Analysis of Thaw Subsidence Impacts on Production Wells

Jueren Xie

C-FER Technologies, Edmonton, Alberta, Canada

Abstract: *For the past few decades, with depletion of hydrocarbons in more readily accessible regions, petroleum operators have shown increasing interests in exploring onshore oil and gas reserves in Arctic areas, which are typically overlain by substantial permafrost layers on the order of 150 to 500 m thick. A key challenge to the completion of these wells is how to manage the impact of thaw subsidence of permafrost layers throughout expected well life.*

This paper presents a methodology for analyzing well deformation under the thaw subsidence loading. The well evaluation methodology includes several analysis programs in sequence, such as wellbore hydraulic and heat transfer analysis, to determine the heat input to the permafrost interval due to the production of hydrocarbons; geothermal analysis, to estimate the extent of the permafrost thaw; geomechanical and soil deformation analysis, to calculate the thaw-induced soil stress and movement; and casing-formation interaction analysis, to evaluate the impact of thaw subsidence on the potential deformations and mechanical and hydraulic integrity of well casing systems. Two examples are presented to demonstrate potential well failures, such as buckling and shear, caused by thaw subsidence movement for single and multiple well design scenarios, respectively. The presented methodology is recommended for optimizing well completion designs to minimize the well failure potentials.

Keywords: *Arctic, Casing, Casing-soil Interaction, Connection, Buckling, Formation Shear, Geothermal, Geomechanical, Heat Transfer Analysis, Permafrost, Plasticity, Pore Pressure, Strain-based Design, Thaw Subsidence, Three-dimensional Beam Elements.*

1. Introduction

Petroleum operators have shown significant interests in exploring onshore oil and gas reserves in Arctic regions. This interest has been increasing in recent years with the depletion of hydrocarbon reservoirs in more readily accessible regions, and improvements in techniques for recovering oil and gas in these demanding conditions. The Arctic areas are typically overlain by substantial permafrost layers on the order of 150 to 500 m thick, which can be continuous from the surfaces, or discontinuous with intermittent unfrozen zones. Figure 1 shows the extent of continuous and discontinuous permafrost regions throughout the Northern Hemispheres.

Exploring such oil and gas reserves has been challenging from the drilling, completion and operation perspectives. A key issue in completing wells in these regions is how to manage the impact of thaw subsidence of permafrost layers throughout the expected life of these wells. In many permafrost oil and gas fields, the thaw sizes can be from a few to over ten meters in radius after 20~25 years of production of a typical well life. As a result of permafrost thaw, the formation can compact and induce loads on the wellbore system and in turn on the wellhead and surface piping and equipment. After apparent surface subsidence, damage to surface equipment or loss of access to the wellbore is the first indication that thaw-induced subsidence has occurred. The thaw subsidence can be attributed to the following reasons:

- Melting of excess ice in upper layers – For excess ice layers near surface, melting can decrease the ice volume, causing formation to compact due to loss of support;
- Consolidation with fluid expulsion – In ice rich soils near surface, pressures exceeding hydrostatic are generated during thaw, causing fluid flow out of the thawed zone and soil compaction;
- Reduction of pore pressure – In normally compacted permafrost, phase change contraction with thaw of pore ice is accompanied by a decrease in pore pressure, resulting in an increase in intergranular stress and soil compaction; and
- Reduction of formation stiffness – As permafrost thaws, the soil becomes softer and easier to deform due to loss of support provided by the pore ice.

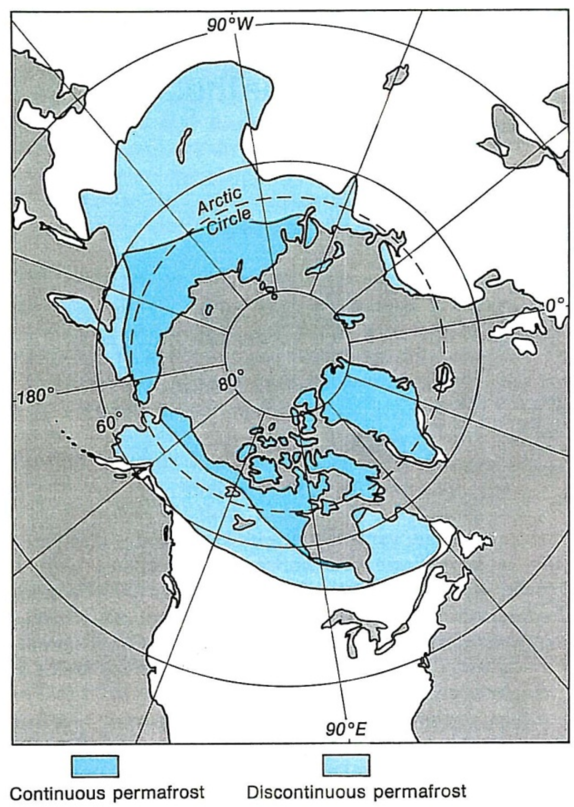


Figure 1. Permafrost in the northern hemisphere covers large portions of Alaska, Canada, Greenland and Russia (after Ferrians et al., 1969).

