Evaluation of Stress and Strain Induced by the Rock Compaction on a Hydrocarbon Well Completion Using Contact Interfaces with Abaqus

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Abstract: The development plan of a hydrocarbon field includes the design of all the production/injection wells forecasted for the scenario considered. The pressure depletion occurring during the hydrocarbon reservoir exploitation induces rock compaction in the near wellbore area, which may result in mechanical actions transmitted to the well completions, that alter the stress regime in some of their sections. This phenomenon can possibly bring to the failure of the casing and of the cement, eventually leading to the well shutdown and to significant economic loss. By making reference to a case of industrial interest, the paper describes a procedure to evaluate stresses and strains in the completion structure induced by the rock deformation by using Abaqus.

Keywords: Well stability, Geomechanics, Failure criteria, Contact Interface.

1. Introduction

The well completion design represents one section of the field development plan for the exploitation of a hydrocarbon reservoir. The most basic completion type is represented by the open-hole: in this case the wellbore is left open in correspondence to the producing layers, without any protective structure. However, this completion type does not prevent well instability induced by rock failures, possibly generated as a consequence of the rock stress regime modified by the production process.

More often, the completion design includes the casing, i.e. a steel pipe that is inserted into the drilled hole, which is then connected with the surrounding rock by the cement introduced in the annulus between the formation and the steel casing.

According to the routine procedures for well design, the structural elements of the completion system are dimensioned with regard to the actions developing during the completion phase itself; however, the pressure depletion occurring in the near-wellbore area during the production period may induce rock compaction and, as a consequence, mechanical actions on the cement and the steel casing transferred through the rock/cement/casing interfaces.

The magnitude of the stress and strains transmitted to the completion system is mainly dependant on the drawdown occurring at the well and on the compressibility of the rock formation interested by the phenomenon. However, the assessment of the stability of the completion system in the long-term is strongly recommended, since the casing/cement failure may cause significant productivity reduction till the well shutdown, with consequent huge economic loss.

This paper presents a procedure implemented internally in eni E&P to carry out a long-term stability study of standard completed wells by using Abaqus. This procedure was developed with reference to a real case of particular interest for the company, for which a previous study evidenced the unfeasibility of open-hole completions (Capasso et al., 2008). First, a brief overview of the problem is provided, followed by a detailed description of the workflow developed to build and run the finite element model; finally, the application of the approach to a real case of industrial interest is illustrated.

2. Problem overview

During the process of hydrocarbon withdrawal from the subsurface, the pressure of the fluid saturating the pore space decreases, thus inducing compaction in the rock layers interested by the production. The basic law governing the phenomenon is the Terazaghi's principle of effective stresses, formulating the interaction between the solid skeleton and the pore fluid, stating that:

$$\sigma_{ij}' = \sigma_{ij} - \delta_{ij} p \qquad (1)$$

where σ_{ij}' is the effective stress, σ_{ij} is the total stress and p is the pore pressure. The effective stress governs the mechanical behavior of the porous medium since "all measurable effects of a change of stress, such as compression, distortion and a change of shearing resistance, are exclusively due to changes in the effective stress" (Terzaghi, 1936).

With reference to a reservoir, the above principle can be applied by considering that the weight of the overburden is supported partially by the rock matrix and partially by the pressurized fluid in its pore space; the reduction of the pore pressure due to the reservoir exploitation will induce an increase of the effective stress with a consequent compaction effect on the formation. The compaction in the near-wellbore area is transferred as mechanical actions to the well system (cement and casing) through the shear stresses at the interfaces (see Figure 1). As a consequence, the stress acting on the well completion may induce different well failure mechanisms, such as casing compression and buckling (Bruno, 2001).

To study this phenomenon, analytical methods have been developed in the past and are available in the relevant literature (Bruno, 1992, 2001). In most cases, the deformation experienced by the rock formation is evaluated with the simplifying hypothesis of oedometer conditions, i.e. every reservoir producing layer only experiences vertical displacements, which are dependant on the rock compressibility and on the magnitude of the pressure decrease, the latter considered uniform in the wellbore area; a further common hypothesis is that the rock deformation is totally transferred on the completion system, then assuming complete contact at the interfaces. However, the oedometric consolidation hypothesis can be considered as reasonable only in the case of thin, flat geological mineralized layers, where the symmetry conditions impose no lateral strain. Real reservoir layers may have more or less pronounced slopes with respect to the horizontal direction; also, when dealing with a problem at well scale, the underlying hypothesis of uniform distribution of the pressure depletion is not realistic, being the fluid flow driven by pressure gradients between the far field and the well. It should also be considered that standard analytical approaches assume that the rock constitutive law is linear elastic, while it is known that the rocks usually have a highly non linear behavior, that can be described properly only through more complex constitutive models. Moreover, the approach considering perfect contact between rock and well system represents the ‘worst case’ scenario, as it neglects any possible slip at both interfaces (rock formation/cement and cement/casing) thus maximizing the stress arising on the casing because of strain compliance. It is known from the current practice that this hypothesis is very pessimistic.

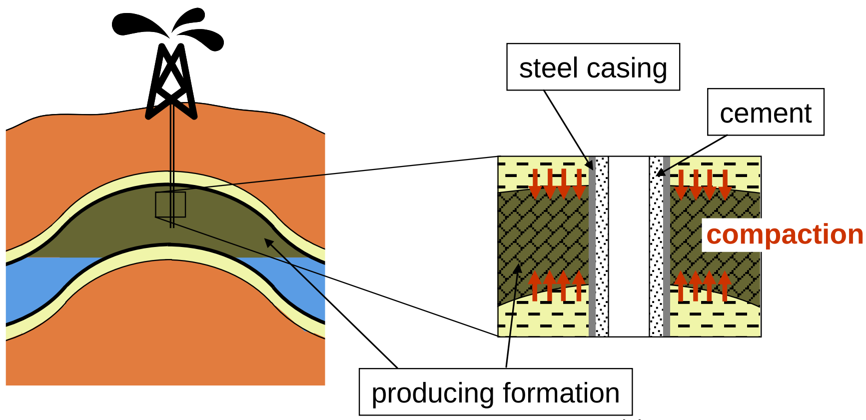

Figure 1. Compaction of the producing layers and actions on the well completion.

