Buckling analysis for the long-term integrity evaluation of a hydrocarbon well

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Abstract: During the exploitation of a reservoir the displacements occurring in the near wellbore areas may induce mechanical actions on the well completions, including the steel casing and the cemented annulus, bringing to instability and failure of the well structure, with strong impacts on the economics of the field. The evaluation of the well completion integrity in the long-term is therefore a critical issue in the design phase. With reference to a synthetic case, the paper describes the procedure developed using Abaqus to evaluate the casing and cement integrity for a producing well. In addition to the evaluation of possible well damages related to the stress/strain evolution in the well completion, the well integrity assessment has been performed by forecasting the buckling risk in Abaqus/Standard at every production step. A safety factor related to the stability of the slender well structures has, thus, been computed and a sensitivity analysis has been performed on the characteristics of the steel used for the casing material. In conclusion, the results of the numerical simulations performed with Abaqus may provide highly valuable information and knowledge to build a proper design of the well completion, able to ensure the stability of the well during the whole production life of the field.

Keywords: Geomechanics, Wellbore Stability, Buckling, Contact Interface.

1. Introduction

In the oil industry, cased-hole completions represent the standard completion method used in the production wells of hydrocarbon fields. Cased hole completion consists of a series of steel pipes (i.e. the casings) inserted in the wellbore having diameters decreasing with the depth; they may be surrounded by a cement annulus connecting them to the rock formation as represented in Figure 1.

The design phase of a well completion includes the definition of the number of casings, their geometry (i.e. length and thickness) and material; moreover, the sections where cementation is needed have to be defined. This well design phase always takes into account the mechanical actions that are expected to develop on the system during the completion phase itself; however, the rock strains induced by the pressure depletion during the hydrocarbon production may cause additional mechanical actions on the well-system: significant strains may then be generated in the well structure, causing damages and leading, in the worst cases, to the well collapse. In order to prevent well damage and failure, a well integrity evaluation long-term, i.e. taking into account the stress/strain evolution during the field exploitation, should always be included in the well design process, especially when dealing with high compacting reservoirs (Bruno, 1992).

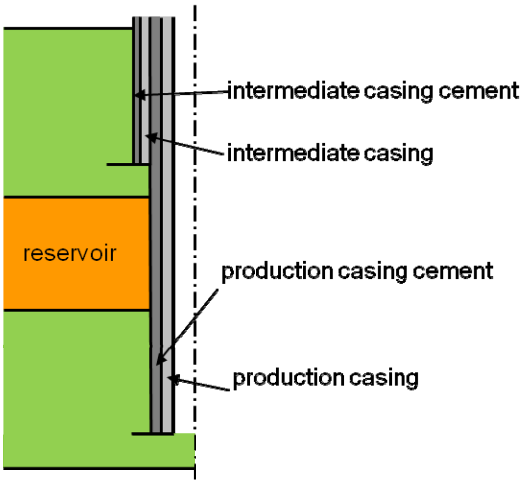

Figure 1. Typical cased-hole well-system.

In this paper, a workflow implemented to carry-out a long-term well integrity evaluation using Abaqus will be presented. With this approach, stress and strain profiles along the well column can be determined, so that the suitability of the proposed completion structure can be evaluated as a function of the forecasted production. Buckling analyses on the well structure are also included in the workflow and safety factors can be associated to the designed completion in order to quantify the risk of well collapse. The results of the analysis will then provide valuable information for the well design phase, such as optimal completion material and/or geometry.

After a brief problem overview, the implemented workflow will be described in detail and applied to a synthetic case. The type of results generated with the proposed approach and their practical use in the well design process will be illustrated and discussed.

2. Problem overview

The Terzaghi's principle of effective stresses (Terzaghi, 1936):

$$\sigma_{ij} = \sigma_{ij}' + \delta_{ij} p$$

(where σ_{ij} is the total stress, σ_{ij}' is the effective stress and p is the pore pressure) represents the basic law governing the physical process according to which the subsurface fluid exploitation causes compaction of the productive layers of a reservoir: with the total stress remaining approximately constant, the pore pressure decrease due to hydrocarbon production induces an increase of the effective stresses, which, in turn, causes the deep compaction of the reservoir rock formation.

As represented in Figure 2, rock strains in the near wellbore area are transferred to the well structure through the rock/cement/casing interfaces; they may cause severe damages to the completion system or even lead to well failure if phenomena like casing buckling are generated (Bruno, 2001).

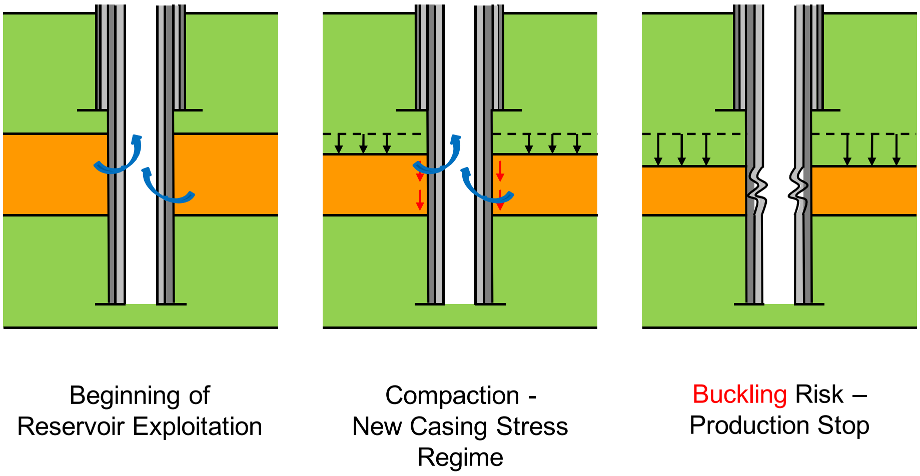

Figure 2. Buckling risk due to exploitation of reservoir layers.