This paper focuses on thaw subsidence loading in deep wells, due to pore pressure change and formation stiffness reduction. Figure 2 illustrates the wellbore loading created by such formation deformation mechanisms. Pore pressure reduction in thawed permafrost acts across the thawed-frozen interface and generates body forces in the vertical direction. These loads induce alternating compression-tension in layered lithology, and potential uplift of the permafrost base. In inclined and fractured reservoirs, these deformations can also result in shear loads. In addition, stiffness reduction due to thaw can cause lateral loads across thaw front and vertical body force loads.

It has been noted that until now, relatively little numerical work has been published in the methodology for analysis of thaw subsidence loading on production wells, due to complicated features of loading mechanisms and formation material behavior related to permafrost thaw subsidence. Using the finite element program Abaqus as a primary analysis platform, this paper proposes a new numerical methodology for analyzing well casing deformations induced by formation thaw subsidence. This paper will also present a couple of analysis examples to demonstrate the application of the proposed analysis methodology for analyzing single and multiple well (e.g. pads or cluster of wells) design scenarios.

In order to minimize the impact of thaw subsidence, various mitigation strategies, such as passive insulation and active refrigeration systems have been proposed and applied. The proposed analysis methodology can be used to study the effect of such mitigation strategies. Note that this paper will focus on demonstrating the methodology for analyzing thaw subsidence loading, and the details of potential mitigation strategies will not be discussed in this paper.

While this paper will focus primarily on production wells, the methodology and approach could also be applied to injection and production wells in secondary and enhanced recovery (e.g. steam injection) applications, oil and gas wells, and geothermal wells.

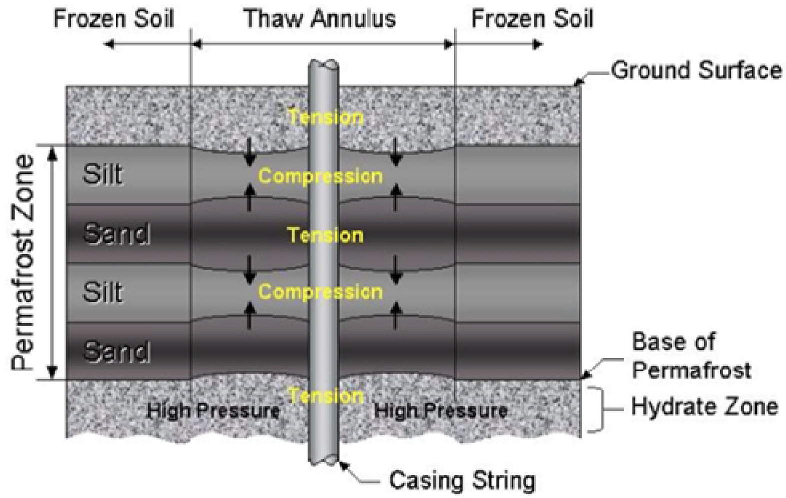


Figure 2. Schematic of thaw subsidence loading in production wells.

2. Analysis Models

The following analysis programs are proposed for analyzing thaw subsidence loads:

- Wellbore hydraulic and heat transfer analysis – determination of the heat input to the permafrost interval based on the production conditions and well design over the expected well life.
- Geothermal analysis – estimation of the extent of the permafrost thaw that may occur around individual or pad wells based on the prescribed heat input.
- Geomechanical and soil deformation analysis – calculation of the thaw-induced soil stresses and movements as well as the magnitude of the ground subsidence at surface.
- Casing-soil interaction analysis – evaluation of the permafrost thaw subsidence impacts on the loading, serviceability and mechanical and hydraulic integrity of the well casing systems.

2.1 Wellbore Hydraulic and Heat Transfer Analysis

The wellbore hydraulic and heat transfer analysis serves to predict the temperature profile of the fluid inside the tubing along the length of the wellbore and to quantify the overall resistance to heat flow between the fluid and the outside of the wellbore over the production life of the wells. Various well construction elements including the casing strings, cement and/or annular fluids, as well as formation are included in the analysis. The results of the hydraulic and heat transfer analysis serve as the input to the geothermal analysis.

