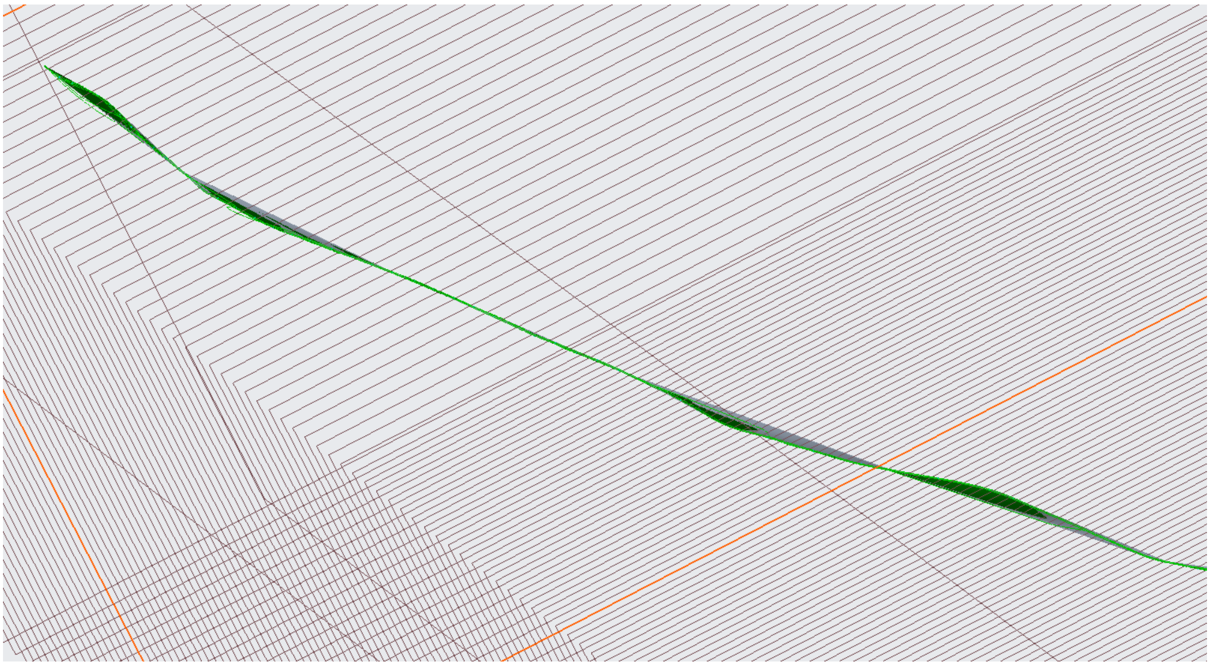

Figure 10- Distortion of Rod model body

Subsequently, while the loadings and constraints could be readily added to the model, generating a mesh also proved impassable.

At this point, the model goals were re-assessed, and a decision made to construct a simpler geometry. Rather than a highly discretised set of points through 3D space, a set of four points through space was adopted instead, with nominal deviations from vertical (and the other segments), to a total length of 1000m.

