FEA Modelling of Expandable Sand Screens Interactions with Rock Formations

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Abstract: Expandable sand screens are a sand control system, which is used to control the ingress of solids in oil and gas reservoirs with weak and unconsolidated formations. There are two different variations of expandable screens; a system based on a slotted basepipe which are easy to expand compliant to the formation but is relatively low in strength and a system based on a drilled basepipe which is very strong but is more difficult to expand compliantly.

FEA has been used to model the slotted basepipe type to better understand the interaction of the expanded screen with the rock formations. Initially the entire structure of the screen was modelled and the results compared to physical test data. The simulations fitted the test data very well, with run times of the order of a few hours depending on details of the simulation. The full simulations were adequate for research purposes but for routine screening of applications the models were simplified. An equivalent representation of the screen was developed to match the gross behaviour of the screen in terms of stiffness and yield. This approach was very computationally efficient and allowed rapid investigation of formation screen interactions.

The model was used to study the effects of formation screen interactions in inclined wellbores, through multiple rock layers. The model is also routinely used to study new applications for potential problems.

Keywords: include Geomechanics, Soil-Structure Interaction and Wellbore

1. Introduction

Expandable sand screens (ESS™) are a relatively new sand control product with approximately 800 installations worldwide over all vendors. They come in 2 different types; either a system based on a slotted basepipe or a system based on a drilled basepipe. The slotted basepipe system is the most common, with around 600 installations since 1997. The advantage of the slotted basepipe system is that it is relatively easy to expand into full contact with a wellbore which typically varies in shape and diameter, to give a truly compliant system. This has advantages both in well productivity, sand retention capability and reliability (Hembling et al 2008). The drilled basepipe

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system on the other hand is more difficult to expand especially in an irregular wellbore, however it is stronger.

Initially the relatively low strength of the slotted basepipe expandable sand screen was a concern. However initial testing with small scale systems showed that the ESS greatly strengthened the wellbore. The question then arose as to how the full size ESS would react. To address this a joint industry project (JIP) was undertaken. This study measured the deformation of a full sized ESS in a wellbore in weak sands and sandstones. The experiments were performed in a large pressure vessel or poly-axial cells which could recreate the high stresses experienced in a downhole situation. The results of these tests showed that for any reasonable reservoir material there was very little deformation of the ESS. The only situation where large deformations were experienced were for very low friction angle shales.

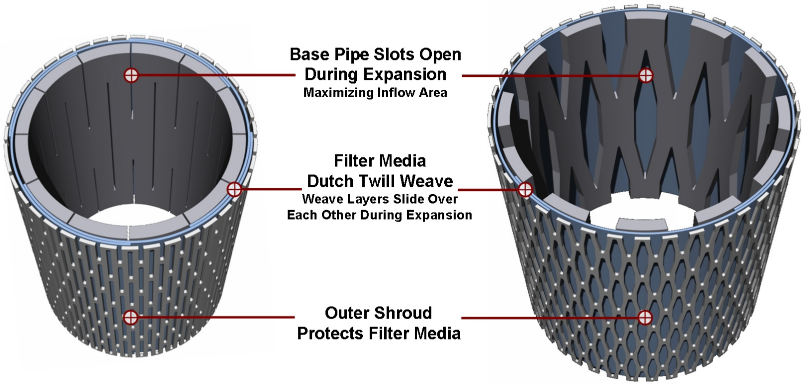

Figure 1 Details of the construction of the ESS

Simple analytical models of the ESS were also developed (Abbassian et al 2002, Jones et al 2005) which could be used as design tools. The JIP tests were also used to calibrate and verify the simple models. FEA models were also used to analyze the results of the JIP tests and for application qualification (Willson et al 2002). One important result of early FEA modeling was that the deformation measured in the geometry of the JIP tests was likely to over estimate that found in the field situation for the same rock material and stress change.

Weatherford analyzes every openhole ESS installation to determine how much deformation will take place during the projected life of the installation. This requires a knowledge of the downhole stress conditions, the formation strength and the projected production history of the well. Initially a simple analytical model was used (Jones et al 2005). Recently FEA has been used for this analysis (Jones and Watson 2008). The FEA model allows more complex formation screen interactions to be analyzed. This work details the development of a simplified equivalent ESS model and its use in determining the deformation of the ESS in an inclined wellbore in a sand shale sequence with varying thicknesses of weak shale.