There are three main different heat transfer modes including conduction, convection and radiation. In a wellbore, depending on the wellbore conditions, these three modes of heat transfer occur to varying degrees. Abaqus can be used to analyze these heat transfer modes and establish the heat flow resistance along the wellbore. In addition, in some applications (e.g. high rate gas wells) the Joule-Thompson effect should also be considered in evaluating the tubing fluid temperature (Wylen and Sonntag, 1985).

2.2 Geothermal Analysis

Based on wellbore heat transfer analysis results, geothermal analyses can subsequently be performed to predict the extent of thaw around production wells with time. This analysis program should simulate transient heat conduction with change of phase resulting from ice thaw in formations. Hwang (1976) discussed the theoretical formulation that can be used for this type of geothermal analysis.

2.3 Geomechanical and Soil Deformation Analysis

Based on the thaw radius profile with time derived from the geothermal analysis, specialized finite element analysis can be performed to determine soil stiffness properties, and soil deformations associated with changes in volumetric strain, pore pressure and stiffness along the wellbore as a function of time.

Inputs for the geomechanical and soil deformation analysis include the soil stratigraphy, thaw profile, soil stiffness (i.e. both frozen and unfrozen), pore pressure upon thaw and thaw strain.

Phase change contraction due to thaw is caused by a volumetric contraction as ice changes its phase to water.

While some of this geomechanical soil deformation analysis tools rely on non-commercial finite element programs, it would be possible to use Abaqus program, along with user subroutines to establish the relationships between phase change and soil deformation. For example, empirical equations are often used to estimate the volumetric strain, pore pressure and soil stiffness as functions of frozen and unfrozen water contents and soil effective stress. Different relationships are used for fine and coarse grained soils as well as for different soil types (e.g. aggregates, sandstone and clay). Some discussions on thaw strain and pore pressure can be found in Roggensack (1977). Soil stiffness can be estimated based on the relationship presented by Duncan et al. (1980) that embodied the effective stress dependence of the tangent modulus in soils.

The outcome from the soil deformation analysis includes an estimation of the surface subsidence in the wellbore vicinity, vertical and lateral soil displacements, and vertical and lateral soil stiffness and strength as a function of time. The soil deformation analysis results can subsequently be used as the input to the casing-soil interaction analysis.

2.4 Casing-soil Interaction Analysis

The casing deformation analysis focuses primarily on establishing the casing deformations caused by the principally vertical soil movements (subsidence/heave) induced by permafrost thaw subsidence. The soil subsidence or heave drives the casing strings to deform through the drag forces generated by the differential displacements that occur between the casing system and adjacent soil layers. In the multiple well design cases, the permafrost thaw can also introduce lateral formation movements which are considered important in terms of their increased potential for developing casing buckling and shear deformations.

Figure 3 shows a schematic representation of the casing deformation analysis model. The following considerations are included in the casing deformation analysis and design assessment:

- The casing model starts at the surface level, where relative movement between casing and formation is permitted; and ends at a depth where the soil movements derived from soil deformation analysis become insignificant.
- Various casing strings, such as conduct pipes, surface casing and production casing, are included in the model. To suitably model non-axisymmetric loading and deformation, these casing strings are modeled using three-dimensional beam elements. It is assumed these casing strings are fully cemented, and therefore they can be modeled by sharing common nodes along the length. The casing material is modeled using elastic-plastic constitutive relationships with considerations of the effects of temperature and time dependence. The cement is also modeled using three-dimensional beam elements, with the cement material modeled using Abaqus Concrete model.
- The analysis focuses on the impacts of the soil deformation loading. The soil is modeled using separate soil spring elements in the vertical direction (x) and the two transverse directions (y and z). One end of each soil spring is connected to the casing system, while the corresponding soil displacements are imposed at the other end. The vertical soil-springs are represented by a bi-linear force-displacement relationship (Figure 4a), assuming the soil shear strength increases linearly until reaching a maximum when the

bond between the soil and wellbore is broken and the slippage occurs at their interface. The lateral soil-springs are represented by a multi-linear force-displacement relationship (Figure 4b), whereby the soil displacement is dependent upon the degree of soil shear strength mobilization. The force-displacement relationships for the soil springs are defined as temperature and time dependent.

- Since the thaw subsidence loading is controlled and bounded by the magnitude of the well temperature and operating conditions and the deformation prediction in the soil deformation analyses, the strain-based design concept can be used for assessing casing designs for wells in such permafrost application. This design concept acknowledges that some limited amount of plastic strain is acceptable provided that the driving forces are displacement-controlled. The allowable casing strain is often defined by the wellbore serviceability functions and the structural and hydraulic integrity requirements of casing connections. For the structural limit of the connections, previous research by Xie (2008) suggested that a longitudinal casing strain limit of 1.5% may be employed for casing strings using API buttress connections and premium connections. Note that a casing strain limit does not necessarily satisfy the requirement for connection sealability, as a casing connection may leak under little or even no loading.