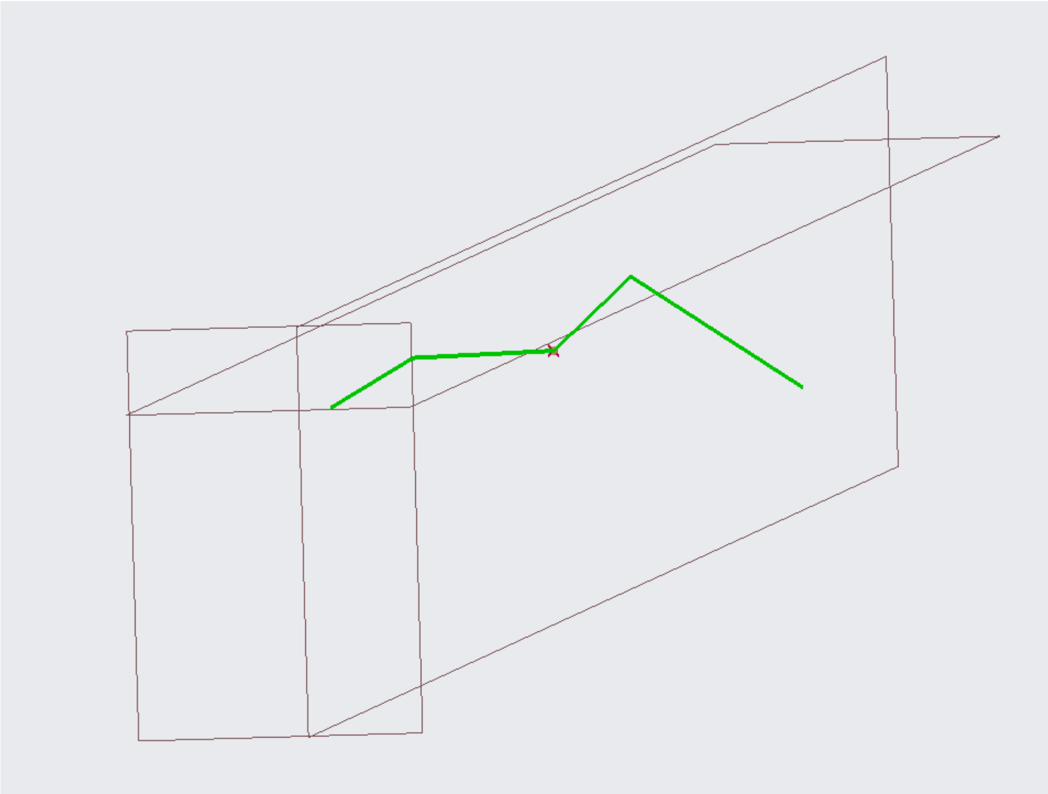

Figure 11- Simplified "four-part" Well geometry

This alleviated blending issues, but meshing issues remained: the geometry was simply too physically large (and slender especially) to be easily handled by the software.

Further simplifications were attempted: shortening the wellbore to 400 metres; then 200, 50 and finally 20 metres, along with various mesh refinements. Only the shortest lengths were able to achieve functional meshes: some larger sizes could also mesh, but were generally of extremely large size and so suffered heavy computation time and/or violated student licence limits.

Further revision to the model outputs and the project goals was thus warranted.

A finely-tuned, highly reliable predictive model for individual wellbores is evidently beyond the scope of the available software, hardware and skills. The ability to precisely predict individual (<10m) regions of highest loading was therefore not feasible to achieve.

In this context, more modest goals were set. If precise questions could not be answered, then perhaps more general questions could. A primary uncertainty in the original question is the extent to which the deviation of a given wellbore affects wear life, as opposed to any outward forces generated by the torsional buckling of the rods. Two simple models would therefore be developed; one to assess stresses generated at the sharpest sections of a well's deviation, and another to assess buckling behaviour under a range of typical operational torques. Each would be a 20-metre-long section of rod, with one end fixed and the other with a loading applied.

4.1 Consideration of Lateral Displacement

Consideration of a relevant well shows that one of the sharpest areas of deviation in the well creates a lateral displacement of 10 centimetres over a depth of 20 metres.