On the base of the above considerations, it can be affirmed that, as already evidenced in past studies (da Silva et al., 1990; Cernocky et al, 1995; Patillo et al., 2002; Gray et al., 2007), the use of finite element models is much more suitable in order to correctly describe the real behavior of the rock material, of the completion material and of the interfaces developing between them. Moreover, the pressure evolution during the production can be included with its real distribution from the well walls towards the far field. A workflow has then been developed internally in eni E&P by using Abaqus as the main numerical tool for geomechanical simulations at well scale.

3. Workflow overview

A proper workflow has been developed using Abaqus to evaluate the effects of pressure changes on the mechanical behavior of the reservoir rock and on the designed completion in order to determine the mechanical actions on the well system induced by the forecasted production. The quantitative assessment of stress and strain on the casing steel and the cement sheet allows failure checks to be performed and the designed sections be verified over the entire life of the wells considered. An accurate selection and pre-processing of all the data needed to define the problem has to be performed; then, different successive phases of model construction and calibration have to be carried out to build the final simulations.

The workflow includes the following steps:

- FE model setting:
    - Model construction: the model at well scale is built according to the well and reservoir geometry;
    - Property assignment: the model is populated with the properties relevant for the rock formation, the completion material and the behavior at the interfaces;
    - Initialization: initial stress state, pore pressure distribution and void ratio are imposed to the model.
- Model calibration: FE simulations of the drilling phase of reference appraisal wells are run in order to calibrate the initial stress state in the area of interest.
- Simulation procedure: FE simulations are performed with sensitivities on the parameters defining the contact interfaces and including the following phases:
    - Geostatic equilibrium
    - Drilling steps
    - Completion phases
    - Production phases.

The steps outlined above will be detailed in the following sections.

4. FE model setting

4.1 Model construction

Being the objective of the study the evaluation of the mechanical actions induced on the well completion by the compacting rock, the model is built at well scale including, in the vertical direction, not only the reservoir layers but also overburden layers: the reservoir deformation may induce stress on the well system and this action may propagate in correspondence of the overburden layers as well, even if the rock deformation is mainly concentrated in the productive layers.

The FE geomechanical model relies on the hydrodynamic simulation usually available for the field: the reservoir layering at the location of reference can be extracted from the hydrodynamic model thus allowing for a good consistency with the structural information of the geological study (Capasso et al., 2006). Then, layers belonging to the overburden on the top of the reservoir can be added according to the seismic information available (see Figure 2).

The mesh discretization has to be adopted, in the vertical direction, coherently with the layering of the geological structure of the field in the near wellbore area. In the radial direction a logarithmic function is used (with element size increasing from the well walls towards the boundaries of the model) to accurately simulate the behavior in the region close to the borehole. In the hoop direction the elements are created with uniform size instead.

As far as the mesh for the completion system is concerned, the vertical discretization is the same adopted in the nearby rock elements; uniform discretization is then assumed both in the radial and hoop directions, as shown in Figure 3.

Note that, in the case of a vertical well, one quarter of the geometry can be used given the symmetries involved.

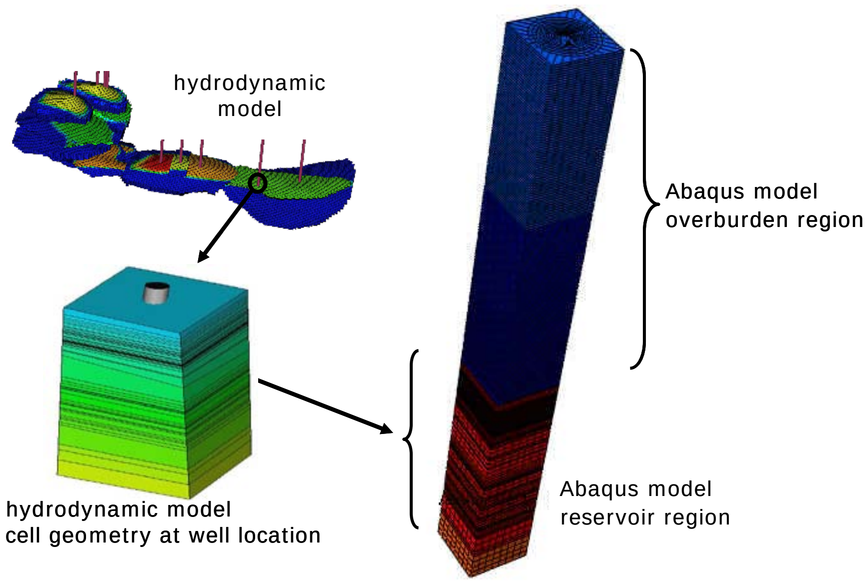

Figure 2. Abaqus model construction

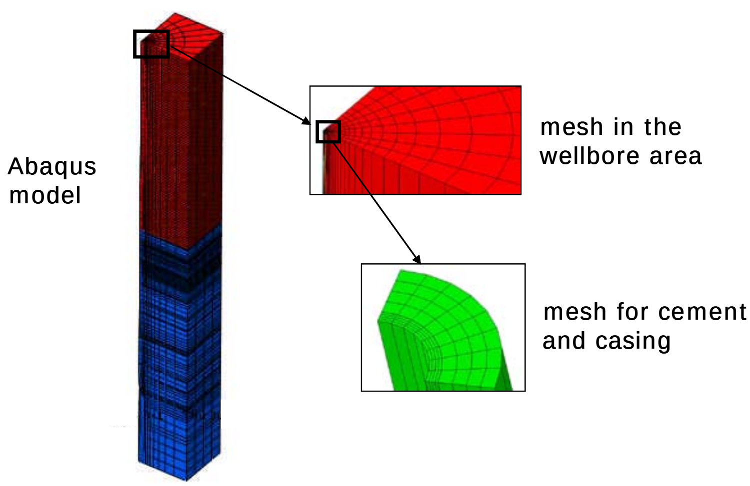

Figure 3. Model discretization.