In the past, both analytical and numerical models have been proposed to study this matter.

Analytical models include several simplifying hypotheses, mainly related to the material behaviour, considered as linear elastic, to the behaviour at the interfaces, considered as perfect contacts, and to the compaction conditions, considered uniaxial. Even if some hypotheses, such as perfect adhesion between rock and well structure, can be released by applying the transfer function method (Musso et al., 2010), the structure response obtained when applying analytical models is still highly approximated. Such models should then be used only as preliminary evaluation methods.

Finite Element (FE) models at the well scale (da Silva et al., 1990; Cernocky et al., 1995; Capasso et al., 2008; Capasso and Musso, 2010) let the release of several hypotheses. In particular, they give a proper description of the compaction phenomenon in the near wellbore area, use correct interface models between rock and well-structure and can describe the material behaviour with realistic constitutive models (e.g. elastic-plastic models). For this reason they should be preferred in order to obtain more reliable results even with the higher computational cost they require.

The numerical studies cited above, however, do not include proper treatment of the buckling risk; to the knowledge of the authors, the literature mainly proposes approaches making use of analytical or simplified formulations to study this phenomenon (Timoshenko and Gere, 1961; Bruno, 1992).

In the following, a new workflow developed in eni e&p using FE at well scale with Abaqus/CAE and Abaqus/Standard will be presented. This workflow allows not only the evaluation of stresses and strains in the well system induced by the production, but also includes a complete buckling analysis and the assessment of the collapse risk possibly occurring prior to the plasticization-induced failure.

3. Workflow Scheme

The present workflow, related to the construction of a geomechanical model at well scale, has been implemented considering the availability of a field scale geomechanical model (Capasso and Mantica, 2006). In this case, the field scale model provides the stress/strain evolution in the reservoir and in the surrounding regions; they can be extracted along the well trajectory of interest for each production time step and applied to the rock elements of the well scale model as loads or boundary conditions (see Figure 3).

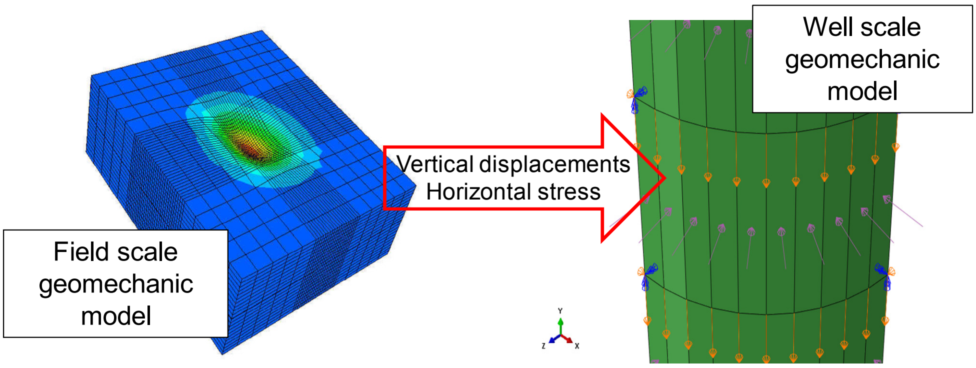

Figure 3. From field scale model to well scale model.

The implemented workflow consists of the following steps:

- Well scale model design with Abaqus/CAE:
  - geometry definition;
  - material property assignment;
  - interface contact modelling;
  - mesh generation;
  - boundary conditions and loads assignment.
- Boundary conditions definition with the Matlab code (given the complexity of the model, part of the boundary conditions cannot be assigned using Abaqus/CAE, but a Matlab code has been developed to this end):
  - rock node displacements assignment;
  - definition of the horizontal stresses on the external rock surface.
- Simulation runs:
  - production phases;
  - eigenvalues buckling analysis.
- Result analysis:
  - compaction induced stresses and strains on the well;
  - plastic deformation of the completion elements;
  - long term stability evaluation.

3.1 Model Design with Abaqus/CAE

The model is built at well scale in order to properly simulate the phenomena occurring in the completion elements when the reservoir undergoes compaction during the production phase. It has been realized with Abaqus/CAE by constructing the different parts constituting the well system (i.e. the casings, cements and the rock in the near wellbore area) and assigning proper interface models at the contact surfaces. Then, the material properties have been assigned using Abaqus/CAE. In the end, the mesh has been realized with the automatic procedure available and the needed boundary and load conditions have been applied.

3.1.1 FE Model Geometry Definition

The definition of the simulation domain implies the choice of the size for the "rocky box" containing the well system. The optimum size is given by a correct balance between result accuracy and reasonable computational time, preventing, furthermore, the influence of the boundary conditions on the simulation results.

The vertical extent of the model has been calibrated considering that, even if the rock deformation during production is mainly occurring in the reservoir layers, the influence of the compaction on the well completion may propagate in the shallower regions (i.e. the *overburden*). Thus, all the reservoir layers and a significant thickness of the overburden rock have to be included in the model with the corresponding well structures (i.e. all casings and relative cementation jobs).

