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Formation Loading and Deformation of Expandable Sand Screens.

Colin Jones, Ken Watson and Quentin Morgan, Weatherford

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Abstract

The slotted version of Expandable Sand Screens (ESS) is easy to expand into compliant contact with the wellbore. This has numerous advantages in sand retention, completion reliability and the maintenance of high productivity. However, the use of a slotted base pipe design will limit mechanical strength.

A joint industry project was undertaken under the auspices of the Production Engineering Association. PEA 182 studied the effect on the ESS of loading at high stress in rocks of various cohesions and friction angles. The project showed that the ESS could withstand any conceivable combination of drawdown and depletion and stay within its design limits except in rocks with a very low friction angle, where excessive deformation was possible.

To ensure against use of the technology in an unsuitable formation, every proposed application is screened using either an analytical or FEA geomechanical model. The results of the PEA 182 tests were used to test the veracity of the FEA methodology. An excellent fit to the experimental data was achieved, both for unconsolidated sands and weak sandstones.

The FEA model of the ESS formation interaction is very versatile and has been used to study a number of different scenarios, such as the effect of sand/shale layers, non-compliance in washouts, solids production and time dependent effects in shales. The model uses the actual structure of the ESS. The first stage of the simulation is to expand the ESS. This ensures that the proper work hardening is included in the analysis. After expansion the mud overbalance is removed, then drawdown and depletion applied in the proper time scales.

The FEA results have also been compared to caliper data and compares reasonably well given the uncertainties in the stress field and the rock strength.

Introduction

The slotted version of the expandable sand screen (ESS) was developed in the late 1990s. It was developed to be an openhole sand control solution as an alternative to gravel packing or standalone screens (SAS). The ESS is deployed in conditioned mud or brine in much the same way as an SAS completion, and can be expanded in the same trip. Once expanded into contact with the borehole wall ESS provides compliant sand control in much the same way as a gravel pack.

The ESS has been successful in a wide range of applications, resulting in good sand control, a very low skin and high productivity. The key to achieving good performance and long term reliability is strict adherence to a “Ten Steps To Sand Control Success” methodology, which encompasses many due diligence aspects to achieve right-first-time deployment of fit-for-purpose sand control completions.

When considering use of ESS, foremost in the due diligence process is evaluation of the interaction of the ESS with the rock formations. Due to its slotted nature the ESS is relatively easy to expand, but it also has relatively low collapse strength. This has often led to concerns about whether the ESS can withstand the loading from the formations during depletions and drawdown. The work described in this paper details results from large scale testing and extensive numerical modeling, which show that under most circumstances the ESS can withstand the formation loading.

Testing

A wide range of tests have been conducted to determine the mechanical properties of ESS and to determine the overall operational envelop. Not all tests are relevant to ESS-formation interactions, such as axial tensile yield and tensile strength. Willson et al[1] describes a set of mechanical crush tests; both diametral compression and axial compression. Results from these tests were used to calibrate a finite element (FEA) model of the ESS construction, with the FEA model subsequently used to conduct ESS-formation interaction studies.

Additional tests were carried out to quantify torsional strength, jacket pull-off rating, hydraulic collapse, and burst strength. Numerous additional large scale triaxial thick wall cylinder tests were also performed to evaluate impact of formation loading. The hydraulic collapse and formation loading tests are described below.

Hydraulic Collapse Testing

Hydraulic collapse testing on all ESS sizes has been performed to determine the maximum pressure each size can withstand when completely plugged. This is not truly relevant to ESS-formation interactions, but it is a relatively simple test, with results used to verify modeling predictions.

The tests are performed in a pressure vessel using an ESS sample which has been deliberately and totally plugged. Several versions of the test exist which give broadly similar results. The ESS can be plugged by either surrounding it with an impermeable membrane, or by using a fluid loss pill to plug the weave. Tests conducted using a fluid loss pill corresponds to the ISO Screen Standard[2] used to quantify mechanical specifications of conventional well screens. However, the majority of the tests were conducted using membranes. In both test methods, pressure is applied by a constant rate positive displacement pump. Cell pressure is monitored and recorded throughout the test. The internal deformation of the ESS is measured using displacement transducers. Typical data is shown in Figure 1 for the 4 ½" ESS. The graph shows that the ESS deforms in a fairly linear fashion up to a peak. After the peak, the structure buckles and the load bearing capacity drops slowly. The hydraulic collapse rating of the 4 ½" ESS is 180psi. The hydraulic collapse ratings for all ESS sizes are shown in Table 1.