Two different types of elements are used to build the model: the elements representing the overburden rock material do not require the pore pressure as a degree of freedom, since no depletion is occurring, and “C3D8” elements are adopted. The same type of elements is used to describe the cement and the steel of the completion system. Differently, the reservoir rock model is built by using elements including the pore pressure as a degree of freedom. In this case, “C3D8P” elements are adopted. They are appropriate to represent the porous nature of the rock, so that the characterization through properties related both to the rock matrix and to the fluid saturating the pores will be required.

4.2 Property assignment

As far as the rock geomechanical characterization is concerned, the analysis of the available laboratory and in situ data represents the necessary step in order to define the more appropriate constitutive law to be adopted in the model, as well as the property values to be used to characterize the various reservoir and overburden level.

Depending on the case studied, different constitutive behavior may be adopted to describe the response of the rock material; in the case shown later in this paper, elasto-plastic laws based on Mohr-Coulomb and Hoek & Brown (Hoek et al., 1997) strength criteria have been adopted, as illustrated in §7.

Elasto-plastic laws are also adopted to characterize the completion materials; in particular, Mohr-Coulomb criterion is used to describe the cement behavior while a Von Mises criterion with isotropic hardening is used for the steel.

As it has been pointed out already, interfaces between the rock formation and the cement, as well as between the cement and the steel casing, are introduced in the model to correctly assess the stress transfer among the different structural components. These interfaces are set up in the Abaqus FE simulation by defining surfaces on the relevant elements and imposing the contact behavior between the two couples (rock/cement and cement/casing) shown in Figure 4.

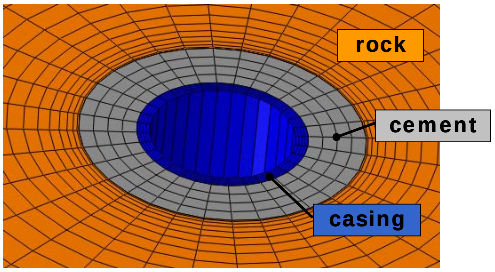

Figure 4. Modeling of the interfaces.

Both interfaces are defined as frictional with finite sliding allowed. The model selected is an isotropic Coulomb model, characterized with a friction coefficient μ as shown in Figure 5; moreover, a maximum value τ_{max} of the shear stress that can be carried by the interface has been imposed.

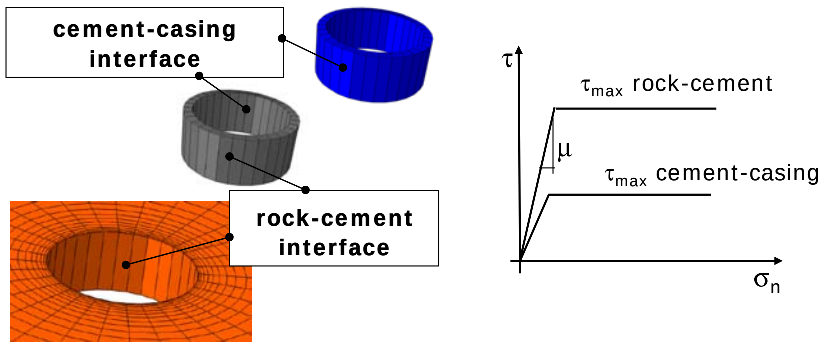

Figure 5. Interface mechanical behavior.

4.3 Initialization

A key step in the model construction is the definition of the initial conditions, in terms of void ratio and stress state.

The initial void ratio, as well as the initial pore pressure values, is derived from the reference hydro-dynamic model at the location of the well of interest; the definition of the local geostatic stress field, instead, has to be carried out as a dedicated pre-processing phase as illustrated hereafter.

Except for particular cases, the vertical stress and the minimum horizontal stress can be evaluated using in-situ tests; on the contrary, a direct determination of the maximum horizontal stress is not possible and its assessment is gained, in the current workflow, thanks to an inversion procedure which integrates the evidence of tensile failures and break-outs detected in the appraisal wells with its analytical reconstruction (Capasso et al., 2008). This procedure, however, relies on an analytical formulation based on simplifying hypotheses (linear elastic behavior, plane strain configuration); the stress calibration is then refined by removing these restrictive assumptions using Finite Element models, as described in the following section.

5. Model calibration

The calibration carried out by using the analytical formulation allows the definition of an initial stress field range for the problem considered; however, numerical simulations of the drilling phase for an existing appraisal well of reference are run with the FE method to calibrate more accurately the initial stress by honoring the measured failure events.

The drilling phase is simulated in subsequent steps by progressively removing the well inner material and by applying the mud pressure at the borehole walls (Figure 7); a set of runs are carried out by varying the maximum horizontal stress σ_H in a range that is defined with the analytical analysis. The comparison of the calculated failures with the available image log measurements performed in situ allows choosing the simulation runs that better reproduces the measured events; the corresponding σ_H is used to initialize the final model. With reference to the application shown later, the plot in Figure 6 shows (blue dots) the directions of the tensile fractures detected by the image log in the reference appraisal well as a function of depth. It can be observed that tensile failures are occurring along the whole depth of the well in the reservoir formations, oriented, on average, at 73 °N. In the same figure, the red hatching represents the tensile failure zone as calculated with the finally calibrated simulation: the fracture direction is fixed in this case since it depends on the initial horizontal stress directions imposed; the failure spans about 23° and it is obtained by identifying the number of elements with positive plastic shear deformation (PEEQ). A match in the fracture occurrence is apparent for the three formations characterizing the analyzed reservoir.