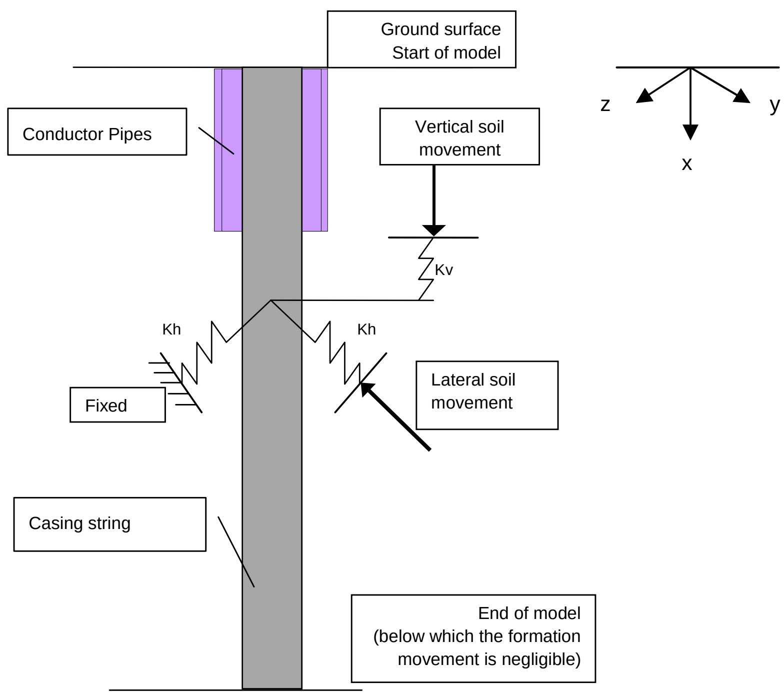
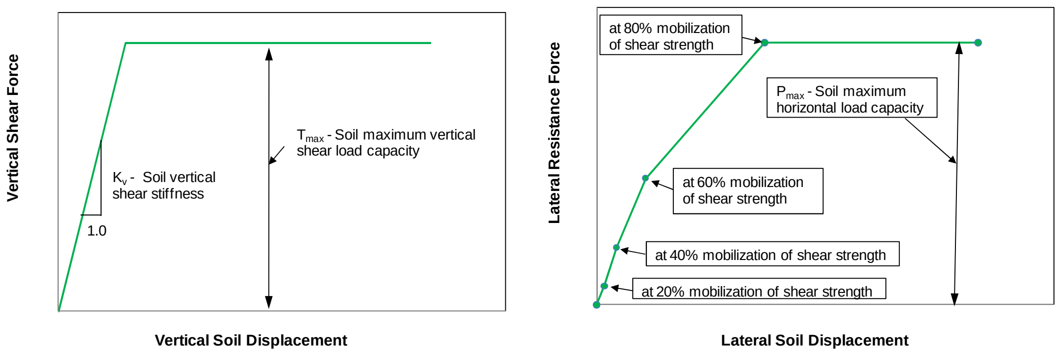


Figure 3. Schematic of casing/formation interaction analysis model.



a) Vertical soil spring model b) Lateral soil spring model

Figure 4. Schematic of force-displacement relationships for soil spring elements.

Another concern associated with well completion in Arctic regions involves the potentially large external pressure that can be generated such as due to change in pore-pressure as a result of thawing and decomposition of gas hydrate zones (Weaver and Stewart, 1982). Casing strings can potentially collapse under the combined loading of external pressures and thaw-induced axial strains. As such, in their application, it is also necessary to consider casing collapse capacity under those conditions. The casing collapse capacity can be assessed by finite element analysis using three-dimensional solid elements to model a casing section under external pressure. This paper focuses on demonstrating the methodology for analyzing thaw subsidence loading, and while casing collapse analysis is not discussed, it will often be a necessary component of the completion design requirements.