2. Development and Qualification of an Equivalent ESS Model.

The ESS is constructed in 3 parts (Figure 1), a slotted basepipe, a Dutch twill filtration weave and a high open area outer shroud. The slotted basepipe contributes most of the strength of the ESS, it is normally made from 316L stainless steel and slotted using a high pressure garnet/water jet. The filtration weave is again made of 316L and is designed to retain the formation sand, it does not have a significant contribution to the strength of the system and is neglected in the analysis. The outer shroud is punched from a flat sheet of 316L, it is 1.5mm thick and has a significant contribution to the strength of the system.

FEA models of the ESS have been built over the last couple of years (Jones & Watson 2008). These have successfully modeled the behavior of the ESS in a wide variety of loading conditions and are used extensively as a design tool. In a typical model the slotted basepipe may have around 33,000 elements and the shroud 100,000 elements C3D8R. Figure 2 shows the complexity of the meshing on the shroud. Simulating the expansion of the ESS and subsequent loading to collapse can take several hours on a powerful quad core desktop. This is more than adequate for a design tool but is rather slow for an analysis tool for screening multiple application scenarios. Also there is a need for the analysis to be done quickly on a laptop in remote locations around the world.

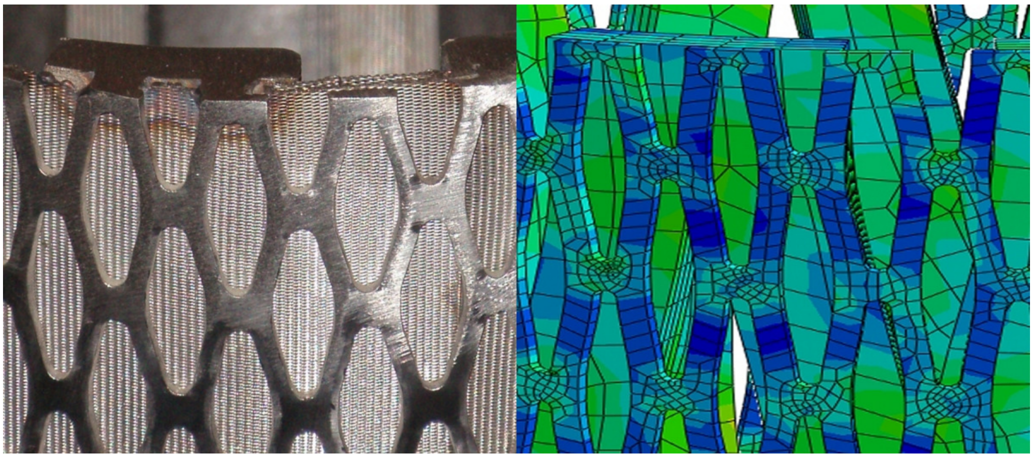

Figure 2 Details of ESS Construction Showing Complexity of the Meshing on the shroud

A simple representation of the ESS was developed. The equivalent ESS consisted of a plain pipe with the ID/OD dimensions of the expanded ESS. In the case of the 5 ½" ESS the OD was 8 ½" and the ID was 7.984. The Elastic and plastic properties of the material were adjusted to fit the hydraulic collapse data and FEA models of the whole slotted system. The results of the fit were very good and are shown in Figure 3.

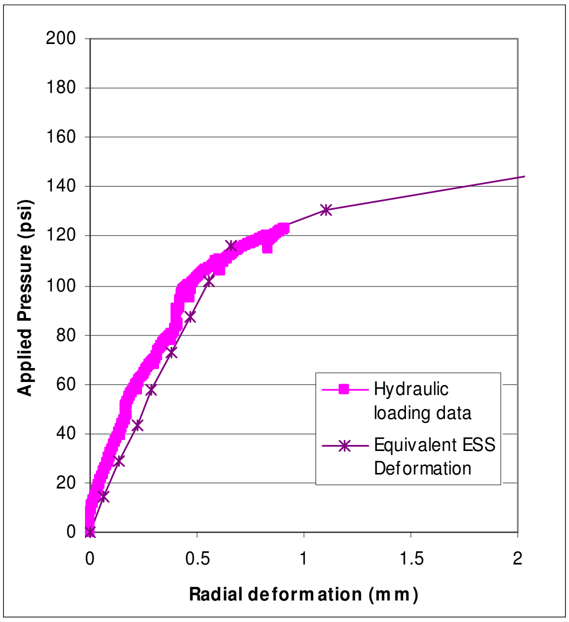

Figure 3 Comparison between the measured deformation, the full scale simulation and the equivalent simulation.