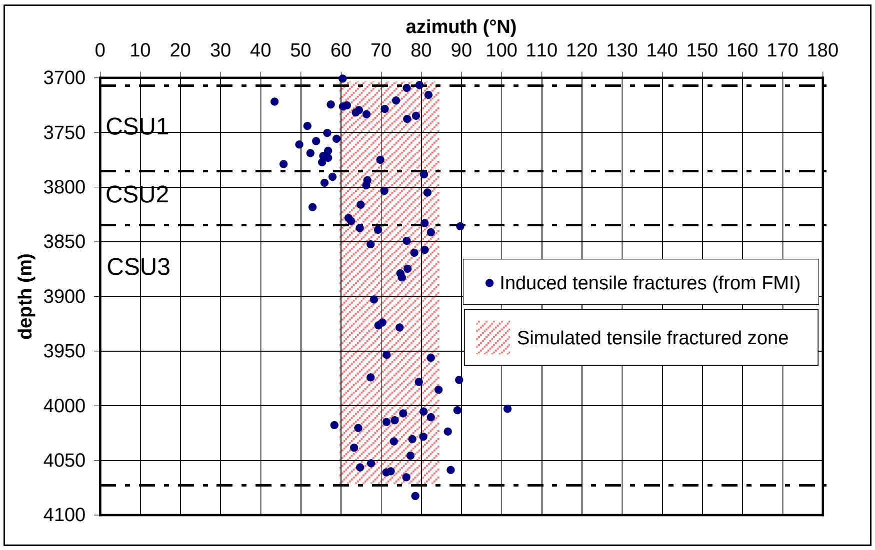

Figure 6. Appraisal well: measured and simulated induced tensile fractures.

6. Simulation procedure

In order to carry out the simulations aiming at evaluating the mechanical actions on the well system, the finite element analyses are performed in this study using a staged approach. The well to be analyzed and the surrounding rock region are simulated from the initial unperturbed state to the end of the production, with the following successive simulation stages:

1. Geostatic step: unperturbed state definition.
2. Drilling steps: rock excavation and mud insertion.
3. Completion steps:
    - casing/liner introduction;
    - fluid cement introduction;
    - cement slurry hardening and interface activation.

4. Production steps: pore pressure decrease in the reservoir formations and well drawdown acting in the wellbore.

It must be underlined that, according to the simulation practice when a staged approach is adopted, all the elements representing the whole domain investigated are present from the beginning of the calculation; part of them is set as inactive (`*Model change, remove`) in the simulation steps where they are not yet introduced. More in detail, the model is set up including the rock formation in the near-wellbore area, the rock material inside the well (existing before the drilling), the steel casing and the cement in the well with the position they will occupy when they will be introduced.

6.1 Geostatic step

It is of utmost importance to correctly define the initial stress state in the models in the undisturbed situation, i.e. prior of the drilling activity. This represents a delicate step in the model construction, since the consequences of any subsequent action (drilling, completion and production) in terms of stress and deformation is strongly influenced by the initial conditions imposed, being the materials characterized with a non-linear and inelastic behavior.

The material properties (rock and pore fluid densities) are assigned coherently with the initial stress state and pore pressure, so that equilibrium is assured. However, in order to check that the initial state equilibrium is actually achieved, a "geostatic" step is performed: this calculation only balances the initial conditions with the internal body forces. Care must be taken in ensuring that only small displacements occur during this simulation phase, meaning the correctness of the conditions imposed.

At this stage the model includes only the rock formations, as the borehole is not drilled yet.

6.2 Drilling steps

As schematically represented in Figure 7, the drilling process is simulated in this study by the removal, in several successive steps, of part of the inner rock material; at the same time the mud is introduced in the excavated volume and its action is simulated by the application of a hydrostatic pressure on the borehole walls. The simulation of this phase allows the definition of the stress and strain conditions in the rock surrounding the borehole prior to any other operation on the well.

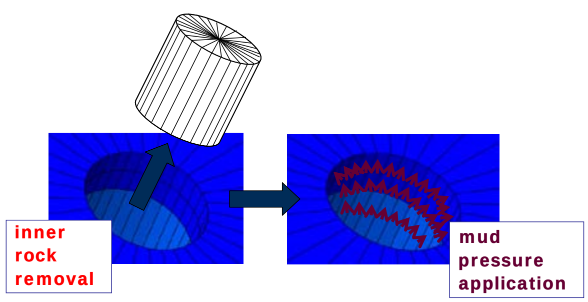

Figure 7. Drilling phase: inner rock material removal and mud pressure application.

6.3 Completion steps

As mentioned above, the completion process is simulated in this study with three different steps, each of them schematizing a successive operation.

Casing introduction

In this step, the steel casing is inserted into the wellbore. Once in the well, the casing is loaded on both sides (inside and on the gap between the casing and the formation) with the hydrostatic pressure of the mud present in the wellbore (Figure 8, a).

Fluid cement introduction

At this stage, the cement is introduced in the gap between the formation and the steel casing as fluid phase. It replaces the mud in the annulus, and it applies a hydrostatic pressure on the rock formation and on the outer side of the casing (Figure 8, b). This pressure is different from the previous mud pressure since the two fluids have similar but not identical specific weights. The pressure applied by the fluid cement is increased by the pressure imposed at the surface: in order to replace the mud, the cement applies at the base of the model (bottom of the reservoir) the same pressure previously applied by the mud at the same depth; then the distribution is defined by the cement weight.

In this step the mud pressure is still applied on the inner side of the casing.