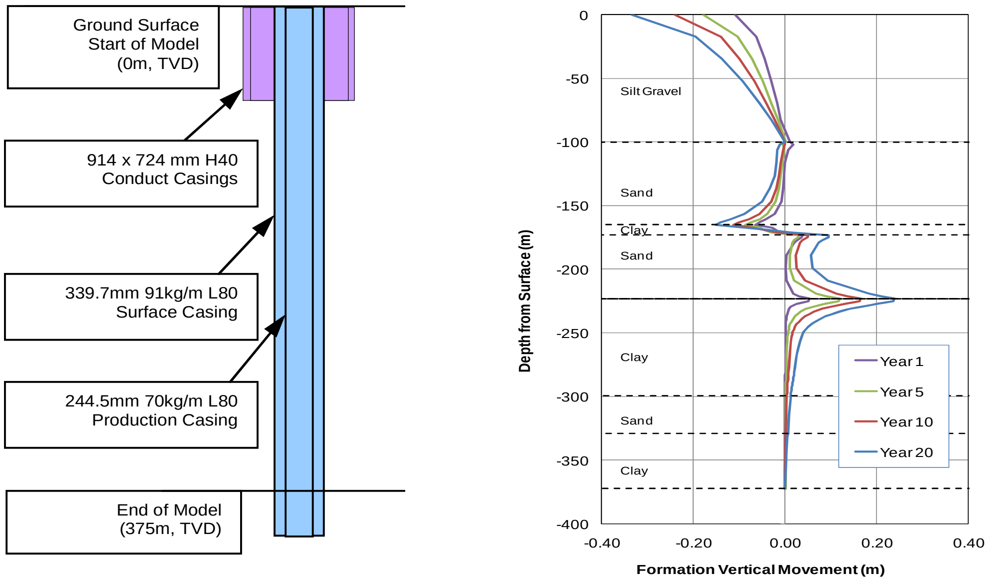
3. Analysis Examples

Two examples are presented to illustrate the applications of the proposed Abaqus model and analyses methods in the evaluation of wellbore completion scenarios for production wells in permafrost conditions. Examples 1 and 2 are single and multiple well scenarios, respectively.

3.1 Example 1 – Single Well Thaw Subsidence

Well Completion and Production Design

This example considers a production well for exploring a highly prolific natural gas reservoir at a depth of approximately 3,000 m TVD. The permafrost layers are distributed over the top 350 m depth with various soil layers of sands, silts and clays. The average annual temperature is –6°C near the surface and increases to 0°C at 350 m TVD. The well is designed to have 20 years of production life. The well production analysis shows that the tubing temperature can reach to an average 50°C over the permafrost interval after 1 year, and slowly increases thereafter to approximately 60°C after 20 years of well production. Note that the tubing string is inside the casing and the tubing-casing annulus is assumed to be filled with gelled diesel. Figure 5a shows the well completion including: 914 x 724 mm H40 dual conductor pipes installed to a depth of 75 m, 339.7 mm 91 kg/m L80 surface casing, and 244.5 mm, 70 kg/m L80 production casing.



a) Model schematic b) Predicted formation vertical movement with time

Figure 5. Schematic of well completion design and predicted soil vertical movements (Example 1).

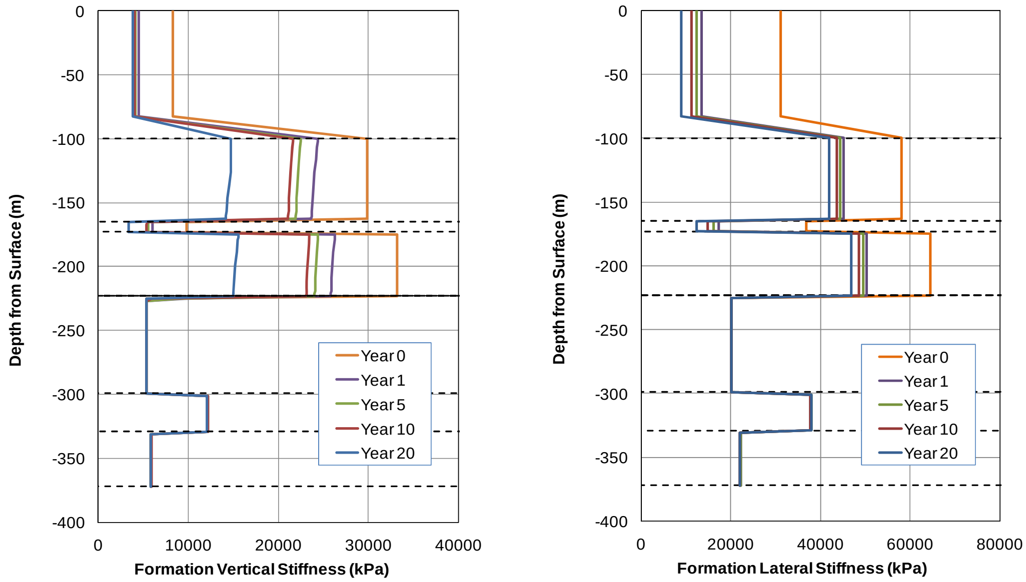
Thaw Radius

The geothermal analysis shows that the thaw radius develops to an average of 2 m after 1 year, and to an average of approximately 5 m after 20 years of production.