The radial extent of the model should be chosen around 20 times the well radius in order to prevent the simulation results being biased by the boundary conditions imposed.

A horizontal section of an example model is represented in Figure 4: note that, being the simulations relevant for vertical wells, the symmetry of the problem has been exploited so that only a quarter of the well-system has been modelled.

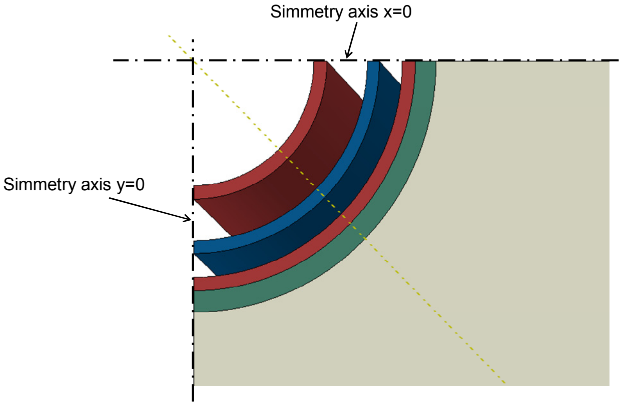

Figure 4. Section of the well geometry and symmetry boundary conditions.

3.1.2 Material Property Assignment

In the current workflow, the completion materials have been described using elasto-plasticity in order to properly simulate their non linear behaviour during the load history (see §4.1). The assignment has been performed using the features available with Abaqus/CAE.

3.1.3 Contact Property Assignment

The interfaces cement-steel and rock-cement have been modelled using the frictional Coulomb's law. According to this model, the shear stress τ is proportional to the normal stress σ_n, acting at the interface as follows:

$$\tau = \mu \cdot \sigma_n$$

where μ represents the friction coefficient between the two materials. When τ value reaches a maximum value called τ_{max}, the interface behaves as perfectly plastic. In Figure 5 the elasto-plastic interface law is shown, with indication of the stick and slip regions.

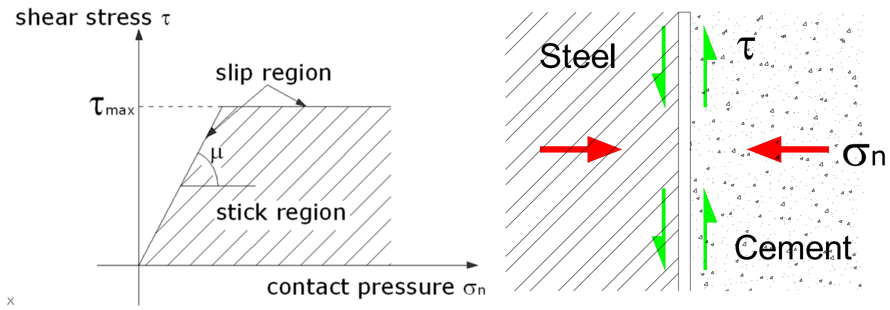

Figure 5. Interface frictional model.

3.1.4 Mesh Generation

The mesh used in the model, represented in Figure 6 and Figure 7, has been selected with the aim of obtaining both a good discretization scheme and a reasonable computational time. Being the rock elements only needed in the model for transferring loads and displacements to the well, they have been generated with a coarser mesh, having logarithmic increasing size in the radial direction. Completion elements have been meshed, on the contrary, with a more refined grid. In the vertical direction the meshes have been realized with the same discretization for all the parts included in the model.

The element type used is C3D8R: three dimensional elements with 8 nodes and with a reduced number of integration points, allowing faster analyses while preserving a realistic stiffness behaviour (Abaqus Analysis User's Manual, version 6.10-1).

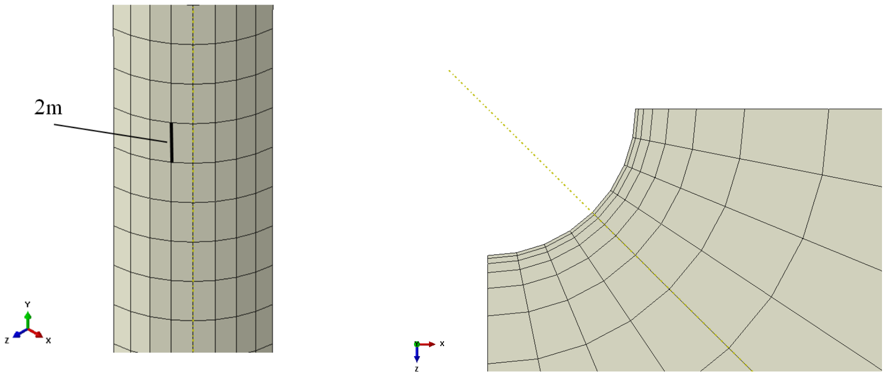

Figure 6. Logarithmic coarse mesh used in the rock formation.

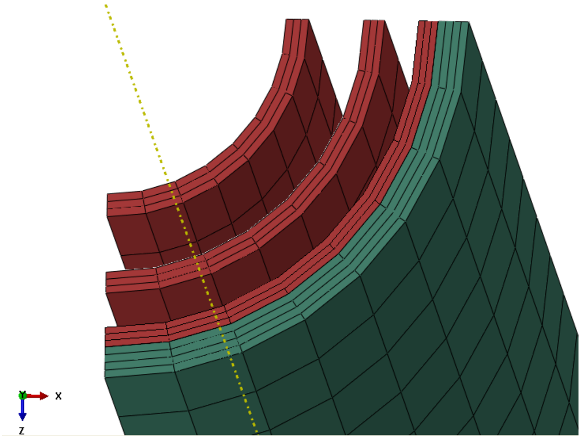

Figure 7. Refined grid used in the completion elements. The green part is the outer cement while three casings are represented in red. In the section shown, no intermediate cementation is present.