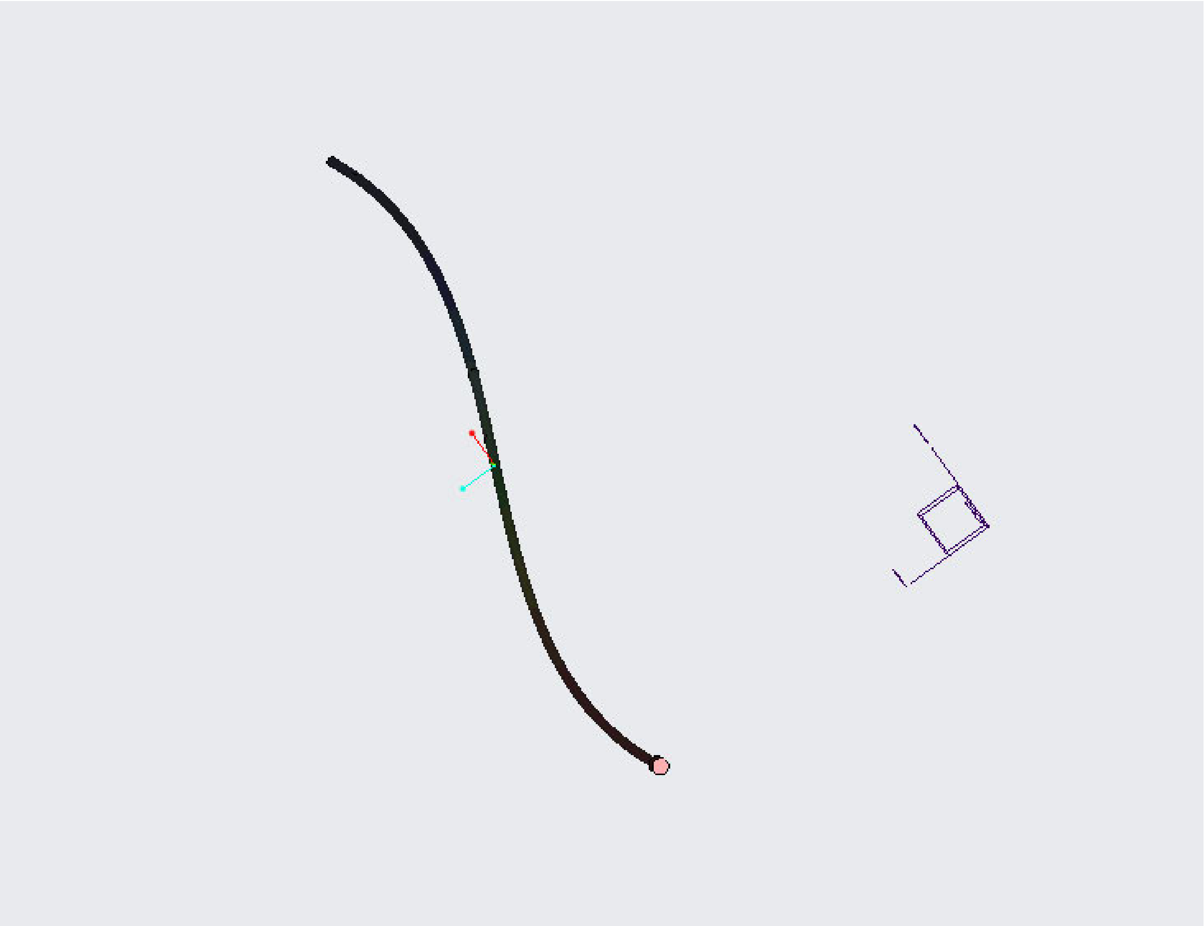

Figure 12- Lateral displacement of a rod section

4.2 Consideration of Torsion

Similarly, a 20-metre rod section will be considered under a range of typical operational torques to observe their behaviour. A moment will be applied to one end, starting from 250Nm, and increasing in increments of 250Nm until buckling contact with the tubing wall can be observed; as well as a nominal system maximum of 1400Nm.

The scenario will assume a rod size of 1", with a coupling size of 1.625in, inside a tubing ID of 1.995in. This gives a lateral clearance of 4.70mm in any one radial direction before a couple would contact against the tubing wall (and thus create wearing forces)