To further test the veracity of the equivalent ESS approach, a model was built to simulate some large scale testing of the ESS in a thick walled cylinder (TWC) of rock. In this testing a section of 5 ½" ESS was expanded into contact with the inner bore of the TWC of weak sandstone. The expansion was performed with the TWC installed in a large pressure vessel. The large stresses were applied to the outside and end surfaces of the TWC to simulate deep burial in the earth. The vessel is able to apply stresses which simulate burial to between 15000 and 20000ft. The applied stresses caused failure of the weak sandstone initially at the wellbore, then progressively through the entire section of the TWC. The failed rock pushed on the ESS causing deformation. The deformation experience by the ESS is shown in Figure 4 on two perpendicular axes. The deformation starts at around 500psi applied external pressure and accelerates rapidly, attaining 1" deformation at 3000psi. The FEA gives a very good fit to the experimental data.

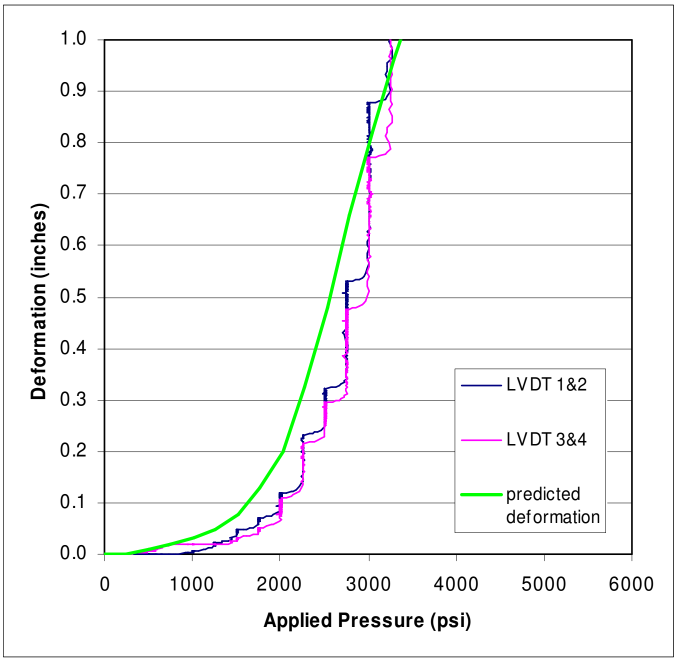

Figure 4 Deformation of 5 1/2" ESS in a large cylinder of weak sandstone, with prediction using the equivalent ESS model.

3. Oilwell lifecycle and re-circularization

The next stage of the project was to analyze the deformation of the ESS through-out the entire lifecycle of the well. When a hole is drilled through a rock at depth, the removal of the material causes a concentration of stress in the formations close to the wellbore. Basically the rock material close to the wellbore has to carry the stresses which were carried by the material which has been drilled out. Elastic solutions exist to quantify the stresses around the hole. They show that the stresses can be very large and will cause some failure of the near wellbore formations especially if they are weak. The hole is drilled by a drillbit which is flushed by a drilling fluid which is designed to have a static pressure greater than the reservoir pressure. The drilling fluid has a complex design and performs many functions. It keeps the hydrocarbons in place in the reservoir, lifts rock cuttings to the surface and stabilizes weak formations.

When the drillbit drills past a given weak formation there is some rock failure and relaxation of stress. This causes the wellbore wall to move into the centre of the wellbore slightly to give a "tight hole". This extra material is either reamed off immediately by gauge cutters on the bit or is reamed later. In any event the drillbit must remove the displaced material to be able to be withdrawn from the hole.

In these FEA simulations of the drilling process, the starting point is a block of rock with a hole. The initial stresses and mud over balance are applied. This causes some movement of the wellbore wall. If the rocks are very weak the movement can be very large. In the modeling the hole must be re-circularized so as to physically represent the finished drilling process.