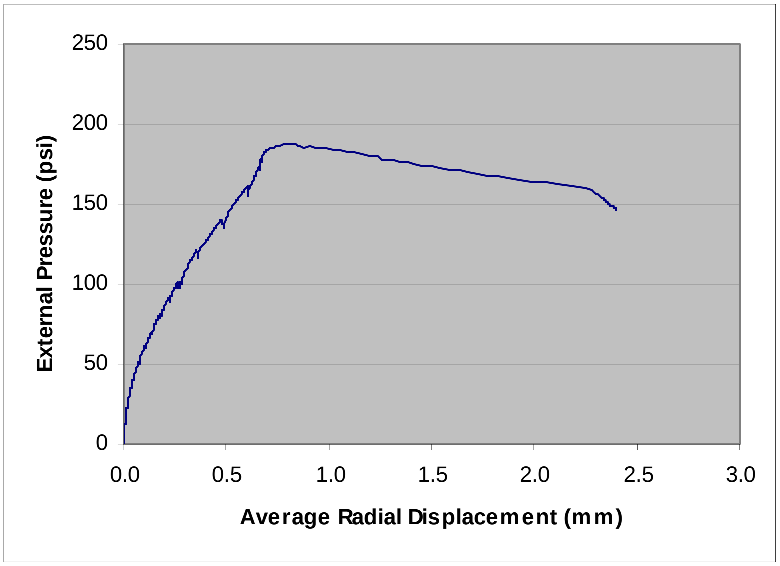

Figure 1: Data for hydraulic collapse of the 4 ½" ESS

ESS Size	Hydraulic Collapse Rating
4" 316L	170psi
4 ½" 316L	180psi
5 ½" 316L	123psi
7" 316L	350psi
7" 25Cr	460psi

Table 1: Hydraulic collapse ratings for current ESS systems

PEA 182 Tests

PEA[3] 182 was a joint industry project (JIP), designed to investigate the properties, including collapse resistance, of expandable sand screens, including Weatherford's slotted variety. The sponsors of the project were BHP, BP, Chevron, ExxonMobil, Norsk Hydro, Saudi Aramco, Shell, Total, Unocal and Weatherford. Eleven tests were performed, nine on ESS, one on an expandable sand screen featuring a pre-drilled basepipe, and one test on a conventional sand screen. Two types of test were performed on ESS; sand box (SB) and pressure vessel (PV) tests. In each experiment the ESS deformation was measured and video streams recorded from cameras placed in the bore of the ESS samples.

In the sand box tests an ESS sample (4" or 5 ½" expanded to 6" or 8 3/8") is embedded horizontally in an unconsolidated sand pack, with approximate dimensions 29"x29"x35". Stresses are applied vertically up to a maximum of 5,600psi, with up to 2,500 psi horizontal stresses generated by the flat jacks. A schematic is shown in Figure 2.

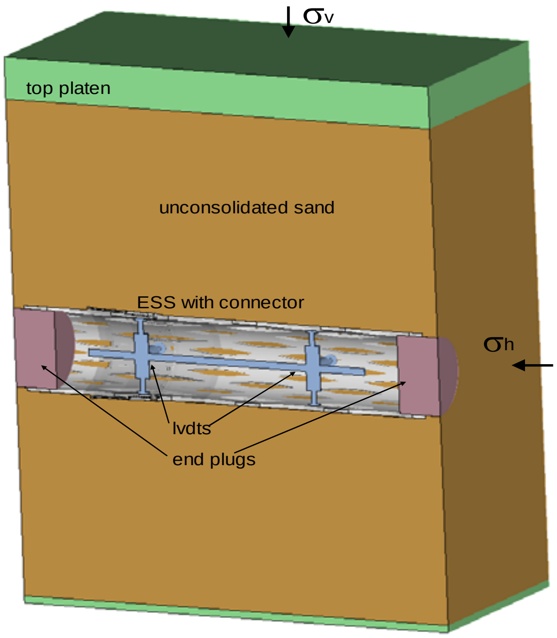

Figure 2: Schematic of the Sand Box test fixture

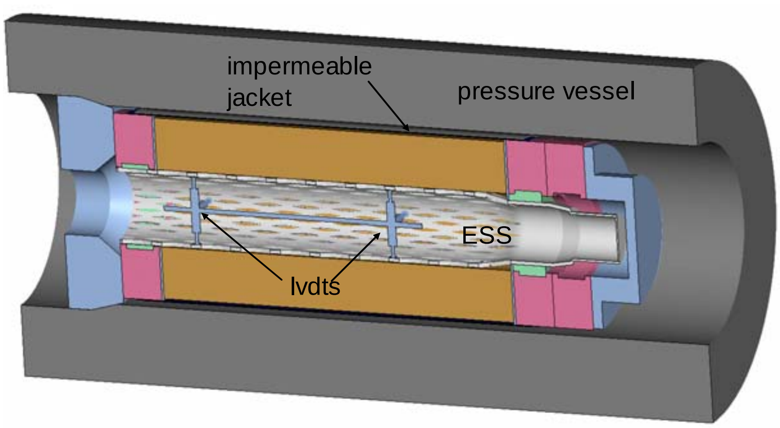

Figure 3: Schematic of Pressure Vessel test fixture

In the pressure vessel tests, large rock cores, 41" long by 19.5" OD, were bored to accommodate either 4" or 5 ½" ESS, creating large scale thick wall cylinders. The ESS samples were either expanded in-situ to either be compliant, or to leave an annulus of known dimensions, or were pre-expanded when an unconsolidated material was used. The stresses were applied using hydraulic pressure to the jacketed outside surface of the core and to the ends of the core. The core was then saturated to light oil, with the same oil also flowed through the core into the wellbore, during the application of the stresses. In most of the pressure vessel tests the maximum applied stress reached 10,000psi; the safe working limit of the PV. At this limit the ESS was deformed, but stable. A schematic of the PV setup is shown in Figure 3. A photograph of a partially disassembled sample is shown in Figure 6.