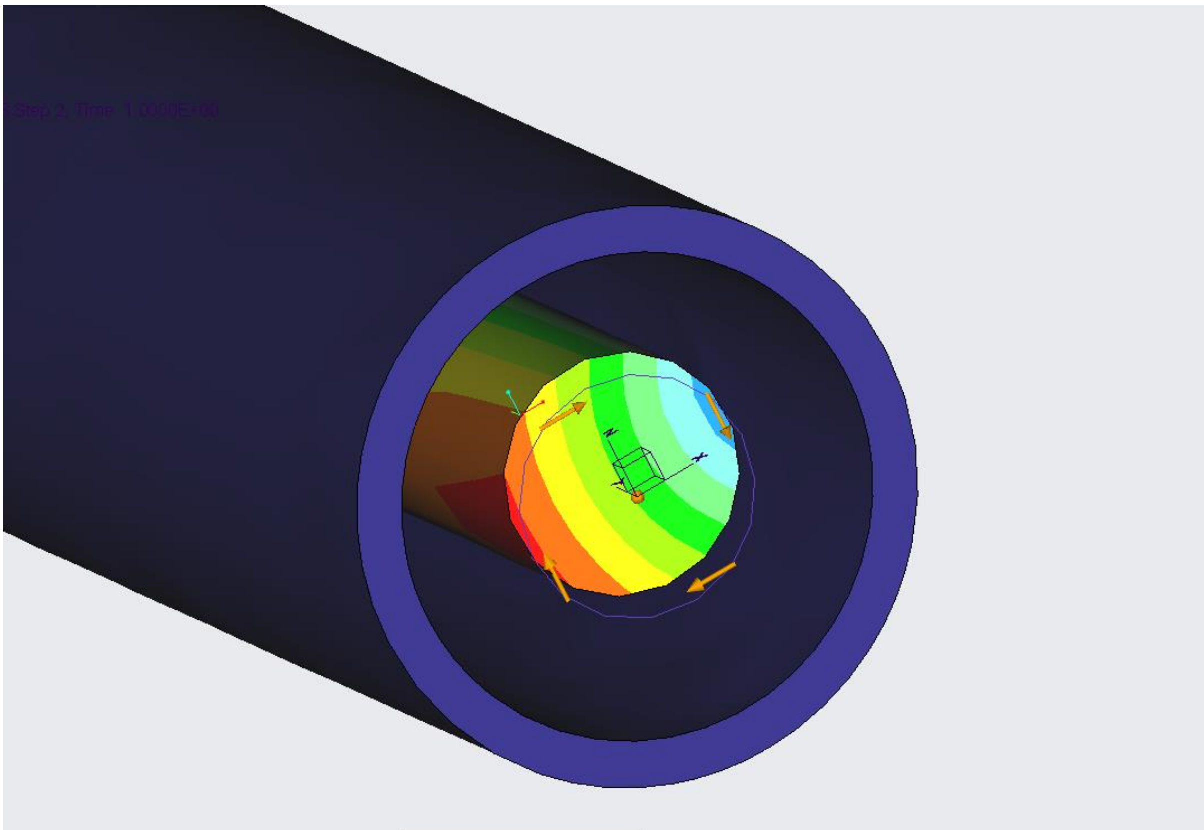

Figure 13- Torsion model showing displacement of rod due to applied Torque

Chapter 5: Discussion of Results

5.1 Consideration of Lateral Displacement

By inspection, it is observed that viewed in isolation, even relatively severe deviation sections appear to be very slight in terms of lateral deviation in the context of the length considered- only 10 or 20 centimetres over a 20-metre length. If considered as a simple cantilever beam, it is apparent only very slight forces are needed to induce the lateral movement needed to meet the deviation profile: thanks to a long lever arm (20 metres) combined with a thin cross-section (1in).

This appears to be reflected in the modelling: only slight strains and stresses are evident despite the displacement.

5.2 Consideration of Torsion

At a torsion of 250Nm, only a very slight lateral displacement was observed: ¬1.5mm, and thus insufficient to generate contact. A 500Nm torque created a radial displacement of 3.11mm; meanwhile a 750Nm torque reached 4.67mm- which can be regarded as near enough to contact as to be practically be it. Meanwhile, a 1400Nm torque created a displacement of 8.68mm.

5.3 Tables of Results

5.3.1 Lateral Displacement

Strain Direction	Strain Max ($x10^{-6}$)	Strain Min ($x10^{-6}$)
XY	4.40	4.13
XZ	1.17	-1.56
YZ	5.69	-2.42
Max Principal	9.61	-8.57

Table 5- Strain Measurements from Lateral Displacement Model

5.3.2 Torsion

Torque Applied (Nm)	Lateral deflection (mm)
250	1.5
500	3.11
750	4.67
1400	8.68

Table 6- Lateral displacement measurements from Torsion Model

Strain Direction	Strain Max ($x10^{-3}$)	Strain Min ($x10^{-3}$)
XY	5.55	-5.89
XZ	4.02	-3.73
YZ	5.89	-5.67
Max Principal	4.77	¬0

Table 7- Strain Measurements from Torsion Model

The very small forces involved in the lateral displacement is intriguing: it suggests that at least in the static view, there would be very limited wear contribution from deviations of this nature. In the analysis, the contact point (or point of lateral force load) was effectively assumed to be applied, (and therefore concentrated) at a single point at the end of the 20m rod. In reality, the contact will be spread across several points: a 4in-long coupling every 25 ft, and then two, three or commonly four polymer rod guides evenly spaced along the rod between each coupling, each also being ¬4in long.