This was done by having two separate models. The first model was loaded to produce the stressed and deformed state. The second model, essentially a copy of the first, then has the solution from the first model mapped over it, i.e. it is undeformed but already in the loaded/stressed state. This used the keyword *map solution. The second model then carries on with further loading steps. This process led to the desired circular wellbore at the end of the initial loading stage. However, due to a small degree of artificial strain whilst mapping the first model solution onto the second undeformed model, there was a small change in the von mises stress output values, typically 5%. The slight changes were considered acceptable as the benefits of attaining the desired re-circularized wellbore far outweighed the minor inconsistency that was observed. The map solution method is not directly executable within CAE, it needs to be done using the Keywords Editor. The models are executed from the command line. The method for performing the recircularisation is detailed in the appendix.

Once the wellbore has been re-circularized the next stage is to simulate the production of fluids from the formations. The production of fluids impacts on rock failure by the effects of depletion and drawdown. Depletion is the gradual reduction of fluid pressure in the reservoir caused by the removal of the hydrocarbon fluids. Drawdown is a pressure difference between the reservoir and the wellbore which causes the fluids to flow from the reservoir into the wellbore.

4. Vertical-Horizontal Well Application Screening Tool

One of the aims of the modeling was to provide a tool for screening potential applications for excessive deformation. Excessive formation induced deformation of the ESS is undesirable because it restricts access to the well and might cause a loss of sand control. Extensive testing in the joint industry project showed that the ESS could withstand large deformations without collapsing or losing the ability to control the sand. A limit of 20% deformation was set based on the results of the testing. The 20% value includes a large safety factor.

Models were built for an actual application. The well parameters are shown below in Table 1. The material properties are shown in Table 2 in the sandstone column. The sandstone material properties came from a suite of triaxial tests done on actual core. This sandstone is very weak

Figure 5 shows the results of simulation done as part of the application screening process for this well, plotted as deformation during the life cycle of the well. The four parts of the well life cycle are shown. Firstly the initial stresses are applied to the rock mass containing the wellbore, and then the mud overbalance is removed. At this point the well can start to flow. The pore pressure reduces due to depletion and there will be some drawdown.

Two different types of simulations were performed, in each case C3d8RP pore pressure elements were used. The lower curve shows the deformation for a non re-circularized wellbore. After the initial stresses are applied there is a 1.5mm reduction in ESS ID. For the re-circularized hole the deformation is zero. When the mud over balance is removed the near wellbore formations weaken