The nine tests were conducted on a variety of weak rocks and unconsolidated sands. The tests investigated the effect of an open annulus, bore hole breakouts and the interface between weak and strong rock materials. The materials used are shown in Table 2. The results of all the tests are summarised in Table 3.

Rock	Test	Properties	Comments
Unconsolidated 1 (UC1)	1,8	UCS=0, FA~30°	TerraTek standard U/C sand
Unconsolidated 2 (UC2)	7	UCS=0, FA high	Designed to be a high friction angle
Unconsolidated 3 (UC3)	6	UCS=0, FA low	Sand clay mixture 60/40 , low friction angle
Castlegate SS (CSS)	2,3,4,5	UCS=1500psi	Weak to medium strength sandstone
Saltwash South SS (SWSSS)	8, 11	UCS=400psi	Weak sandstone
Pierre Shale (PS)	6, 11	UCS=350psi, FA 0-34°	Surface shale

Table 2: Rocks used in the tests

Test	ESS Size	Test Type, Rock Type	Borehole	Maximum Stress (psi)	Maximum Deformation	Maximum Decrease in ID
1	5 ½" c/w connector	SB, UC1		5600	1.07"	15%
2	4"	PV, CSS	6.1"	9000	0.3"	6%
3	4"	PV, CSS	6.1" + 6.6"	10000	0.75"	15%
4	4"	PV, CSS	6.1" c/w Breakouts	10000	1.03"	21%
5	4" c/w connector	PV, CSS	6.1" + 6.6"	10000	0.95"	19%
6	4"	PV, PS,UC3	6.1"	3000	0.7" in UC3	14%
7	4" Incolloy	SB, UC2		1500	1"	20%
8	5 ½" (8.44" OD)	PV,SWSSS,UC1	8.73"	5000	2.5"	34%
11	7" 25Cr (8.6" OD)	PV, PS, SWSSS	8.7"	1600	2.5"	32%

Table 3: Summary of test results

Test 1 was conducted using a 5 ½" ESS sample with an expandable flow-through connector in the SB configuration. This test showed that the connector underwent slightly more deformation, but the effect was minimal. The maximum deformation on the body of the ESS after the stress was applied was 1.00", with the connector experiencing 1.07" maximum deformation. In test 2, involving deformation of 4" ESS in the PV, very little deformation was observed. Test 3 was a repeat of test 2, but with an out of gauge section, simulating a wash out extending beyond the expansion range of the ESS. This caused more deformation. Test 4 was conducted in a wellbore featuring breakouts. In a precursor to test 4, the rock sample was stressed in the PV to induce failure and create wellbore breakouts (Figure 4). The breakout occurred at 2,500psi confining pressure, equating to the strength of the unsupported wellbore. At this point the rock sample was in danger of total collapse. The ESS was then expanded compliantly into the curved sections of the broken wellbore, but not across the breakout, and the rock sample re-stressed. Confining pressure was increased to 10,000psi, with the ESS sample still stable and sand-tight. The borehole support provided by the ESS had thus conferred a fourfold increase in borehole strength. Test 5 was a repeat of test 3, but with an expandable flow-through connector present.

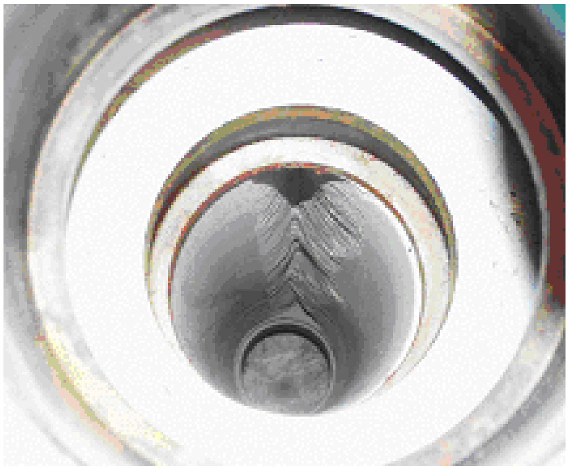

Figure 4: Breakouts formed prior to test 4

Test 6 was performed on a composite Pierre shale and unconsolidated sand-clay mixture. Test 11 was performed with a composite Pierre shale and Saltwash South sandstone sample. The deformation in the UC3 material was small, but the deformation in the Pierre shale material was very large. This was due to the properties of the Pierre shale.