Thaw Subsidence Loading

Based on the geothermal analyses, geomechanical and soil deformation analysis is performed. The analysis derives the following outputs, which can be used as inputs for the casing/formation interaction analysis:

- Soil Vertical Displacement (Figure 5b) – The soil layers above 175 m TVD would mainly subside downward, although relative movements between some soil layers may create some localized tension zones. Below 175 m TVD, the soil layers experience heave, and the soil movement become negligible below 375 m TVD. The predicted surface subsidence displacements are 0.11, 0.18, 0.24 and 0.33 m corresponding to 1, 5, 10 and 20 years.
- Vertical Soil Spring Properties (Figure 6a) – The vertical soil-springs are represented by a bi-linear force-displacement relationship, as shown in Figure 4a. Figure 6a shows that in most soil layers in the upper permafrost region of the well, the vertical soil spring stiffness typically decreases with time due to the thaw effects.
- Lateral Soil Spring Properties (Figure 6b) – The lateral soil-springs are represented by a multi-linear force-displacement relationship, as shown in Figure 4b. Figure 6b shows that the lateral soil spring stiffness typically decreases with time due to the thaw effects.



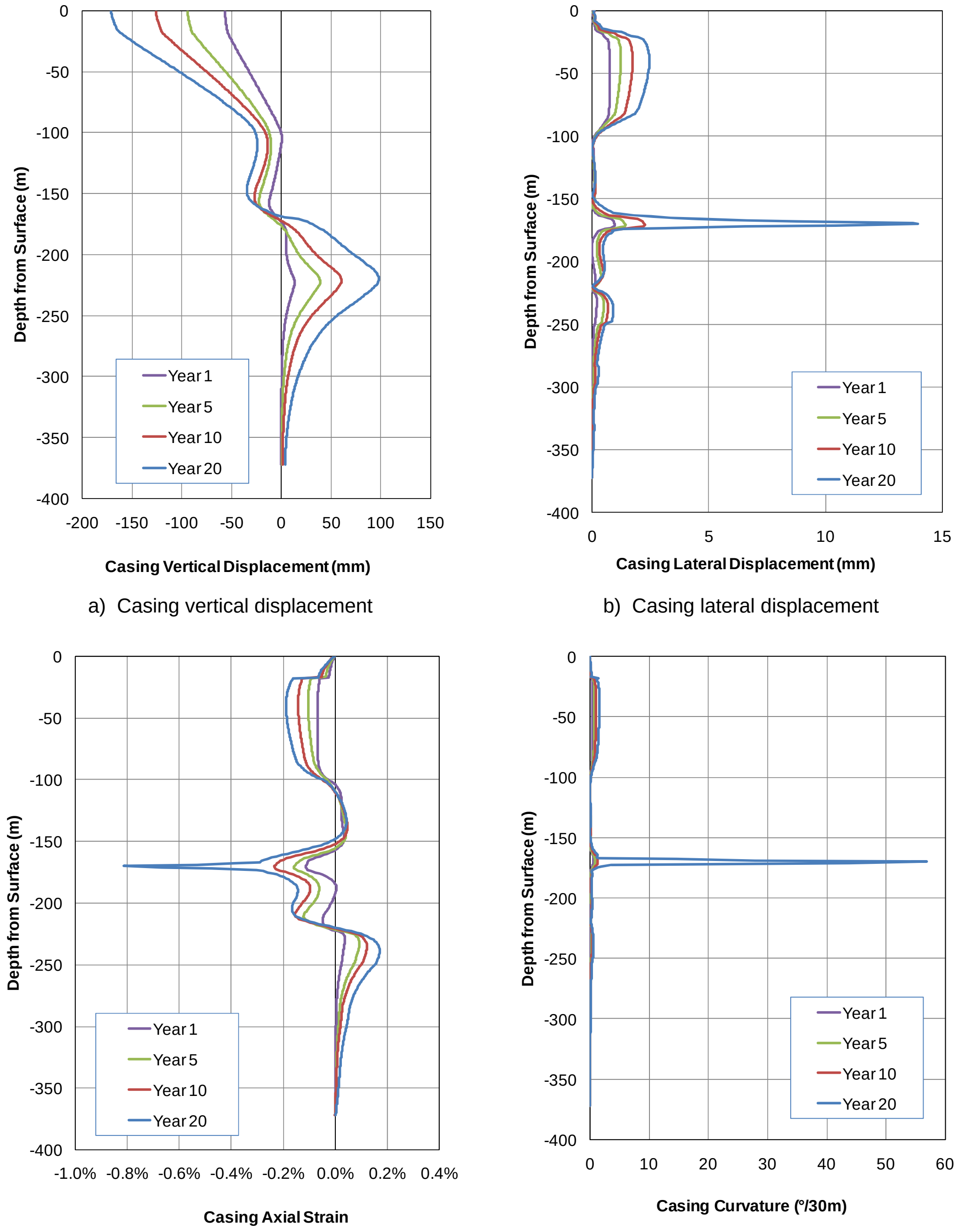
a) Vertical formation stiffness b) Lateral formation stiffness

Figure 6. Predicted formation stiffness for soil springs (Example 1).