Cement hardening

During the third completion step the cement is introduced as solid phase: the elements representing the cement are activated at this point of the calculation (Figure 8, c). When introduced, the cement is loaded with its own weight and with the hydrostatic pressure inherited by its previous fluid condition (Gray et al., 2007); the mud pressure is still applied on the inner side of the casing/liner.

At this stage all the contact interactions between rock formation and cement, and cement and steel casing, are activated.

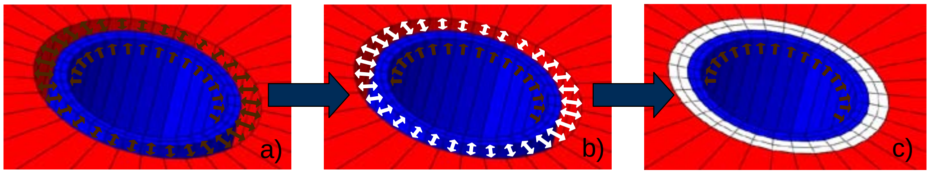

Figure 8. Completion steps: a) casing introduction; b) fluid cement introduction; c) cement hardening.

The solid cement occupies the gap existing between the rock formation and the casing, which is a volume that has evolved during the previous drilling and completion steps. As briefly mentioned above, the elements included in the finite element model (representing the rock, the cement and the casing) have to be defined at the beginning of the calculation in terms of geometry, type and material properties. It is evident, however, that the correct geometry of the annulus between the borehole and the external surface of the casing, defining the cement geometry, is not known at the start of the simulation, since it evolves during the drilling phase and the first two completion steps. In order to manage this occurrence, the following procedure has been adopted: a ‘pre-simulation’ is run ending at the second completion step, corresponding to the introduction of the fluid cement; the node coordinates of the annulus are produced as output; the cement geometry of the final simulation is built using the correct coordinates provided by the ‘pre-simulation’.

6.4 Production steps

The pressure depletion occurring in the well and in the surrounding porous medium during the production phase represents the load history imposed to the model.

The simulations are carried out in a one-way coupled scheme: the pressure values, decreasing as the time steps advance, are imposed on every reservoir node at every time step of the FE model as internal boundary conditions; this means that the medium, at every time step, is considered instantaneously drained.

The forecasted pressure evolution is extracted from the hydro-dynamic study at significant dates; then, the average block pressure and the well flowing pressure are used to define the logarithmic pressure distribution to be applied to the FE models as a function of location and time step (Capasso et al., 2008).

More in detail, at every production step, the simulation is executed as follows (see Figure 9):

- the well pressure is applied on the casing inner side and substitutes the mud pressure;
- the forecasted pressure distribution is applied at the model nodes in the reservoir region.

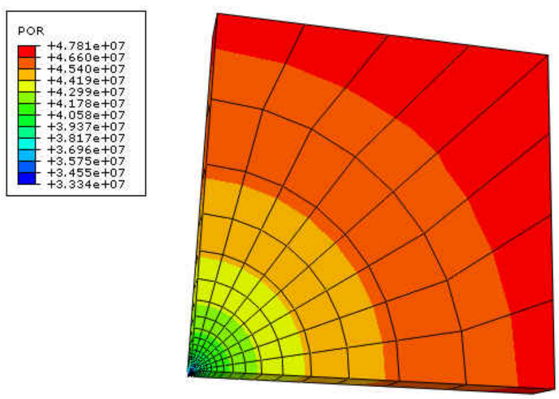

Figure 9. Pore pressure distribution on a model section (unit is Pa in the legend).

7. Application to a real case

In this paragraph we present the application of the proposed procedure to the study of a real case; the analysis of the obtained results will be also shown, with particular focus on the sensitivity cases performed on the parameters controlling the interface behavior.

The application refers to a hydrocarbon oil field hosted in three carbonate rock units of different age (Chrono Stratigraphic Units, CSU); the overburden rock included in the model is instead constituted by two different formations, i.e. shales on the top of the reservoir and salt in the shallower layers. The vertical extent of the model is about 700 m; 102 reservoir layers and 96 overburden layers have been used to discretize the model, while 34 and 32 elements have been used in the radial and hoop direction respectively. Totally, the model (one quarter of the geometry, see Figure 3) results in 80784 elements and 106138 nodes, corresponding to 312843 degrees of freedom.

Regarding the overburden rock, the analysis of the available data proved suitable the application of the “Mohr Coulomb plasticity model”, as defined in the Abaqus simulator; then, the relevant properties have been assigned defining two macro-regions identified as the salt layers and the shale layers.

As far as the reservoir rock is concerned, the behavior of each reservoir CSU is assigned as elastic perfectly plastic, based on the processing of the available rock mechanics laboratory tests. Before yielding, the behavior is assumed linear elastic; the properties E and ν are assigned, layer by layer, as a function of the initial void ratio e. In order to characterize the behavior at failure, the Hoek & Brown strength criterion has been used in an extended formulation, where the strength properties (index m and unconfined compressive strength C_0) are made functions of the initial void ratio e for every CSU:

$$\sigma_1{}^f = \sigma_3 + C_0(e)\sqrt{m(e)\frac{\sigma_3}{C_0} + 1} \qquad (2)$$

The 3D failure envelope for the formation CSU3, compared against the experimental results, is shown, as an example, in Figure 10.

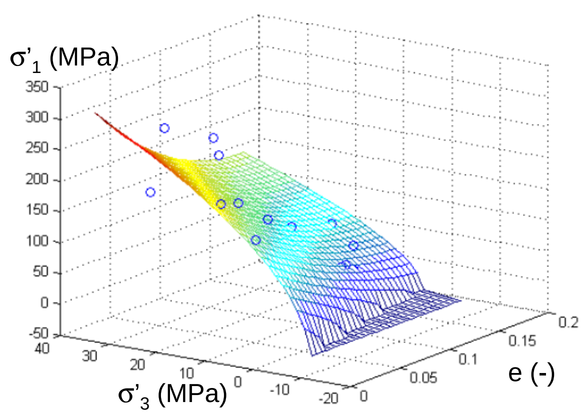

Figure 10. ‘Extended Hoek & Brown’ failure criterion for the CSU3.