Pierre shale (PS) is a common outcrop shale in Utah. It is very weak, with roughly 40% clay content, of which the predominant clay mineral is montmorillonite[4]. In test 11 a set of core plugs was taken from the plug removed from the wellbore to create the thick wall cylinder sample. Triaxial strength measurements were performed on these core plugs. The results (Figure 5) show a very low strength, with UCS values between 1 and 3MPa, and friction angles between 2 and 5 degrees. The unconsolidated material (UC3) was a mixture of 60% sand and 40% clay.

For test 6 the deformation in the UC3 was 0.7” at 3,000psi. The deformation in the PS was much larger, with the wellbore closing up rapidly on the instruments inside. The large deformations observed in the PS are due to the very weak nature of this surface material. The deformation in the UC3 material is more realistic and can be taken as representative of the behaviour in a poor quality sand. In test 11 the stronger 7” 25Cr version of the ESS was used. The deformation of the ESS in the PS was 2.5” at 1,600psi.

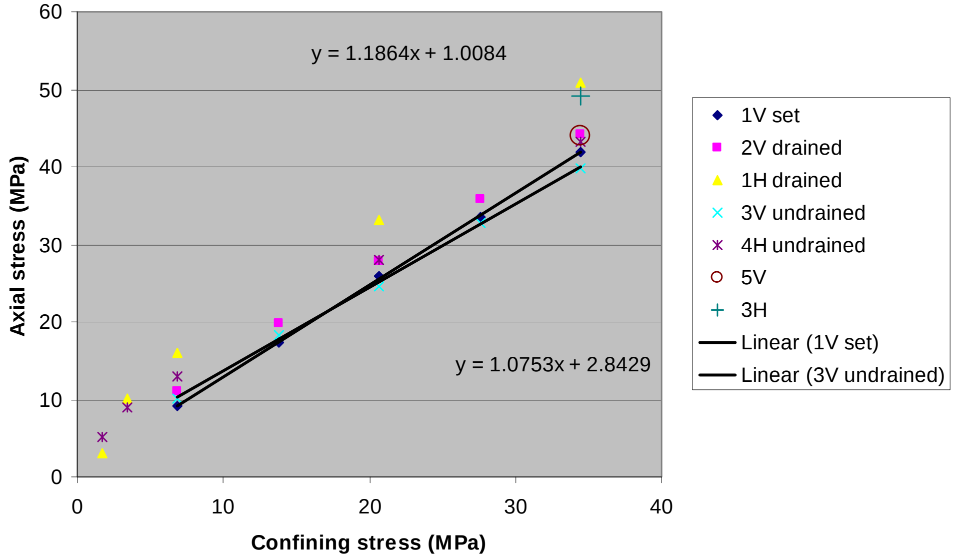

Figure 5: Compilation of triaxial test data on Pierre shale

Test 7 was performed on a sample of ESS manufactured from Incolloy CRA metallurgy, and placed in the SB with what was designed to be a high friction angle sand. Technical problems caused premature termination of this test.

Test 8 involved use of 5 ½” ESS, expanded to 8 1/2”. There was a relatively large deformation of 2.5” at 5000psi. Detailed FEA modeling of this test suggests that a large part of the deformation was due to the small OD/ID ratio; there was an 8.73” ID borehole inside a 19.85” OD rock sample, giving an OD/ID ratio of 2.3. The relatively thin annulus of rock in this test did not allow the development of a stable arch of unfailed material. The numerical prediction is supported by the fact that the rock sample is more disrupted than in previous tests. The deformed zone had propagated through the entire thickness of the rock. In the tests which used a 4” ESS expanded in a 6.1” borehole the OD/ID ratio is 3.3. While this value is larger it still influences the tests, giving larger deformations than would be expected in the field.

Field Limits

The tests are useful for setting limits to the depletion and deformation which an ESS can withstand in a given formation. In a weak to medium strength sandstone (tests 2-5), a change in stress of 10,000psi was observed in the majority of the PV tests. This can be translated into a depletion+drawdown limit of 10,000psi. The unconsolidated materials have lower limits.

Reductions in ESS ID of up to 35% were observed in the tests. Even at this large reduction in ID the ESS remained stable and passed negligible sand. A limit of 20% reduction in ID is therefore used in application screening; equating to 50% safety margin on maximum deformation achieved during the tests; not on failure limit.

Deformation Modeling

The PEA 182 tests showed that in the test configurations used in the programme the ESS could easily withstand large stresses in weak sandstones and unconsolidated sands, but in very weak shales it had a tendency to exhibit large deformations. The challenge was to develop a modeling scheme to apply the results of the tests to field application so that the risk of large deformations could be properly identified and quantified.