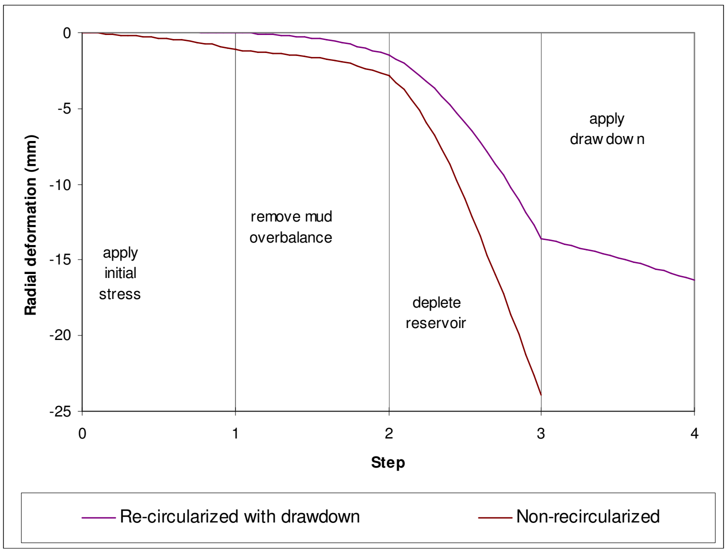

Figure 5 Deformation of the wellbore with and without re-circulatization

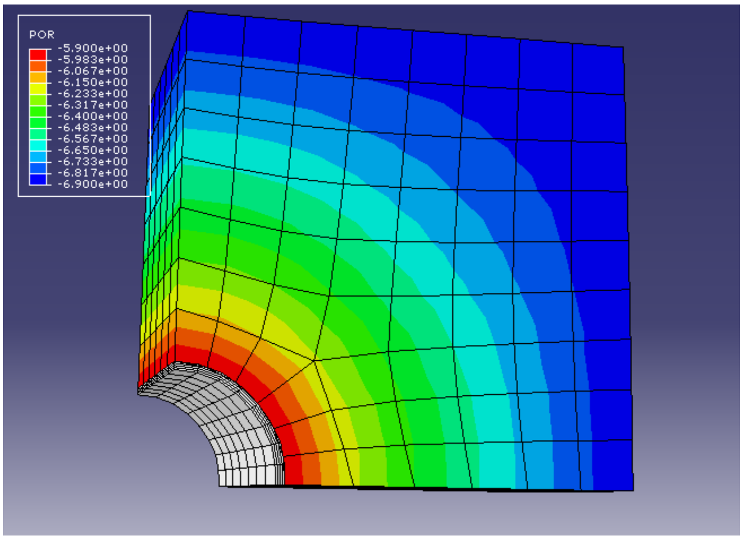

Figure 6 Quarter symmetry model used in the simulations

and load the ESS. During depletion from an initial pore pressure of 19.2MPa to a pore pressure of 6.9Mpa the change in effective stress causes further deformation. At the end of the depletion the ESS in the non re-circularized simulation has deformed by around 25% which is out with limits. The re-circularized wellbore has deformed by 14% which is well with the limits. Even when an additional 1MPa drawdown is applied to the rock the deformation is still with in the limit at 18%.

Figure 6 shows the simple quarter symmetry model used in the simulations. Plotted on the model is pore pressure. A pore pressure boundary condition was set on the outside of the model and a lower pressure boundary condition at the wellbore. This causes some fluid flow to take place.

The quarter symmetry model used here was very simple. More complexity could be added to represent more accurately the complex processes which take place in the downhole environment.

Depth	1900m
Vertical Stress	35MPa
Horizontal stress	32MPa
Initial reservoir pressure	19.2MPa
Mud overbalance	3.5MPa

Table 1Well parameters

Rock	Sandstone	Shale
Density	2500kg/m3	2500kg/m3
Young's Modulus	2069MPa	1379MPa
Poisson's Ratio	0.16	0.16
Friction Angle	20 degrees	13 degrees
Dilatancy Angle	0 degrees	0 degrees

Table 2 Material properties of the sandstone and shale used in the simulations

5. Inclined Wellbore in a Sand Shale Sequence

The modeling shown in the previous section shows how the ESS deforms in a well in a single rock type in either a horizontal or vertical well. Actual wells are much more complex. They can be inclined at any angle and normally more than one rock type is present. To address these issues an inclined wellbore model with multiple layers was developed. This was used to address the effects of inclination, interfaces between different rocks and different rock types.

One of the rock types chosen to investigate was a weak shale. Shales are the most common rock type encountered in oil and gas well drilling, accounting for roughly 60% of drilled footage. Exact definitions of what a shale is varies, but they are typically very fine grain <4 microns with very low permeability, they have a high percentage of clay minerals such as montmorillonite and illite, they are fissile and weak with low friction angles. Mechanically, shales are very complex, they are highly anisotropic, they tend to exhibit creep, and due to their low permeability pore pressure equilibrium takes a very long time. As a consequence of this, deformation tends to be undrained.

In drilling they are responsible for the majority of hole stability problems. For the ESS there is evidence that shales are responsible for large deformations both in laboratory testing and in the field.

Figure 7 shows the setup of the block. The block dimensions were 5m x 5m by 3m deep. The block was partitioned to allow for finer meshing closer to the wellbore (Figure 8). The block was also in 3 sections to which different material properties were assigned. The central section was further split into 5 sections. This allowed shale layers from 0.2m to 3m to be modeled.

Three sets of simulations were run. A bare 8 ½” wellbore with 0.2 – 1 m layers of shale. A 8 ½” wellbore with a 5 ½” ESS installed expanded out to 8 ½” OD and the same wellbore with a 7” ESS installed expanded out to 8 ½” OD. The material properties are shown in Table 2. The stresses used are shown in Table 1. In each case effective stresses were used, no permeability effects were used; this may over-estimate the deformation in the shale. The shale used in the simulations was also very weak with a very low friction angle.

The modeling and analysis shows several interesting effects. Figure 9 shows a close-up of the central shale layer. For the base wellbore there is much more deformation in the shale than the sand on either side, this is a function of the higher friction angle in the sand even although the cohesion of the sand is lower. The sand appears to support or restrain the shale at the interface, so that the deformation of the shale is less close to the sand. Figure 10 shows the deformation of the central shale as a function of shale layer thickness. The deformation decreases as the shale layer becomes thinner due to the support from the surrounding sand.