3.1.5 Boundary Conditions and Load Assignment with Abaqus/CAE

The last step of the model construction in Abaqus/CAE concerns the definition of the first part of the boundary conditions.

Well and rock displacements are negligible at the bottom of the model, thus both well system and rock nodes are locked at the base.

As already shown in Figure 4, symmetry conditions have been applied on two sides of the model, preventing displacements in the circumferential direction.

The well-head typically used in hydrocarbon wells is a heavy system leant on the ground top used to manage fluid rate and pressure. From the modelling point of view, it has been represented by imposing at the top equal displacements to the well and the rock; a multipoint constrain between casings and reservoir rock at the model top has, therefore, been used.

The last condition applied is a hydrostatic fluid pressure (commonly used in the well system to assure the stability of the production tubing) on the internal surface of the inner casing, as detailed in Figure 8. The condition is applied considering a typical completion fluid density.

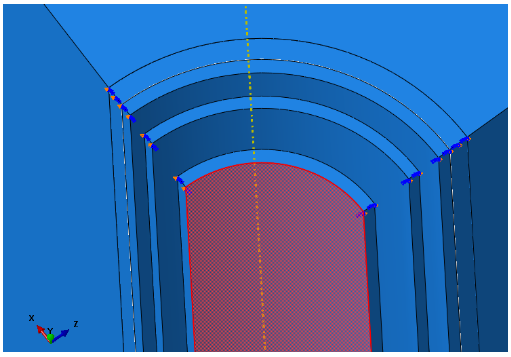

Figure 8. Internal surface of the production casing with the fluid pressure applied.

3.2 Boundary Conditions and Loads Assignment with a Matlab Code

Further conditions, derived from the geomechanical full field model, have to be applied:

- rock displacements applied to rock nodes: they are function of depth and of the production step considered and are applied as boundary conditions;
- horizontal isotropic total stresses applied to the faces of the external rock elements: they are function of depth and of the production step considered and are applied as surface loads.

These conditions have been applied to the Abaqus/Standard *input* file through proper *include* files created with a Matlab code that automatically reads the output of the field scale model and writes the data of interest with the proper Abaqus format. An example of these input data is shown in Figure 10.

3.3 Simulation Runs: Static and Buckling Analyses

Two types of simulation runs are carried out:

- static analysis at every production step: the analysis provides the stress regime and the strains on the completion system during the reservoir exploitation;
- eigenvalues buckling analysis: the analysis allows defining, at every production step, a safety factor (λ_i) related to the stability of the slender completion structures.

The critical load that may bring to buckling failure is evaluated starting from a so called *Base State* of the structure: this is the state of the model after the last step of analysis performed (in this case a static analysis). The Base State includes the pre-loads (called *Dead Loads*, *DL*) derived from the steps run before the buckling analysis. An incremental load history (called *Live Loads*, *LL*) is then applied to the structure during the buckling step. The magnitude of this load is scaled by the load multipliers (λ_i) obtained from the eigenvalues problem solution. Thus, the critical load P_{cr} can be defined as:

$$P_{cr} = DL + \lambda_i LL$$

Eigenvalues (λ_i) can be, therefore, considered as safety factors: they represent the multiplying factors for the live loads leading to critical state for the structure (or for a part of it).

In order to test the buckling risk at a selected time step, the buckling analysis is performed, in the present workflow, as follows:

- the simulation is run until the previous step by including all loads and displacements (see §3.2) as derived from the full field model, considered as *DL*;
- a step including only the loads acting on the rock at the selected time step is run, always considered as *DL*;
- the buckle step is run including the rock displacements relevant for the time step selected; these are then considered as *LL*.

An example is reported below, relevant for the buckling analysis at the second production time step:

```
*Step, name=1_year_PROD, nlgeom=YES
*Static
1., 1., 1e-05, 1.
*INCLUDE, INPUT=Disp_1_year.inc
*INCLUDE, INPUT=Hor_Stress_1_year.inc
*End Step
**
*Step, name=Step-2_years_PROD, nlgeom=YES
*Static
1., 1., 1e-05, 1.
*INCLUDE, INPUT=Hor_Stress_2_years.inc
*End Step
**
*Step, name="Buckling Analysis", perturbation
*Buckle
1, , 18, 30
*INCLUDE, INPUT=Disp_2_years.inc
```

This procedure has been chosen in order to evaluate the completion collapse risk related specifically to the stress/strain state transferred to the well system by the rock compaction during production.

3.4 Result Analysis

The analysis of the simulation results is performed to investigate in detail:

- stress and strain of the casing steel: strains obtained at different production steps have to be compared to relevant literature values in order to identify the occurrence of possible critical situations related to plasticity-induced instability;

- plasticity regions: the location of the zones where plastic strains arise must be identified, since they represent the casing part where the instability phenomena may occur (Abou-Sayed et al., 2003);
- eigenvalues from the buckling analyses can be used as safety factors: values lower than 1 point out an instability risk for the well during the forecasted production.

4. Application to a Synthetic Case

An application of the workflow illustrated above to a synthetic case will be presented. After a brief description of the input parameters required, results will be shown and discussed.