Casing Deformation Analysis Results

The casing-soil interaction analysis model starts at the surface level, and ends at 375 m TVD where the soil displacement becomes negligible. The following are findings from casing/formation interaction analysis:

- Casing Displacements (Figures 7a and 7b) – The maximum downward displacement is approximately 0.17 m at the ground surface and the maximum upward displacement is 0.094 m at 213 m TVD, both occurring after 20 years of production. The maximum lateral displacement is 0.014 m and is largely localized over a very short interval at a depth of approximately 170 m TVD.
- Casing Deformation (Figures 7c and 7d) – After 20 years of production, the maximum axial compressive strain is 0.81% occurring at 170 m TVD in a weak clay interval. The analysis shows that casing buckling could be induced after 10 years by a large formation compaction, as well as weaken formation stiffness due to thaw in the thin clay interval located at this depth. The impact of casing buckling can be measured by casing curvature representing the degree of casing bending about the direction normal to the casing axis. As shown in Figure 7d, the casing curvature increases to 57°/30m after 20 years of production. This corresponds to 0.56% predicted flexural strain in the surface casing, calculated by multiplying casing curvature by the casing radius. Nonetheless, the maximum total longitudinal strain (i.e. axial strain plus flexural strain) for the surface casing is 1.37%, which is significant but still slightly less than the proposed design limit of 1.5%. Therefore, based on the predicted deformation, this design can be considered to have a sufficient structural integrity for the expected 20 years of well life.



a) Casing vertical displacement

b) Casing lateral displacement

c) Casing axial strain

d) Casing curvature

Figure 7. Example 1 single well casing analysis results over 20 year life of a production well.

3.2 Example 2 – Multiple Well Thaw Subsidence

The second example illustrates the impact of thaw subsidence loading on multiple adjacent production wells, such as might occur in Arctic regions with multiple wells drilled from a common surface location to minimize surface footprints, equipments and facilities. The same well completion design, formation intervals and formation properties used in Example 1 are analyzed in this second example. The multiple well pad has ten wells in a row with an average inter well spacing of 6 m. All of the wells are vertical in the upper region considered. Geothermal and geomechanical analysis shows that the end wells in the pad are most critical since their lateral formation movements are predicted to be the largest among all the wells in the pad.

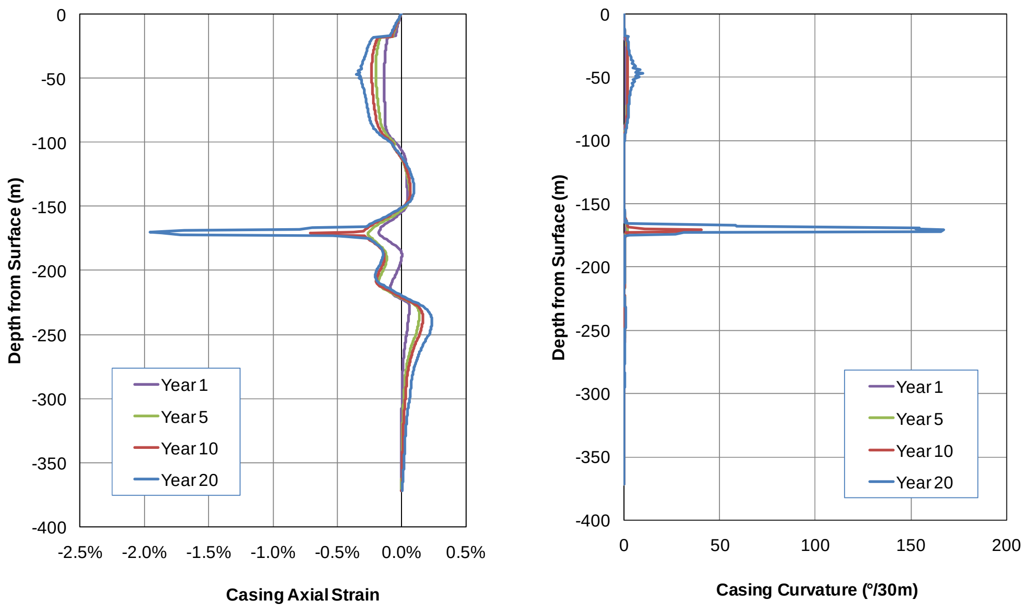
The geothermal analysis also shows that the thaw radius develops to an average of approximately 2 m after 1 year of production, similar to the single well design. However, after five years of production, the well thaw radius of each of the wells becomes sufficient enough to join the neighboring wells' thaw radii, creating a continuous thaw bulb or slot along the thermal well pad. The average width of thaw slot reaches approximately 18 m after 20 years of production.