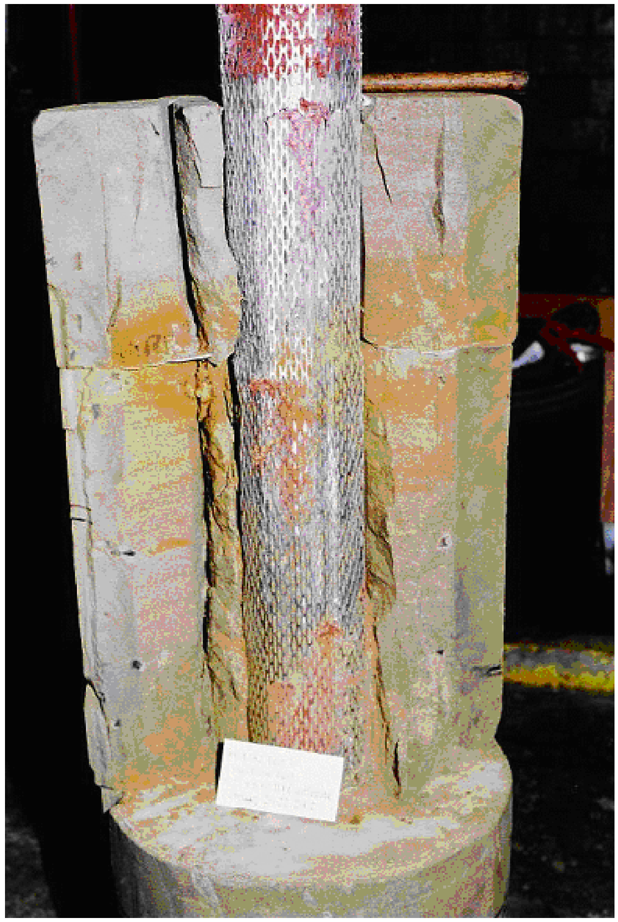

Figure 6: Test 3 showing the Castlegate sandstone and ESS

Early Analytical Models

The first model which was developed was the ESS Well Bore Stability (EWBS) model. This is based on yield zone theory, which was used in the past to determine tunnel support in coal mines[5] and in wellbore stability studies[6]. The yield zone model was adapted for use in screening ESS applications[7]. The EWBS model was compared with the results of the PEA 182 test and gave similar deformations. It has also been compared with both in-house and 3rd party FEA predictions and gives comparable results in unconsolidated sands and weak sandstones. The inputs to the EWBS model are the stress state, the orientation of the completion relative to the stress field and rock properties. The model generates a plot showing the change in ESS ID during well life. The model is used to screen every potential ESS application and has resulted in the rejection of some.

FEA Models

The EWBS model is a reasonable model for screening applications, and is still used for that purpose. However, the model makes use of a number of assumptions and simplifications, imposing limitations on in-situ conditions that can be analysed accurately. Most significantly, the EWBS model assumes rock yielding will be in accordance with the Mohr-Coulomb failure criterion, with yielded rock exhibiting dilatant behaviour. However, many sedimentary materials compact and are not well described by a Mohr-Coulomb relationship. The EWBS is also essentially a one dimensional model.

Developing a FEA based screening model was the next step. It is a fully three dimensional model and the actual ESS geometry is used. The ESS expansion process is also simulated and material models can be developed that can fit the actual behavior of different sedimentary formations. Many different aspects of the formation-ESS interaction can also be studied, such as multiple layers, interfaces between strong and weak materials, cyclic loading, and the effect of an annulus and coupled stress fluid flow models.

FEA models have already been constructed of ESS. Willson et al (1) developed FEA models of the ESS using software know as ELFIN[8]. The models have been used for 3rd party screening of ESS applications, plus the early analysis of the PEA 182 tests.

Abaqus was chosen as the system on which to base the new in-house FEA modeling technique. The reason for choosing Abaqus is that it is used extensively in geomechanics and sand prediction studies, and it is designed to deal with the large plastic strains involved in ESS expansion and rock failure around the wellbore.

Model Development

The first stage involved the construction of FEA models simulating the ESS expansion process, both fixed cone and compliant hydraulic expansion, and comparing the results to known expansion forces. CAD drawings of unexpanded ESS and shroud were imported into Abaqus. The parts were meshed generally using swept brick elements, although tetrahedral elements were used for the shroud, due to the relatively complex shape. The simulations were run on a powerful desktop workstation and lasted a few minutes to a few days, depending on the complexity of the problem being analysed. Simulations of ESS cone expansion (Figure 7) give expansion forces peaking at just over 30,000lbs. This is a reasonable fit to the measured forces, which average 27,000lbs.