Thus, whatever light force is required to create the static bending would be diluted and spread across these contact points. It suggests that, at least up to some point, the deviation would be imparting very minimal force to a rod.

Meanwhile, the buckling force is also relatively light: while definitely present at higher torque loads, it is absent below ¬750Nm: this would suggest then, that for the considered well field, where deviations are typically in the range examined, and torques also below 750Nm, these two factors would present to be only minor contributors to side loading, and thus worn hole-in-tubing failures in general.

It is also noteworthy that at the maximum torque of 1400Nm, the free rod end had only displaced 8.68mm: 4mm greater than the freedom it has before contacting the tubing wall. Thus, if it is possible for rod deflection to upset and dynamically displace the tubing in a lateral fashion, any such displacement must be very minor. That is to say, that even if the tubing were free to displace and did not oppose the motion of the rod string, the tubing would only shift some 4mm- in truth it will of course have its own constraints.

How then, to explain the phenomenon of worn holes away from zones of deviation?

Several avenues invite further investigation:

1. Dynamic behaviour. The static load appears minute, but what are the dynamic forces when the string is rotating at 100, 200, even up to 300 RPM? It is suspected as light given the slender geometry, but is not currently known. The action of a coupling 'slapping' against the tubing repeatedly could pose as a cause of abnormal wear, if such behaviour could be shown as possible.
2. Loading of gravity, especially if the wellbore geometry could conspire somehow with rod weight to apply an abnormal side loading at a point in the string
3. Deeper review of the existing well and failures data: sufficient unusual wear locations triggered the concept of this modelling, but a complete review has not yet been completed. Gathering this (though laborious) would give a greater dataset with which to validate other findings
4. The possible effect of any quality issues with individual rod guides in a string. If a well of nominal 750m depth had 100 sucker rods each with 4 guides, it seems a reasonable suspicion that if a very small number of guides had a faulty composition, this could appear as accelerated wear in random sections of random wells at a large enough sample.
5. The effect of variable concentrations of solid particles in the fluid flow and their behaviour and influence on wear rates, especially in concert with (or instead of), (4). Could a guide wearing in an unusual fashion collect an abnormal extra depositing of sediment (that other guides did not), such that the wear was especially accelerated?
6. The complex 3D path of wellbores. For lack of better option, it has been assumed the rod or tubing follows the deviation described by wellbore survey, but in reality, a wellbore with

kinks in multiple directions, corkscrewing and building and falling curves could potentially push the tubing into an unusual path.

With regard to what further work is feasible to conduct in the constraints of the project, it is proposed to consider point (1): undertake some basic dynamic analyses. (3) is also considered valuable, but is likely better suit to the corporate context rather than this paper. (4) Cannot realistically be investigated without first having done (3); likewise (5). (6) has already fallen victim to the issues described earlier in the project; (2) also seems likely to have similar difficulties in confidently isolating particular loads.

5.4 Supplementary Dynamic Analysis

It is proposed to consider the problem idealised as a rotating shaft with a single out-of-balance mass.

The ends of the rod may be considered as the bearing reaction points, and the deviation represented as half the rod's mass rotating a radius 50 mm from the rotational axis, located at the midpoint between the two ends.

Since

$F = m*r*\omega^2$,

$m = 39.8$ kg

$r = 0.05$ m

Thus, reaction forces at the rod ends, at rotational speeds ranging 50 to 300 RPM:

RPM	Rad/sec	r	m	F	Reaction Forces
50	5.236	0.05	39.8	54.6	27.28
100	10.47	0.05	39.8	218.2	109.1
200	20.94	0.05	39.8	872.9	436.5
300	31.42	0.05	39.8	1964	982.0