The geomechanical and soil deformation analysis suggests that the thaw subsidence loading from multiple well production scenarios has the following different features from the single well design:

- Larger Vertical Soil Displacement – Due to a larger thaw slot width, the predicted vertical soil displacement is approximately twice that of the single well case.
- Lateral Soil Displacement – The multiple well scenario can create significant lateral soil movement to the end wells in the pad. At 20 years of production, the lateral displacement is predicted to be approximately 0.21 m at a depth of approximately 170 m.
- Weaker Soil Stiffness – Due to a larger thaw slot width, the average soil stiffness can be reduced by up to 50% as compared to the single well design.

All the above effects would tend to increase the potential for significant casing deformation and casing buckling in such multiple well pads.

Figure 8 presents the analysis results of casing axial strain and casing curvature at 1, 5, 10 and 20 years. Figure 8a shows that the predicted maximum axial compressive strains are 0.17%, 0.26%, 0.71% and 1.96% corresponding to 1, 5, 10 and 20 years, respectively. At the same location of the maximum compressive strain, the analysis shows that casing curvatures are1.04˚/30m, 1.71˚/30m, 40.4˚/30m and 167˚/30m, corresponding to maximum flexural strains of 0.010%, 0.017%, 0.4% and 1.65%, at 1, 5, 10 and 20 years, respectively. The resulting total longitudinal strains are 0.18%, 0.28%, 1.11% and 3.61% at 1, 5, 10 and 20 years, respectively. Using the proposed 1.5% casing strain design threshold, the well life is predicted to be approximately 11.6 years for the multiple well pad scenario.



a) Casing axial strain

b) Casing curvature

Figure 8. Example 2 multiple well casing analysis results.

4. Mitigation Strategies

Mitigation strategies can be proposed to minimize the impact of thaw subsidence loading for single and multiple production well applications in permafrost regions. The typical design alternations commonly considered include: insulated wellbore completion designs (e.g. insulated tubing and annulus fluids), to reduce heat transfer from tubing to formation; refrigerator system, such as actively refrigerated conductor, to reduce heat transfer from the wellbore to formation; and larger well spacing, to prevent inter well thaw region conveyance over the life of the wells. Additional discussions of such mitigation strategies may be found in the literature (e.g. Goodman, 1978). The analysis methodology proposed in this paper can also be used to study the effect of various mitigation strategies, and therefore to assist well design optimizations.

5. Summary and Conclusions

This paper presents a new numerical methodology, using advanced finite element analysis tools such as Abaqus, as the main platform, for analyzing well deformation induced by thaw subsidence loading in permafrost regions. The methodology consists of four segmented analysis programs including wellbore hydraulic and heat transfer analysis, geothermal analysis, geomechanical and soil deformation analysis, and casing-soil interaction analysis. Two analysis examples corresponding to single and multiple well designs are presented to demonstrate the application of the proposed methodology.

The following conclusions can be made based on this study:

- The analysis can establish the relationship among operating conditions, wellbore completion design, formation properties, thaw subsidence displacement, and casing deformation (e.g. buckling). Therefore, the proposed methodology can be used to assess and optimize well completion designs for wells in permafrost regions.
- Advanced finite element analysis programs such as Abaqus can be used as the primary analysis platform for thaw subsidence loading analysis. Due to involved interdependence of the various factors in this analysis, user-defined subroutines are required in order to establish the relationships among thaw content, phase change and soil deformation.
- Analysis examples presented in this paper suggest that multiple well pads may be more critical as compared to the single or isolated well applications due to larger vertical and lateral soil movements and weaker soil stiffness related to larger thaw slot width in such multiple well scenarios.
- Various mitigation strategies can be considered to minimize the impact of thaw subsidence loading, especially for multiple well scenarios, including insulated wellbore completion design, refrigeration systems, and larger well spacing.
- While this paper focuses primarily on production wells, the methodology and approach could also be applied to injection and production wells in secondary and enhanced recovery (e.g. steam injection) applications, oil and gas wells, and geothermal wells.

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