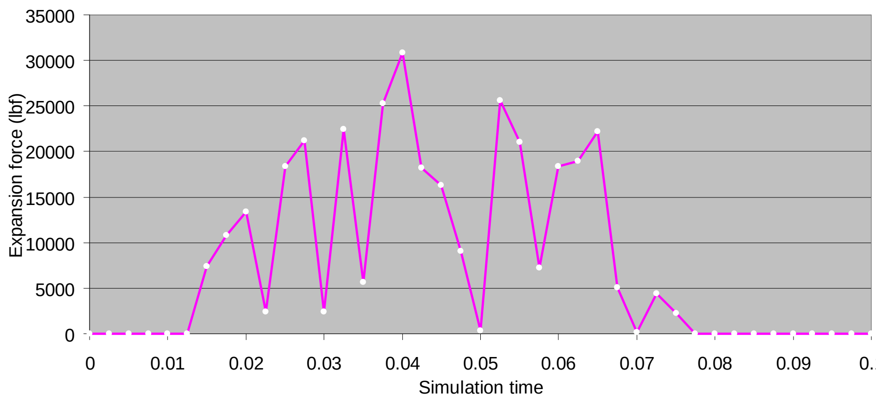

Figure 7 Simulated expansion force for 4 ½" ESS

Figure 10 shows cone expansion of 4 ½" ESS, complete with the perforated outer shroud. The advantage of simulating the expansion process is that it is likely to get the proper plastic strain at the ends of the slots in the ESS basepipe, by factoring into the simulations the work hardening process. The degree of plastic hardening at the ends of the slots is a controlling factor in the strength of the ESS. The simulations used 316L stainless steel, with a yield of 206MPa, a Young's modulus of 210GPa and a Poisson's ratio of 0.3.

The second stage involved simulating hydraulic collapse of the expanded ESS. This gradually deformed the expanded ESS. Initially the deformation is linear and elastic up to a radial displacement of approximately 1.2mm and an external pressure of 70psi. Above this pressure the structure appears to yield and deforms plastically. An image of the partially collapsed ESS is shown in Figure 8. This shows some localized buckling of the structure. As the applied pressure is increased still further the sample eventually flattens completely and the inside surfaces come into contact. Figure 9 shows the radial deformation plotted against applied pressure for the numerical and actual hydraulic collapse test.

The initial slopes of the experimental and numerical pressure displacement curves are virtually identical. After yield the experimental and numerical behaviors depart slightly. In the actual experiment, once a peak pressure was reached, the sample slowly loses its load bearing capacity and gradually collapses. The numerical pressure displacement curve increases after yield.

The reason for the difference is probably to do with either the way the samples are loaded, or heterogeneities in the structure. In the experiment the ESS was fitted with a rubber membrane and mounted inside a pressure vessel. Pressure is applied by a small volume piston pump. The sample ID is measured using a set of extensometers. As volume is added to the pressure vessel the pressure on the sample increases and it deforms. If there is some movement of the sample the change in volume will cause a pressure drop. Also, in the actual sample, there are some departures from an ideal structure. The slotting process is not exact and the pipe is not perfectly round and concentric. All these factors may lead to plastic strain localization and a drop in pressure. In the simulation the pressure is ramped up to a given maximum. The pressure must continue to increase and the sample rapidly flattens at an ever increasing pressure.

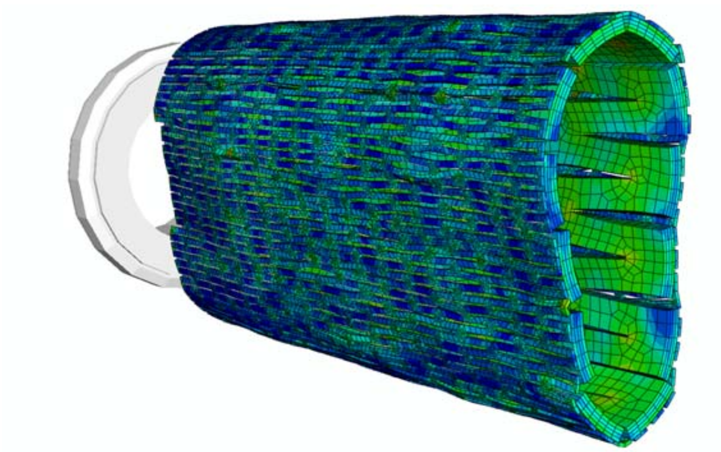

Figure 8: Hydraulically collapsed 4-1/2" ESS Sample

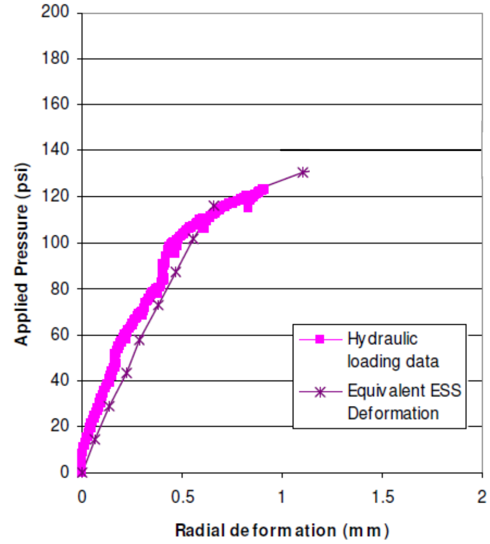

Figure 9: Applied pressure vs radial ESS displacement

The third stage involved the creation of an FEA model simulating the large scale triaxial thick wall cylinder deformation tests conducted under PEA 182, using the pressure vessel, as shown in Figure 11. The yellow and pink traces are the output from the LVDT strain gauges. The brown and green traces are the simulated deformations for two slightly difference starting conditions. The fit between the actual test data and the FEA simulations is very good. The deformations are similar, and the slopes of the deformation vs pressure are very close. The curves cross over each other, but this is likely due to some slight difference in geometry of the experimental ESS and rock samples relative to the more perfect geometry employed in the FEA model.