Table 8- Bearing Reaction forces for out-of-balance rod shaft

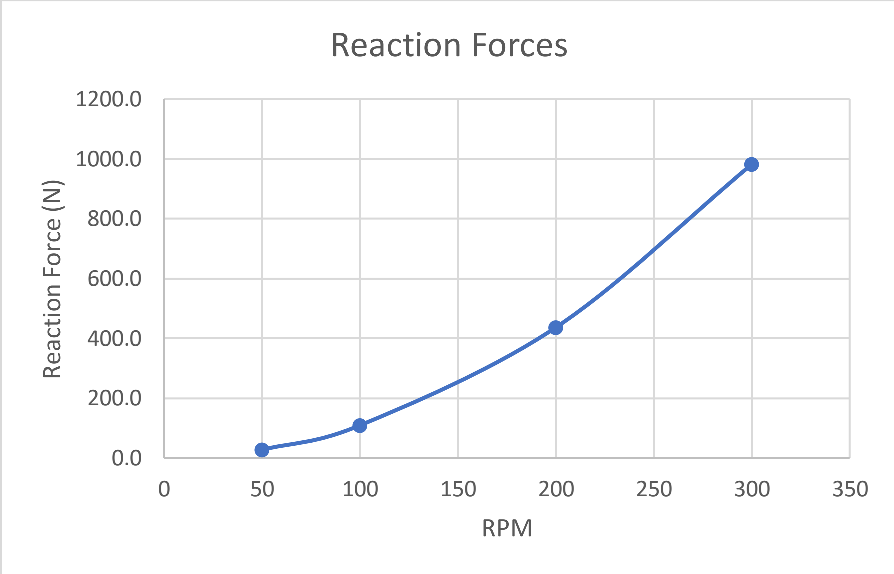

Figure 14- Plot of Reaction forces for out-of-balance shaft

The reaction forces increase on the square of the rotational velocity and are far in excess of those generated from the static bending.

The calculation is crude, but gives confident that scope for further investigation may lie here, suggesting higher speeds may be detrimental to wear life less for ultimate revolution count, and more for the extra centrifugal forces generated.

5.5 Design Implications

It is clear that the problem remains complex and difficult to model. The 'holy grail' of reliable, granular prediction of wear locations remains elusive. More sophisticated modelling may be able to achieve this – but likely at the expense of engaging professional services.

If a granular solution to extending tubing wear life is therefore unattainable (for instance, the placement of hardened components), then it suggests that more general solutions are appropriate: pre-emptive replacement of the rod strings of operating wells could remove the uncertainty associated with particular wear locations, and be achieved at lesser expense than a complete well servicing operation.

Chapter 6: Conclusion

A Finite-element model of a complete Casing-Tubing-Rod system has been attempted and encountered computational difficulties in execution. Simpler models were iterated until reliable insights could be attained.

Subsequently, the contribution of static bending due to wellbore deviation, and buckling to torsional loads, towards lateral loading (and thus tubing wear rate) are shown as minor.

A basic dynamic analysis, comprising a series of out-of-balance shaft calculations; these suggest the reaction forces generated at bearing ends would be significant at higher speeds.

Several avenues of further investigation are suggested, though each present their own complexities and difficulties. A deeper review of historical worn tubing holes is particularly recommended.

Alternative approaches to addressing the underlying engineering/commercial problem are also considered.

Chapter 7: References

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Appendix A: Project Specification and Work Plan

The Specification and Work Plan is enclosed below, as-written at the beginning of 2024 (and adapted from work earlier completed in ENG4110).

Specification and Work Plan 10/02/2024

FEA modelling of Coal-Seam Gas Well Pumping Assembly

Name : Andrew Conroy

Student ID : [redacted]

Supervisor: Assoc Prof Jayantha Epaarachchi

Company Sponsor: Ricardo Cardenas Pardo

Introduction

The pumping systems of coal-seam gas wells in western Queensland are predominantly progressive cavity pumping (PCP) systems, and have long tubing and rod strings to transmit torque from surface down to the pump, and the pumped liquid up to surface. The rod string sits concentrically inside the tubing string, and over time with many thousands of revolutions, can wear holes in the wall of the tubing. Such a hole requires a service rig to perform a workover to replace the worn tubing, incurring the costs of the job and of the lost production revenue. The basic configuration of a PCP system installed in a wellbore is shown in Figure 1,