4.1 Input parameters required

The information required as input include the well geometry, the completion scheme, rock and completion material parameters, loads applied and boundary conditions. Some of them are derived from the full field geomechanical model while other can be obtained from lab test interpretations, relevant literature and technical specs.

4.1.1 Completion Scheme and Materials

The workflow is here applied to a vertical well. The completion scheme is reported in Table 1.

Table 1. Completion scheme.

Casing #	**1**	**2**	**3**
Casing Diameter (in)	16”	13”3/8	19”5/8
Casing Depth (m)	Surf - 720	Surf - 1000	Surf - 1500
Cementation Job	yes	yes	yes

Completion steel has been modelled with classic metal plasticity with isotropic hardening, as represented in Figure 9. Required strength parameters are reported Table 2 as function of the grade of the steel. The same grade has been adopted for every casing and a sensitivity analysis has been next performed in order to evaluate its influences on problem results (see § 4.3).

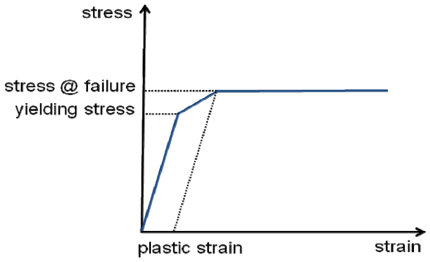

Figure 9. Plasticity model of casing steel.

Table 2. Casing steel strength parameters.

Casing #	**Steel Grade**	**Yielding Stress (MPa)**	**Failure Stress (MPa)**	**Plastic Strain (-)**
1 – 2 – 3	80	552	607	0.01

Cement has been modelled with an elastic perfectly plastic behaviour using Mohr-Coulomb failure criterion. The properties have been derived from the relevant literature (Gray et al., 2007, Capasso and Musso, 2010).

4.1.2 Rock Characterization

Reservoir rock has only the function of transferring pre-calculated stresses and displacements to the well completion system and therefore has been modelled as linear elastic. Relevant properties are summarized in Table 3.

Table 3. Geomechanical rock properties.

Young's Modulus (GPa)	Poisson's Coefficient (-)
1	0.25

Vertical displacements and total stresses, extracted from the field scale geomechanical model using an in-house Matlab code (§ 3.2) are reported in Figure 10, along the well trajectory and for some productive time steps.

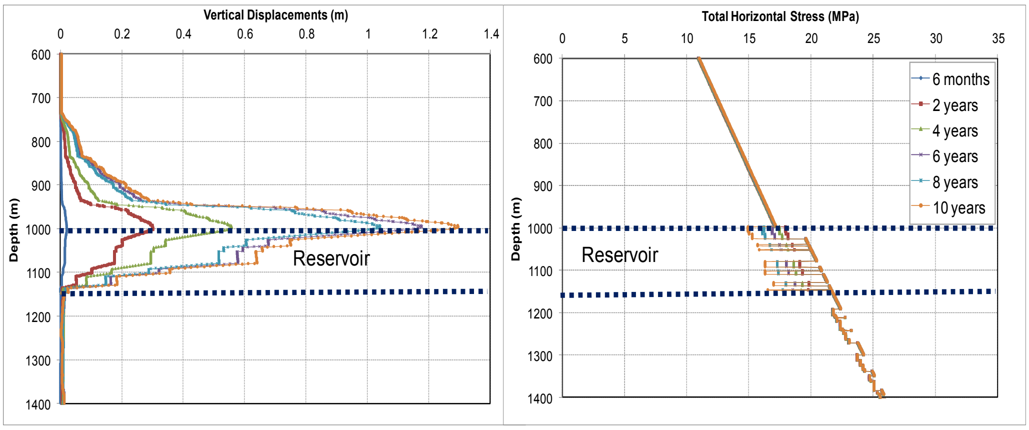

Figure 10. Vertical displacements and total stress acting along the well trajectory at different years of production.

4.1.3 Contact Characterization

Parameters applied at the interface models, obtained from the relevant literature (Coyle and Reese, 1966, Capasso and Musso, 2010) are summarized in Table 4.

Table 4. Interface parameters.

Interface	Friction Coefficient (-)	Max Tangential Stress (kPa)
Cement-steel	0.3	20
Rock-cement	0.5	200

4.2 Static Analysis Results

In the following, the processing of the obtained results is shown for the synthetic case considered.

The model takes into account the whole well system with three casings and their relevant cementation jobs. Thus, the well crosses the overburden and the reservoir layers. However, as expected, the highest stresses and strains occur in well sections corresponding to the reservoir zone (i.e. casing #3). For this reason, only the stress/strain evolution in the production casing will be carefully investigated.

In Figure 11 vertical stresses and strains acting on the production casing are presented. It can be observed that the casing is subjected to a compressive stress regime that reaches its maximum value in the middle of the reservoir. The extent of the zone interested by loading (both over and under the reservoir layers) can be easily assessed from the vertical stress profile.

As far as the analysis of the strain is concerned, different values of maximum vertical strain bearable by the well structure can be obtained from literature and taken as safety limit to prevent the well failure (Bruno, 1992; Dusseault et al., 1998; Abou-Sayed et al., 2003; Li et al., 2003, Furui et al., 2009). In the present study, a reference value of 2% for the total vertical strain has been assumed as limit condition to ensure well integrity, being this value one of the strictest conditions proposed in the available literature. It can be then verified (Figure 11) that the production casing presents no risk of strain-induced instability, thus the steel grade proposed is adequate to bear the loads induced during the well production life.