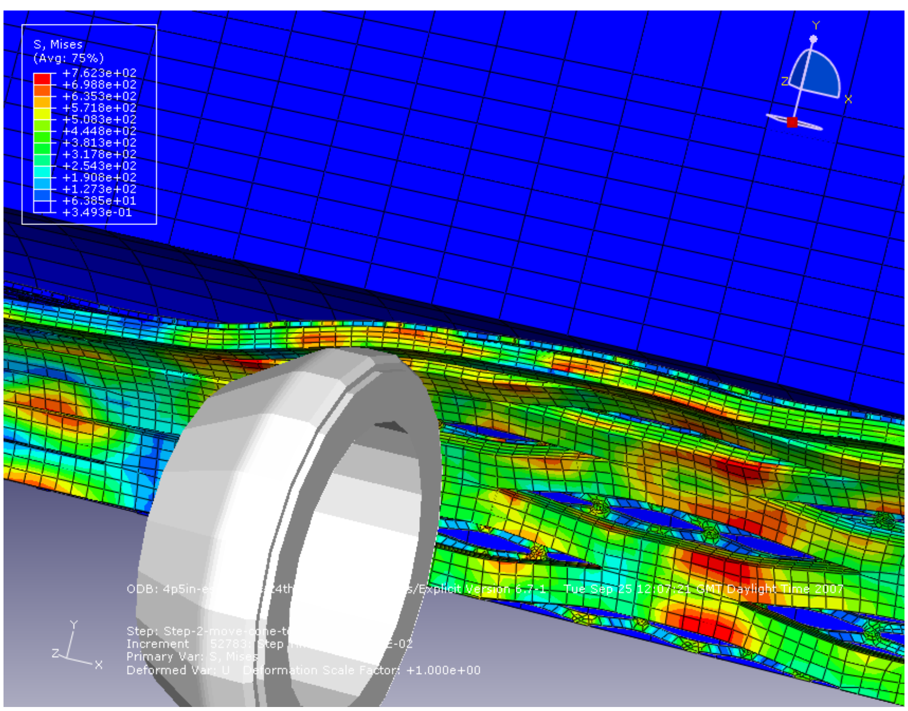

Figure 10: Cone expansion of ESS

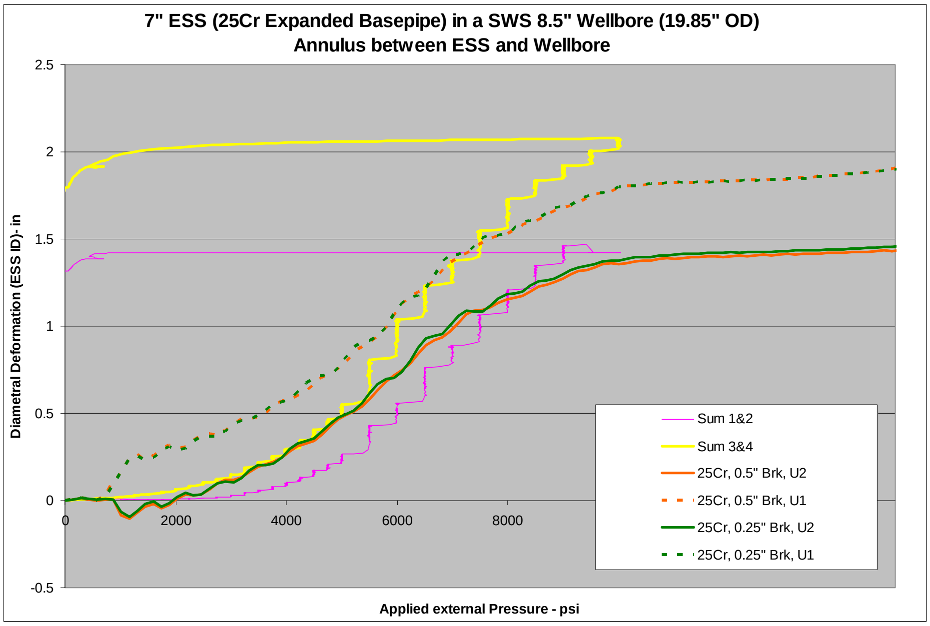

Figure 11: Simulation of 7" ESS

Once the FEA models had been developed and the veracity established through comparison of simulations with experimental data on ESS expansion, hydraulic collapse and deformation recorded in the PEA 182 tests, the fourth and final stage was to build FEA models of an actual application.

FEA Model of a Field Application of ESS

FEA modeling of field applications involves analyzing ESS deformation throughout the entire lifecycle of the well. When a bore 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. This is because the rock material close to the wellbore has to carry the stresses which were originally carried by the removed material. 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 using a fluid of sufficient density to stabilize weak formations. As the drill bit bores through a weak formation there will be some rock failure and relaxation of stress. This causes the wellbore wall to contract slightly into the centre of the wellbore, resulting in a “tight hole”. This extra material is either reamed off immediately by gauge cutters on the bit, or as the drill bit is withdrawn from the hole.