Figure 11 shows the deformation of the bare wellbore, the wellbore supported by a 5 ½” ESS and finally the wellbore supported by the stronger 7” ESS. The results show that the 5 ½” ESS can barely cope with the loading by the shale in that it is over the 20% limit for longer shale sections but the stronger 7” undergoes much less deformation. In this case the stronger 7” ESS would be the system of choice for the conditions in this well.

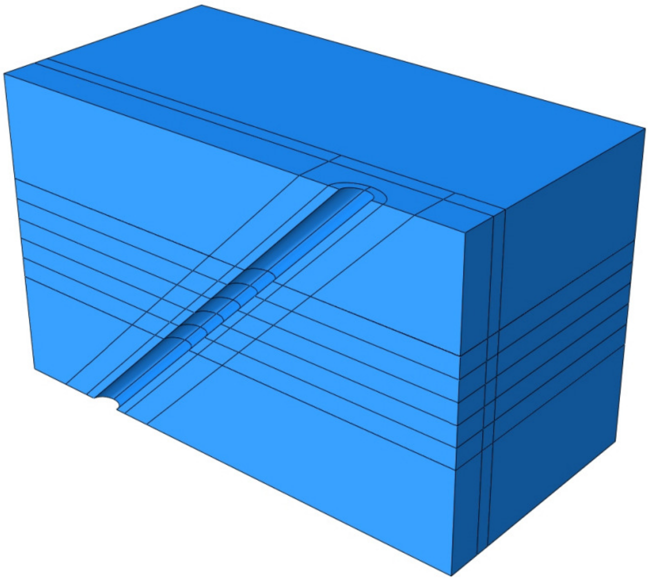

Figure 7 Inclined wellbore in a 5m x 5m x 3m block.