The expressions used to calculate all the parameters are here summarized in Table 1; different formulas relate to the 3 CSUs, and different values are then derived for each of the 102 layers as a function of the initial porosity.

Table 1. Geomechanical properties as function of porosity and CSU.

CSU	E (GPa)	ν	C_0 (MPa)	m
1	$-12.759-17.042\ \ln\frac{e}{1+e}$	0.22	$23.695-14.144\ \ln e$	$7.565-1.1974\ \ln e$
2	$38.933-4.907\ \ln\frac{e}{1+e}$	0.25	$4.7004-14.943\ \ln e$	$0.1361-2.3908\ \ln e$
3	$-22.914-24.527\ \ln\frac{e}{1+e}$	0.32	$-15.303-33.518\ \ln e$	$5.1775-1.792\ \ln e$

It should be pointed out that the Hoek & Brown criterion is not straightforwardly implemented in Abaqus. Then, in order to obtain a non-linear failure envelope, the criterion has been defined in the FE code by using the already implemented Mohr-Coulomb law combined with a fortran user subroutine; in particular, a user defined field corresponding to the variable σ'_3 (minimum principal effective stress) is defined with the subroutine "USDFLD" and the Mohr-Coulomb parameters (cohesion and friction angle) are assigned as a function of the so-defined field.

With this method, Equation (2) has been linearized so that, as a function of the failure shear stress τ^f and the normal stress σ'_n, it can be written as:

$$\tau^f = c(\sigma'_3) + \sigma'_n \tan[\phi(\sigma'_3)] \quad (3)$$

where the cohesion c and friction angle ϕ are given in a tabular form as a function of the minimum effective principal stress σ'_3. The following lines are then inserted in the material definition of the Abaqus input file:

```
*Mohr Coulomb, Dep=1
*Include, input=fri001.dat
*Mohr Coulomb hardening, Dep=1
*Include, input=coh001.dat
*User defined field
*Depvar
 1
```

where the include files, one for each layer, contain the tabular values of the relevant property.

In order to study the mechanical actions induced by the production on the well completion system, a set of simulation scenarios has been selected with the aim of investigating the influence of the interface behavior (rock/cement and cement/casing), representing one of the most uncertain inputs to the model. The property values defining the frictional behavior (see §4.2) have then been considered as sensitivity parameters: Table 2 summarizes the scenarios investigated for the reference development well.

Table 2. Simulation scenarios; (r-c) and (c-c) indicate the interface rock/cement and cement/casing respectively.

CASE	μ (r-c)	μ (c-c)	τ_{max} (r-c) kPa	τ_{max} (c-c) kPa
Base	0.5	0.3	200	20
S-A	0.05	0.03	200	20
S-B	0.5	0.3	20	2
S-C	0.5	0.3	--	--

7.1 Result analysis

The results obtained with the FE simulations are shown in this section with particular focus on the influence of the interface behaviour on the actions transmitted by the reservoir compaction on the well completion.

In order to have a proper representation of the complete state of stress, the two invariants *p* and *q*, representing the mean isotropic stress and the deviatoric (Mises) stress, have been considered. They are reported, for the casing and the cement, in Figure 11 and Figure 12; the plots refer to the final step of the simulations (corresponding to the end of the reservoir life after 42 years of production) that represent the worst stress condition for all materials.

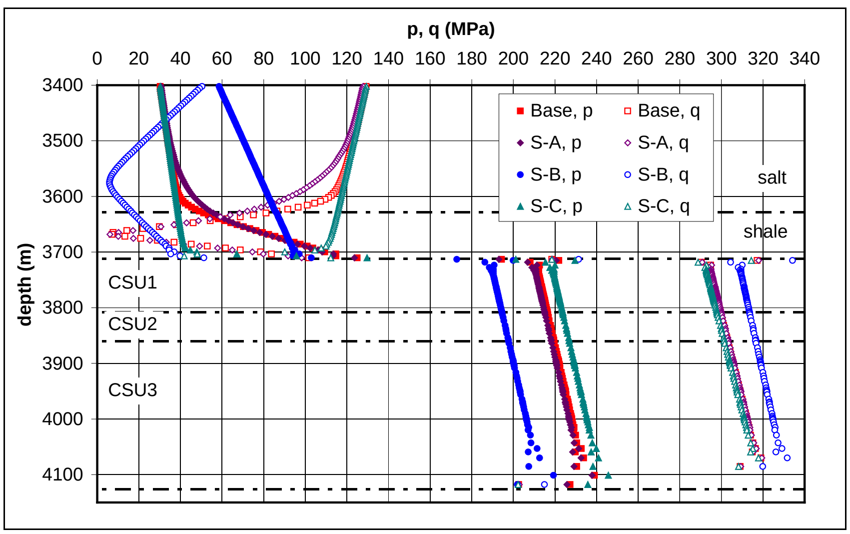

Figure 11. Mean and deviatoric stresses on the casing at the end of the production. Base case and the sensitivity cases.