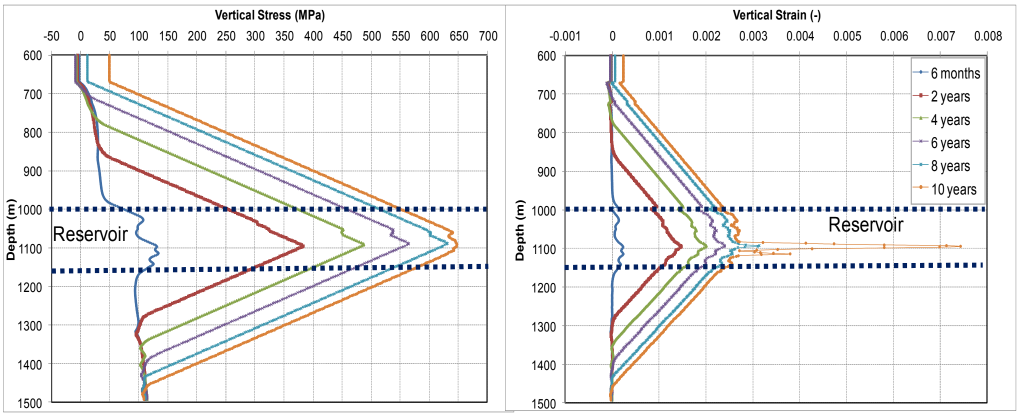

Figure 11. Vertical stress and strain acting on casing #3 at different years of production.

In order to get a complete description of the stress evolution in the completion steel, it is useful to analyze the deviatoric stress values (i.e. *Mises* stress) and compare them with the steel yield stress (Figure 12, left side). This is done in order to get information about the occurrence of plastic strains in the casing material: when the *Mises* stress is higher than the yield stress (after 8 years of production), plastic strains occur. This can be verified in Figure 12, right side, where the equivalent plastic strain (i.e. *PEEQ*) is plotted. Equivalent plastic strain is given by:

$$PEEQ = \frac{\sqrt{3}}{2}\left[\left(\varepsilon_1^{pl} - \varepsilon_2^{pl}\right)^2 + \left(\varepsilon_1^{pl} - \varepsilon_3^{pl}\right)^2 + \left(\varepsilon_2^{pl} - \varepsilon_3^{pl}\right)^2\right]^{\frac{1}{2}}$$

where ε_1^{pl}, ε_2^{pl} and ε_3^{pl} are the principal plastic strains. In the synthetic case shown, *PEEQ* starts after 8 years of production, while after 10 years of production it has reached its maximum value and spatial extent (as represented in Figure 13).

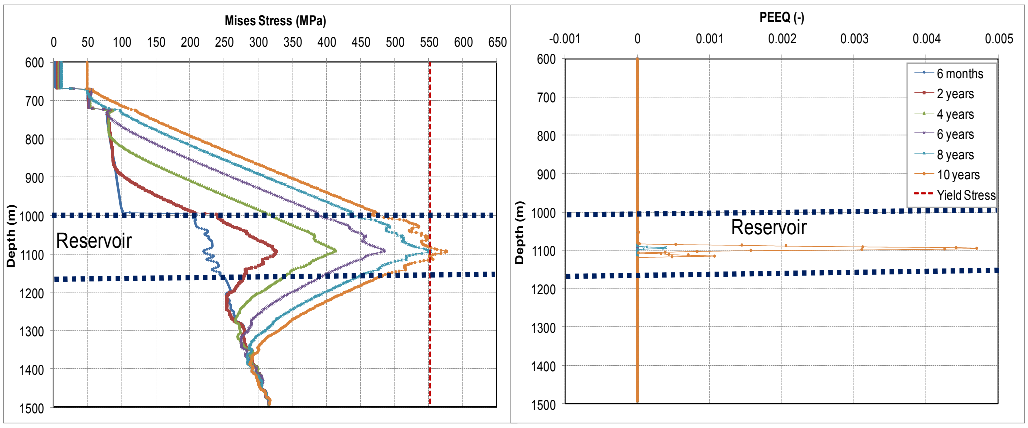

Figure 12. *Mises* stress and equivalent plastic strain acting on casing #3 at different production years.

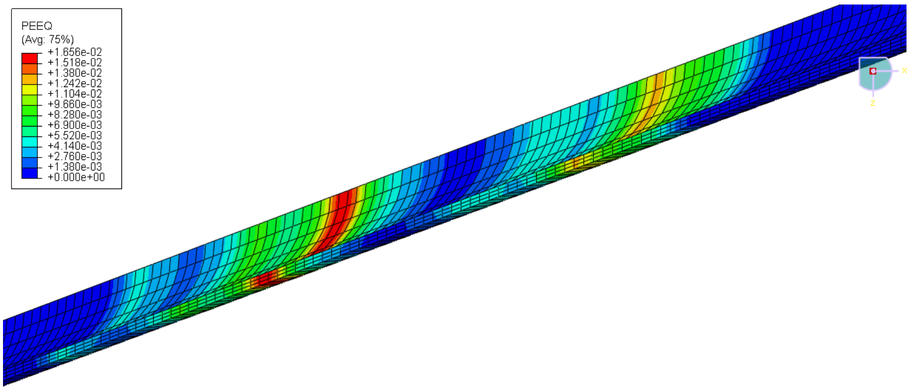

Figure 13. Plastic zone of casing #3 after 10 years of production.