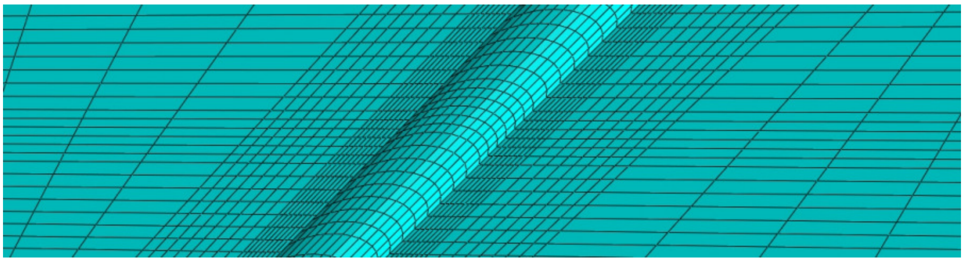

Figure 8 Detail of applied mesh around centre of block

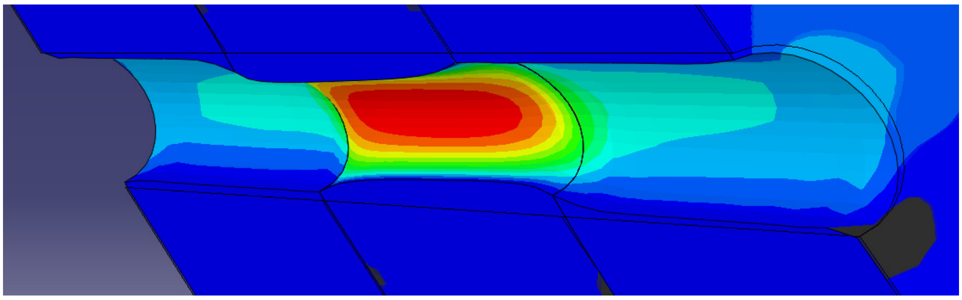

Figure 9 Details of the deformation in the Sandstone and the Shale

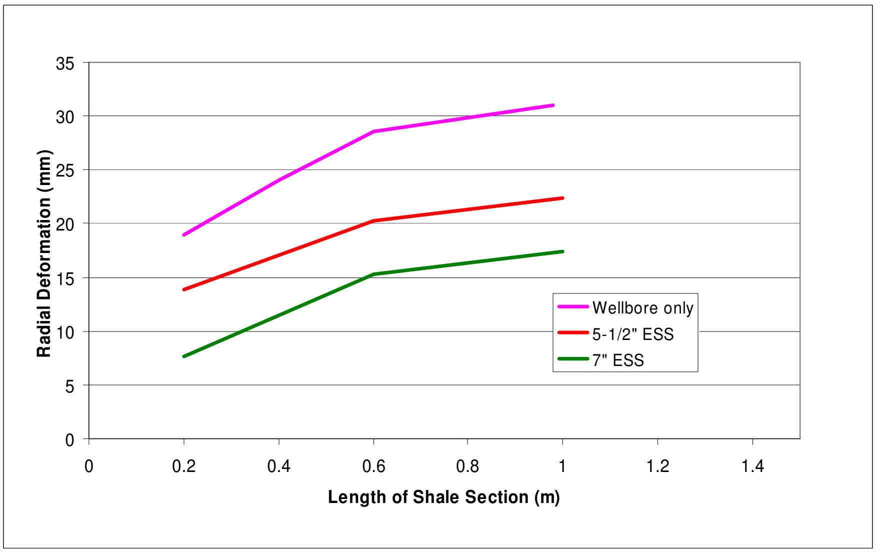

Figure 10 Deformation in the central shale as a function of shale layer thickness.

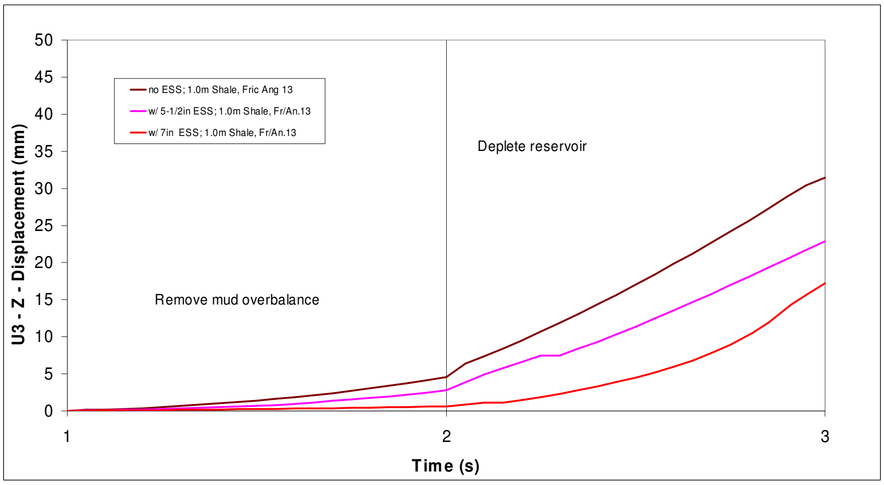

Figure 11 45 Degree Wellbore in a 5m (w) x 5m (d) x 3m (h) Block of Weak Sandstone at Top and Bottom with a Varying thickness of Weak Shale in Middle

Figure 11 graphically shows the different deformations by both thickness of middle shale section and then the addition of 5-1/2" and 7" ESS. The two thicknesses of shale are 0.2m and 1.0m. The original 8.5" OD wellbore profile is highlighted in the four images.

0.2m shale section	deformation 18mm (radially)	17% deformation
1m shale section	deformation 32mm (radially)	29% deformation
1m shale with 5-1/2" ESS	deformation 22.9mm (radially)	21% deformation
1m shale with 7" ESS	deformation 17.2mm (radially)	16% deformation