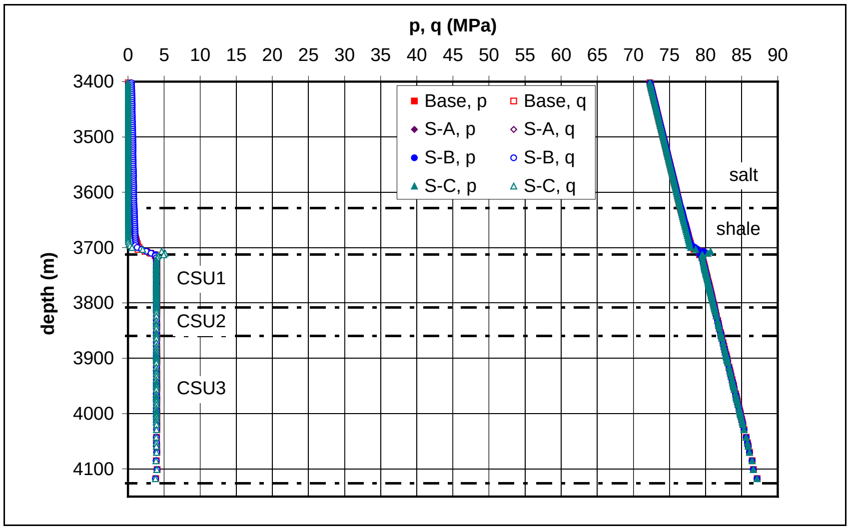

Figure 12. Mean and deviatoric stresses on the cement at the end of the production. Base case and the sensitivity cases.

The analysis of the results obtained in terms of stresses acting on the well system for the different sensitivity cases shows that:

- A reduction, albeit significant, in the friction coefficient (case S-A) does not affect strongly the results: the stress acting on the casing is slightly reduced in the producing layers, but propagates at shallower depths.
- A reduction in the maximum shear stress bearable at the interfaces (case S-B) determines, for the casing, a reduction of the mean stress in the reservoir sections and an increase in the overburden sections, which is explained with the less load transferred by the compacting reservoir; an opposite trend is obtained for the deviatoric stress.
- When there is no limit in the maximum shear stress bearable at the interfaces (S-C) higher load is transferred on the well sections while very limited part is transferred towards the overburden sections.
- Very small influence of the sensitivity parameters is revealed on the cement sheet.

For the case in study, the calculations show that no plastic strain develops either in the casing or in the cement, meaning that no yielding or failure is reached in the completion material for any of the cases considered; however, in order to have a representation of the "distance" from the failure conditions, the calculated stress evolution has been compared with the failure surfaces. With reference to the Base case, the stress path in the *p:q* plane is represented in Figure 13 for the casing material at specific depths; every point of a curve is a simulation step (3 completion steps and 6 production steps). In order to visualize the stress conditions with reference to the yielding surface, a path (the one showing the bigger deviatoric range) is plotted in Figure 14 in the $\sigma_1:\sigma_2:\sigma_3$ (principal stresses) space together with the yielding surface adopted for the steel elements.

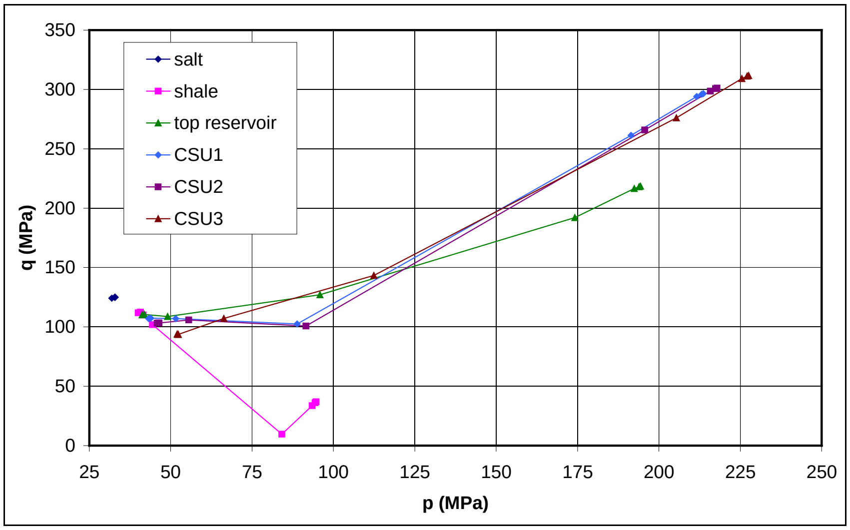

Figure 13. Stress path for the steel elements at selected depths.

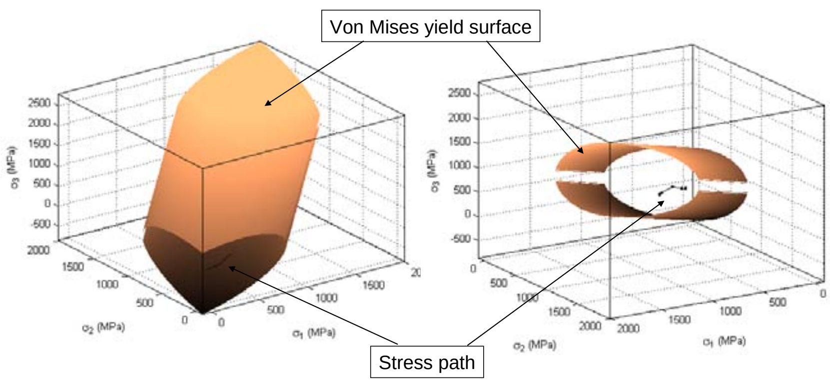

Figure 14. Stress path for the steel elements at a reference depth and von Mises yield surface.

The above figure shows qualitatively that, even for one of the most loaded casing sections, the stress state lies well inside the yielding surface.

In Figure 15 the stress path followed by the cement elements in the same sections is shown in the *p:q* plane. In the same figure, the Mohr-Coulomb failure envelope relevant for the cement material is also reported, showing that the cement, which is subjected to high hydrostatic pressure, remains in elastic conditions far from failure.