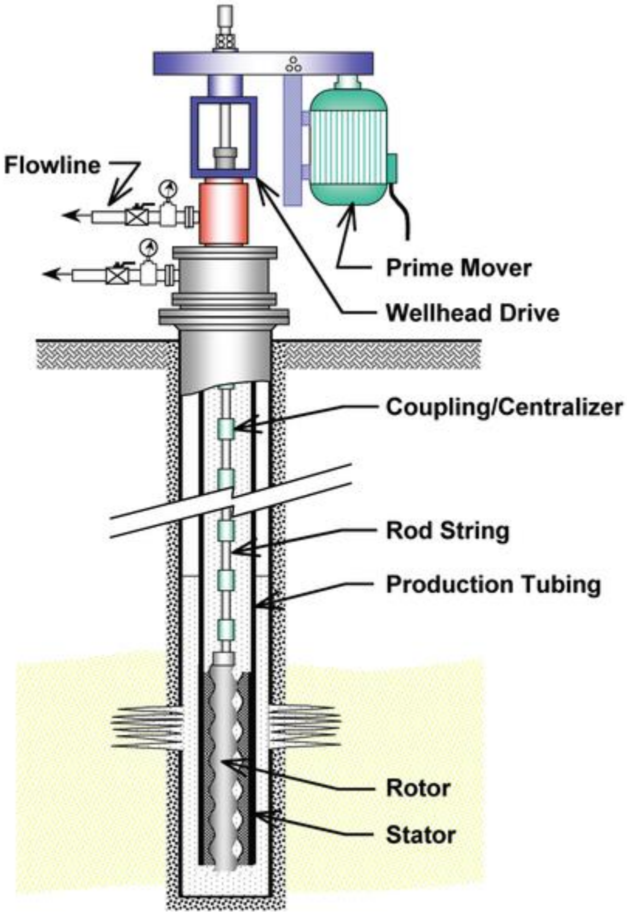

Figure 1- PCP System Overview (Petrowiki 2006)

Design options exist to mitigate the wear rate; but are expensive and thus are typically reserved for reactive installation. Deviation plots of wellbores (which are never perfectly vertical) have been used to predict the locations where the rodstring will press against the tubing, however results have been mixed; suggesting strongest sideloading may not coincide with the regions of greatest wellbore deviation.

It is proposed therefore to develop a Finite-Element model of a well identified as having a history multiple hole-in-tubing failures, or hole-in-tubing failures that do not coincide with deviation. There exists a body of research into the buckling behaviour of slender rods and tubing, but much of this has tended to examine axial loading of these strings, rather than the torsional loading associated with PCP systems.

It is desired to build upon the work of Zhang et al (2019) and (2021), which sought to use FEA methods to analyse the behaviour of the torsional behaviour of a slender column inside a cylinder (i.e.: a rod constrained by tubing), and the effects of rod guides on this buckling.

We wish to build up this work: since rods buckle and apply loading onto the tubing wall, how significant are these loads in the range conditions experiences by PCP installations in the Surat Basin? What influence does the wellbore deviation have?

Objective

The goal of the work is to improve the longevity and reliability of PCP systems by investigating the mode of hole-in-tubing failures by the means of a finite-element analysis. Such a "digital twin" of the system will provide insight to the dynamic behaviour of the rods and tubing under operating conditions and thus allow proactive, rather than reactive, design decisions to be made.

Specific Objectives:

The research aims to provide answers the following four principal questions:

5. Do the regions of highest side-loading align to the regions of highest deviation in the well?
6. Do the regions of experienced hole in tubing align to the regions of highest side loading and/or highest deviation?
7. Do different sized tubing strings induce or alleviate sideloading in a given well?
8. Do different sized rod strings induce or alleviate sideloading in a given well?

Expected Outcomes:

- Reliably identify regions of a given tubular string that are most likely to wear through the fastest, so as to guide pre-emptive design choices
- Or otherwise determine if this cannot be reliably determined, and that other approaches are required

Work Plan

Timeline:

A schedule of works has been devised, with particular regard to the milestone due dates of the ENP4111 course and my own personal circumstances. As I study part-time while working or caring for family full-time, I have designed so as to maintain a realistic and sustainable pattern of effort.