4.3 Sensitivity Analysis

A key objective of the presented workflow is the selection of the proper casing in order to avoid the well failure during the reservoir exploitation. A sensitivity analysis has then been performed varying steel strength parameters (i.e. steel grade) as detailed in Table 5 (where two commercial casing types have been tested) and comparing results together with the case presented above (considering a steel grade equal to 80, Table 2).

In Figure 14 the results are presented for the three steel grades considered after 6 and 10 years of production.

Table 5. Steel parameters used in the sensitivity analysis.

Casing #	Steel Grade	Yielding Stress (MPa)	Failure Stress (MPa)	Plastic Strain (-)
1 – 2 – 3	55	379	417	0.01
1 – 2 – 3	95	655	720	0.01

After 6 years of production, the vertical strain (Figure 14, left upper side) is equal for casing grade 80 and casing grade 95 while it is higher for the grade 55. This is due to the occurrence of plastic strains in the latter, which is confirmed by the *Mises* stress plot (Figure 14, left lower side): grade 55 steel has reached the yield stress limit, thus plastic strains have arisen. After 10 years of production (right side of Figure 14) the grade 80 steel has also reached the plastic zone and the vertical strains increase considerably. Grade 95 steel never reaches plastic strains, keeping the capability of bearing higher stress values.

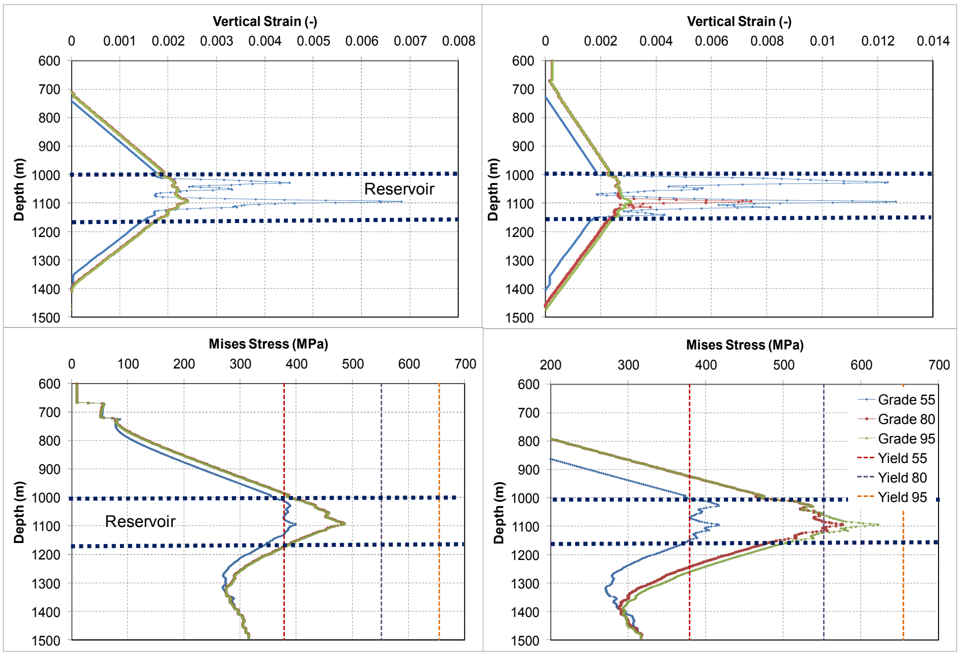

Figure 14. Vertical strain and *Mises* stress at 6 (left) and 10 (right) years of production.

Taking into account the vertical strain limit considered in §4.2 (2%), the optimal casing grade for the case considered is 55; if a criterion of null plastic strain is required, then the optimal choice is grade 95.

4.4 Buckling Analysis Results

A buckling analysis of the well structure has been performed to investigate possible failure risks related to equilibrium instability. This analysis has been performed following the approach described §3.3, takes into account all parts of the well-system (i.e. 3 casings and relevant cementation jobs) and it has been carried out for all the production years. The tested casing grade is equal to 95.

As already mentioned, eigenvalues are used as safety factors, with values smaller than 1 indicating that buckling risk is present for the structure; it is important, in such a case, to identify which part of the analyzed completion undergoes buckling so that a proper design can be proposed by changing the completion geometry and/or material. Anyway, the results obtained should be assessed in any specific case taking into account the model uncertainties and assumptions. In Table 6 the eigenvalues associated to the first buckling mode shape as a function of the year of production are summarized.

Table 6. Eigenvalues obtained during reservoir exploitation.

Years of Production	Eigenvalue
6 months	204
2 years	18
4 years	9.2
6 years	6.2
8 years	4.6
10 years	3.7

Eigenvalues decrease with production, i.e. with the increase of stresses and strains due to reservoir exploitation. Since all the values are larger than one, no buckling risk is found for the whole well structure. A buckle mode shape of the production casing is presented in Figure 15. Buckle mode shapes are normalized vectors and do not represent actual magnitudes of deformation at critical load; they represent a useful outcome of the eigenvalues analysis, since they predict the likely failure mode of the structure (Abaqus Analysis User's Manual, version 6.10-1).

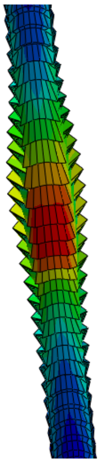

Figure 15. First buckle mode for the production casing after 10 years of simulation.