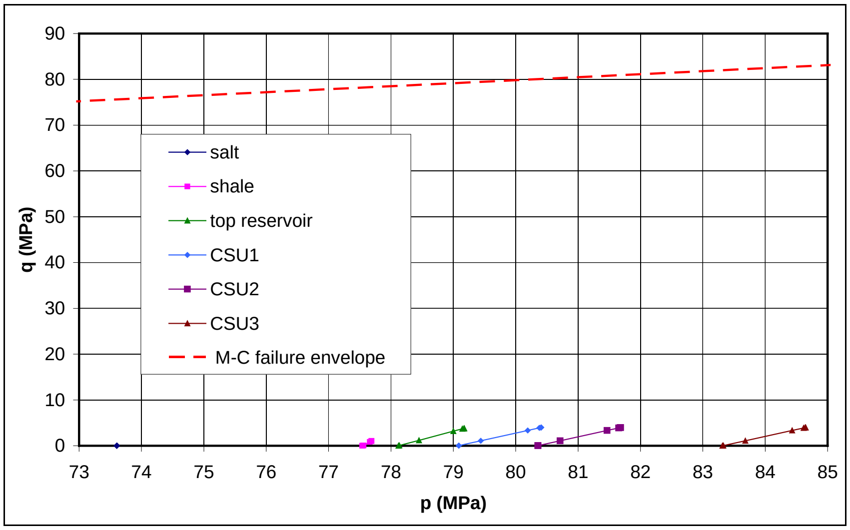

Figure 15. Stress path for the cement elements at selected depths.

The interface behaviour has been further investigated by analyzing the shear stress and the slip developing along the contacts.

The slip occurring at the end of the simulation at the interfaces rock/cement and cement/casing is plotted in Figure 16 with reference to the Base case.

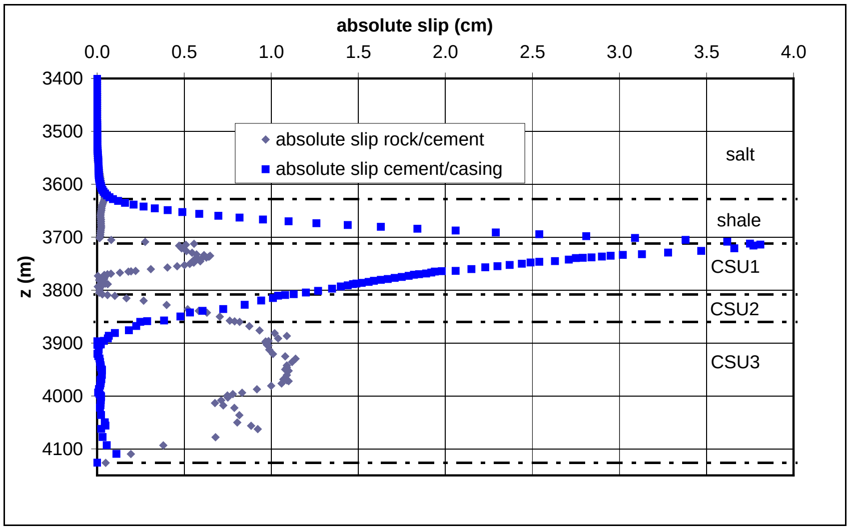

Figure 16. Slip calculated at the end of the simulation between the two interfaces as a function of depth (Base case).

It can be noted that the slip is concentrated in correspondence with the reservoir layers as far as the interface rock/cement is concerned, while it mainly develops at the bottom of the overburden and at the top of the reservoir for the interface cement/casing; higher values are reached at the interface cement/casing, according to the lower friction imposed between the two materials. These high values roughly correspond to the depths where the maximum bearable shear stress is reached, as evident from the analysis of Figure 17.

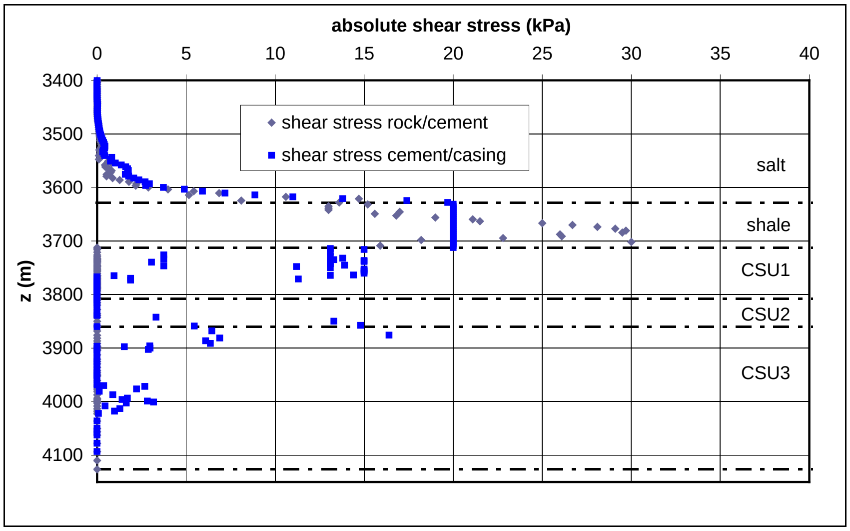

Figure 17. Shear stress calculated at the end of the simulation between the two interfaces as a function of depth (Base case).

8. Conclusions and further developments

The workflow presented in this paper has been developed with the aim of evaluating the entity of the mechanical actions induced by the reservoir production on the well completion, in order to evaluate the well integrity long-term.

The construction of the Abaqus finite element model includes contact interfaces between couples of different materials (rock/cement and cement/steel) that control the stress exchange and, as a consequence, the load that the various structural parts bear in the course of the well life. The developed workflow was successfully applied to a case of industrial interest; here, however, the stiffness of the reservoir rock prevented that high load be transmitted on the completion elements even in the most pessimistic sensitivity case considered, where large friction was supposed to act at the interfaces. In the application case illustrated, the maximum stress calculated on the most slender structures (namely the casing in the reservoir layers, corresponding to the smaller section) was far smaller than the critical load as calculated with the analytical buckling theory; further development of the procedure will include a numerical buckling analysis, to be used in all applications where the reservoir rock evidences significant compressibility.

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10. Acknowledgements

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