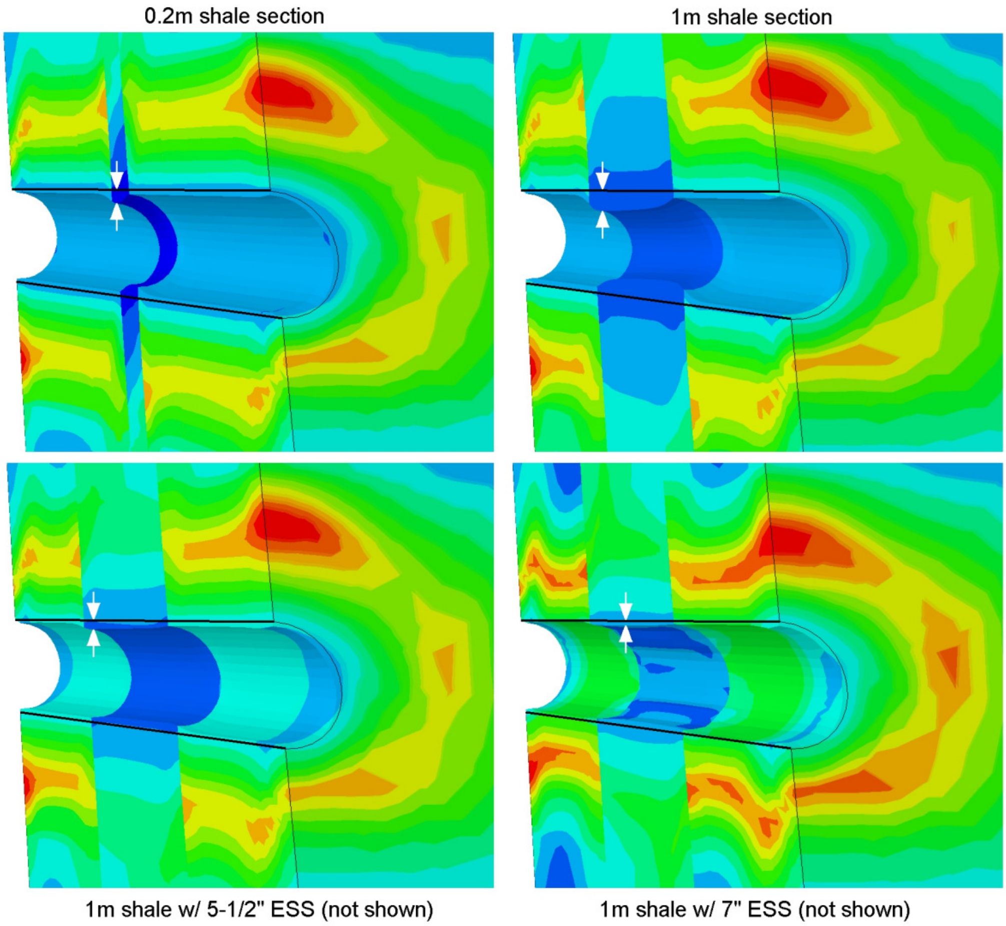

Figure 11 Varying thickness of Weak Shale (top two images)
and the addition of 5-1/2" ESS (bottom left) and 7" ESS (bottom right).

6. Conclusions

Abaqus is now used extensively within Weatherford as a design tool, as an application screening tool and as a research tool. Full scale simulations of the ESS are routinely performed, primarily for the purpose of product enhancement. These simulations are relatively time consuming due to the complexity of the structure and the number of mesh elements needed to describe it adequately. A simplified representation of the ESS was developed to use in a rapid application screening tool. This provides results very rapidly. The simulations fit the available experimental data. The screening tool is currently being used to screen future applications.

The equivalent ESS representation has also been used to model more complex well architectures such as an inclined well crossing multiple layers. This model shows many interesting features and has answered such questions as what happens at sand shale interfaces and how does the deformation vary with shale layer thickness.

7. References

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8. Appendix

<u>A brief guide for Mapping a solution from a deformed Model onto an undeformed Model</u>

<u>Model Creation;</u>

Create a model (call it ***middle***) with all the parts and steps that are required in the whole process. Within the first two steps, initial and first-loading, all the parts/faces require encastred; this will stop any unwanted movement at the mapping stage. This encastre then needs to be made inactive in the later steps.

In the Keywords editor (not available in CAE), the phrase **`*map solution, step=1`** needs to be added immediately before the first STEP.

Copy the model ***middle***, save as ***start***.

Within ***start*** , the later steps can be deleted, it is just the initial and first-loading steps that are required.

Also within ***start*** , delete the map solution line that was added by the keywords editor in ***middle***.

Remove the encastre boundary conditions to allow the necessary movement when loads are applied.

A restart request has to be made for the end of the step. This writes an mdl file, which is (apparently) required later during the DOS prompt analysis run.

<u>Job Creation;</u>

A job is run for the ***start*** model. This produces the desired stress state and has a deformed wellbore.

For the ***middle*** model, a job is created but not run; a write input is performed to generate an input deck

This ***middle***.inp is saved as ***final***.inp (either from DOS or Win.Explorer)

<u>Job Execution;</u>

The DOS prompt command line is then used to facilitate communication between input decks; abaqus job=***final*** oldjob=***start*** (other commands can also be added, such as cpus=4 double ... etc).

<u>Job Analysis;</u>

Within CAE, a new job is created (***final***), but the source is an input file, ***final***.inp

This allows the user to view the results for ***final*** as usual.

At the end of the first-loading step in ***final***, the wellbore should still be undeformed and it is worth checking that the stresses at the end of this first step in ***final*** do indeed match those at the end of the job ***start***, as that is what should have been carried out by the instructions above!