5. Conclusions

In this paper a new workflow for long-term well stability evaluation has been presented. It is applicable when a field scale geomechanical model is already available for the reservoir considered and allows the evaluation of the stress/strain evolution on the well system as a consequence of the reservoir exploitation.

The workflow includes the construction of a well scale FE model along the trajectory of interest; vertical displacements and horizontal stresses are extracted at the corresponding locations from the field scale model and are applied to the well scale model; simulations are performed taking into account the whole productive life of the well, providing the response on the well integrity long-term, evaluating both the possible plasticization-induced failure and buckling-induced collapse.

A sensitivity analysis on the steel type allows suggestions on the optimal steel grade to be used in the different sections of the well in order to ensure stability during the forecasted hydrocarbon production.

Several conclusions can be drawn about the proposed workflow:

- the use of the results proceeding from an available full field model has the advantage of building well models consistently with a larger scale context; moreover, with this approach, the rock has the function of transferring pre-calculated stresses and displacements and can be modelled as non-porous material, thus reducing the computational effort with respect to other approaches requiring the simulation of the rock behaviour (Capasso et al., 2008; Capasso and Musso, 2010);

- accurate models can be built with the approach proposed: real problem geometry is honoured, interfaces between different materials can be properly modelled, non-linear behaviour can been used to correctly describe cement and steel; also, a good mesh discretization can be used even with the slender structural element considered, thanks to the flexibility shown by the features available with Abaqus/CAE and Abaqus/Standard;

- results obtained with the approach proposed give valuable information about the optimal casing type, making the workflow a particularly effective tool during the casing design phase, especially for high compacting reservoirs;

- buckling risk assessment provides key information about the risk of collapse of the well structure and is therefore a very important step of the workflow; eigenvalues used as safety factors allow evaluating the collapse risk of the structure as a function of the forecasted production.

Further developments will include a Riks Method application in order to get a prediction of the collapse of the well system by including all the model non-linearities (geometrical, material and contact interfaces).

6. References

1. Abaqus Analysis User's Manual. Version 6.10-1, Simulia.
2. Abou-Sayed, A.S., Meng, F., Noble, J. E. and Guo Q., "Modeling of Reservoir Compaction and Casing Integrity Evaluation Using Reservoir Simulation", SPE 81072, 2003.
3. Bruno, M. S., "Subsidence-induced Well Failure", SPE Drilling Eng., pp.148-152, 1992.
4. Bruno, M. S., "Geomechanical Analysis and Decision Analysis for Mitigating Compaction Related Casing Damage", SPE 71695, SPE Annual Technical Conference and Exhibition, New Orleans, 2001.
5. Capasso, G. and Mantica, S., "Numerical Simulation of Compaction and Subsidence using Abaqus", Proc. ABAQUS Users' Conference, Boston, USA, 2006.
6. Capasso, G., Musso, G. and Mantica, S., "Long-term Stability Study of open-hole Completions in a producing Hydrocarbon field", ARMA 08-238, Proc. Of 42nd Rock Mechanics Symposium, San Francisco, USA, 2008.
7. Capasso, G. and Musso, G., "Evaluation of Stress and Strain Induced by the Rock Compaction on a Hydrocarbon Well Completion Using Contact Interfaces with Abaqus", Proc. ABAQUS Users' Conference, Providence R. I., USA, 2010.
8. Cernocky, E. P. and Sholibo, F. C., "Approach to Casing Design for Service in Compacting Reservoirs", SPE 30522, SPE Annual Technical Conference and Exhibition, Dallas, 1995.
9. Coyle H.M. and Reese L.C., "Load Transfer of Axially Loaded Piles in Clay", JSMFD, ASCE, vol. 92, SM 2, pp. 1-26, 1966.
10. da Silva, F. V., Debande, G.F., Pereira, C.A. and Plischke, B., "Casing Collapse Analysis Associated with Reservoir Compaction and Overburden Subsidence", SPE 20953, Europec 90, The Hague, Netherlands, 1990.
11. Dusseault M.B., Bruno M.S. and Barrera J., "Casing Shear: Causes, Cases, Cures", SPE 72060, presented SPE International Oil and Gas Conference and Exhibition, Beijing, 1998.
12. Furui K., Fuh G.F. , Abdelmalek N. and Morita N., "A Comprehensive Modeling Analysis of Borehole Stability and Production Liner Deformation for Inclined/Horizontal Wells Completed in a Highly Compacting Chalk Formation", SPE 123651, 2009.
13. Gray K.E., Podnos E. and Becker E., "Finite Element Studies of Near-Wellbore Region During Cementing Operations: Part I", presented at SPE Symposium, Oklahoma City, 2007.
14. Li X., Mitchum F.L., Bruno M.S., Dattillo P.D. and Willson S.M., "Compaction, Subsidence and Associated Casing Damage and Well Failure Assessment for the Gulf of Mexico Shelf Matagorda Island 623 Field", SPE 84553, SPE Annual Technical Conference and Exhibition, Denver, Colorado, 2003.
15. Musso G., Topini, C. and Capasso, G., "Long term well integrity: a semi-analytical approach", ARMA 10-398, Proc. of the 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, Salt Lake City, 2010.
16. Terzaghi, K., "The Shearing Resistance of Satured Soils and the Angle between the Plane of Shear", Proc. Of 1st Int. SMFE Conference, Harvard Mass., Vol. 1, pp. 54-56, 1936.
17. Timoshenko, S.P. and Gere, J.M., "Theory of elastic stability", McGraw-Hill Book Co. Inc., New York City, Second Edition, 1961.

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