- My Trimester 1 workload comprises ENP4111 and two other subjects. However, Trimesters 2 and 3 I have no other subjects.
- I am currently on Parental/Long Service Leave, and have one day per week dedicated to study from now until the end of August
- Our second child is due to be born on 02/07/2024
- I return to work full-time at the end of August

My intent therefore is to maintain a relatively light focus toward ENP4111 until the end of Trimester 1, before heavily focusing on the research project until my return to work at the end of August, at which point I will become relatively time-poor to the end of the year. Thus, the intent is to be able to achieve swift progress throughout the "high intensity focus" period between approximately 01/05/2024 and 01/09/2024, and endeavour to be substantively finished the dissertation before the end of this period.

The intent is to remain agile and flexible throughout the project period: if I complete Trimester 1 work early, then the "high intensity" period of ENP4111 will start sooner. Conversely, redistributing workload after August (e.g. taking more study-dedicated leave days after returning to work) will also be initiated if required. The basic work schedule has thus been designed in a relatively loose manner so as to suit the flexible nature of progress expected. This basic schedule is shown in Table 1; as well, Appendix 1 includes a schedule that better shows the intended "high intensity period".

Table 9- Work Schedule

Stage One	**Literature Review & Early Investigative Modelling**	Start Date	End Date	Days
	Review, expand and finalise the Literature Review, building on the work already completed in ENG4110. Begin some basic test construction in Creo to further inform methodology. Gather preliminary list of well/s to investigate.	11/03/2024	2/04/2024	22
Stage Two	**Finalise Methodology and Begin Modelling**			
	Review, expand and finalise the Methodology, building on the work already completed in ENG4110. Continue building of Creo model. Adjust methodology as required by preliminary works.	3/04/2024	20/05/2024	47
Stage Three	**Build and Test Model; Conduct the Investigative Work**			
	Intensive focus on completing model construction and experimenting against the research objectives.	21/05/2024	1/07/2024	41
Stage Four	**Evaluation**			
	Compile results data Compile and compare with operational well history data Complete written component of Research Project Complete Slideshow presentation and Script	2/07/2024	9/09/2024	69
Final Due Date:		**4/11/2024**		

Resources Required:

- **Equipment:**
  - n/a
- **Software:**
  - Creo modelling software via university cloud/VPN access
  - Various software programs related to well construction and data through employer
- **Access:**
  - VPN/remote access for Creo software
  - Work laptop for various data as needed through employer:
    1. Wellbore deviation surveys
    2. Well runtime & failure history
    3. Workover pull reports

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MEC4108 Thermofluids 3			MEC5100 CFD			ENP4111 Professional Engineer Research Project			
Assessment	Due Date	%	Assessment	Due Date	%	Assessment	Due Date		
								22/01/2024	
								29/01/2024	
Report	8/02/2024	10						5/02/2024	
			Report 1	15/02/2024	20	Specification and work plan	12/02/2024	12/02/2024	
								19/02/2024	
Problem Solving 1	27/02/2024	20	Critique (written)	1/03/2024	10			26/02/2024	
								4/03/2024	
								11/03/2024	
								18/03/2024	
Problem Solving 2	26/03/2024	35						25/03/2024	
			Report 2	2/04/2024	30	Lit Review	2/04/2024	1/04/2024	
								8/04/2024	
								15/04/2024	
Problem Solving 3	22/04/2024	35	Model (theoretical)	26/04/2024	40			22/04/2024	**High Intensity Focus Period**
								29/04/2024	
								6/05/2024	
								13/05/2024	
						Methodology	20/05/2024	20/05/2024	
								27/05/2024	
								3/06/2024	
								10/06/2024	
								17/06/2024	
								24/06/2024	
						Baby due date	2/07/2024	1/07/2024	
								8/07/2024	**Medium Intensity Focus Period**
								15/07/2024	
								22/07/2024	
								29/07/2024	
								5/08/2024	
								12/08/2024	
								19/08/2024	
						End of Parental leave (return to work FT)	26/08/2024	26/08/2024	
								2/09/2024	
						Draft Dissertation	9/09/2024	9/09/2024	
								16/09/2024	
								23/09/2024	
								30/09/2024	
								7/10/2024	
						Presentation	14/10/2024	14/10/2024	
						Reflection	21/10/2024	21/10/2024	
								28/10/2024	
						Dissertation	4/11/2024	4/11/2024	
								11/11/2024	