In these FEA simulations of the drilling process, the starting point is a block of rock with a bore 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 FEA model the hole must be re-circularized so as to physically represent the finished drilling process.

This was achieved by constructing two separate FEA models. The first model is loaded to produce the stressed and deformed state after application of the initial stresses. The second FEA model, essentially a copy of the first, then has the solution from the first model mapped onto it. This gives the proper stress distribution and a gauge hole. The second model then carries on with further loading steps. The procedure was described in detail in a recent publication[9]

Once the wellbore has been re-circularized, the next step is to simulate the production of fluids from the formations. This is done either by changing the effective stresses applied to the block to simulate depletion and drawdown, or by using a fully coupled stress fluid flow simulation.

Application Screening Model

The model developed above is used for screening ESS applications in situations where there is some concern on the veracity of the EWBS model. The standard model used is a thin block of rock of 6m x 6m. The block thickness extends across one full repeat of the ESS basepipe slot pattern. Usually only a quarter or half symmetry block is used. The model configuration and the details of the ESS are shown in Figure 12.

There are a number of steps in the analysis, as described in the preceding section. Firstly, the effective stresses are applied to the block, then the wellbore is recircularised. The ESS is then expanded into contact with the wellbore and the mud over balance removed. The effective stresses are then increased to simulate depletion. A more complex fluid-coupled model can also be used for the total stress and pore pressure distributions.

Figure 13 shows an example of a coupled stress fluid flow simulation of the full life cycle of a 5 ½" ESS expanded out to a hole diameter of 216mm (8 ½"). The reservoir and rock properties are shown in Table 4. The figure shows the deformation of the inner bore of the ESS, either with or without the recircularisation process. For the example without recircularisation, when the initial stress is applied, there is a small movement of the inner bore of the ESS. There is also a small deformation when the mud over-balance is removed. In this case, the largest deformation takes place when the reservoir undergoes depletion. The amount of deformation during depletion is a function of the reduction in pore pressure, which in this case is from 19.2MPa to 6.9MPa. At the end of the depletion step, the deformation for the non recircularised simulation is around 24mm, which corresponds to 25%. This is a substantial deformation, which exceeds the 20% limit determined in the PEA 182 tests.

The recircularisation procedure removes the initial deformation and reduces the deformation during depletion, so that at the end of the depletion step there is approximately 14mm deformation, which corresponds to 15% deformation. A drawdown of 1MPa was applied in the last step. This causes further deformation, leading to a final radial deformation of 16mm or 18%. For this application the deformation is just within the 20% limit.

Inclined Borehole in a Sand Shale Sequence

The screening model was adapted to study the effects of a sand-shale sequence in an inclined borehole to particularly study the effects of the sand-shale interface. Models were built at various inclinations, ranging from 0-90 degrees. Figure 14 shows the model for the 45 degree wellbore. The block is divided into 3 main layers; the outer 2 were sandstone, with shale sandwiched in between. The inner shale layer was also sub-divided into 5 layers to allow for thinner shale layers to be modeled. The properties of the sandstone and shale are given in Table 4. The sandstone has a higher Young's modulus and friction angle than the shale. This is likely to cause more deformation in the shale in both the elastic and plastic regime. The model uses effective stress changes, and the slow change in pore pressure in the shale is not taken into account. This is therefore likely to represent a worst case scenario, since in reality, owing to the extremely low shale permeability, the pore pressure does not change very rapidly, and so the change in effective stress is small. However, it may be a reasonable approximation in thin shale beds, where the shale can drain into surrounding permeable sandstone formations.

Figure 15 shows the results of a simulation in a vertical well. The plot is deformation in one direction only (dark blue is zero and red is maximum movement), and clearly showing the shale layer being squeezed into the wellbore. As expected, there was substantially more deformation in the shale layer than the sandstone. The sandstone also appears to support the shale at the interface between the 2 layers.

Simulation of Production and Injection in Gas Storage Wells

ESS has much to offer as a completion option in gas storage wells, especially in highly depleted reservoirs, where the low fracture gradient precludes any gravel pumping operations. However, there is the concern that the cyclic loading will cause the eventual collapse of the ESS. To study this process, a FEA model was built of a horizontal well. Effective stresses were used and these were cycled to mimic the pore pressure changes associated with summer storage and winter extraction of gas. The rock strength was decreased by 35% during the first 10 cycles to simulation fatigue loading on the rock. The reduction in strength was taken from Ray et al[10].

A set of results from the simulations are shown in Figure 16. The vertical and horizontal deformation of the wellbore fitted with a 7" ESS is shown for 60 cycles of production and injection, with a 12MPa change in pore pressure peak to trough. The deformation increases for the first 30 cycles, even though the reduction in strength just took place over the first 10 cycles. The deformation eventually stabilizes to around 13mm peak deformation at 60 cycles, which corresponds to 16% deformation.

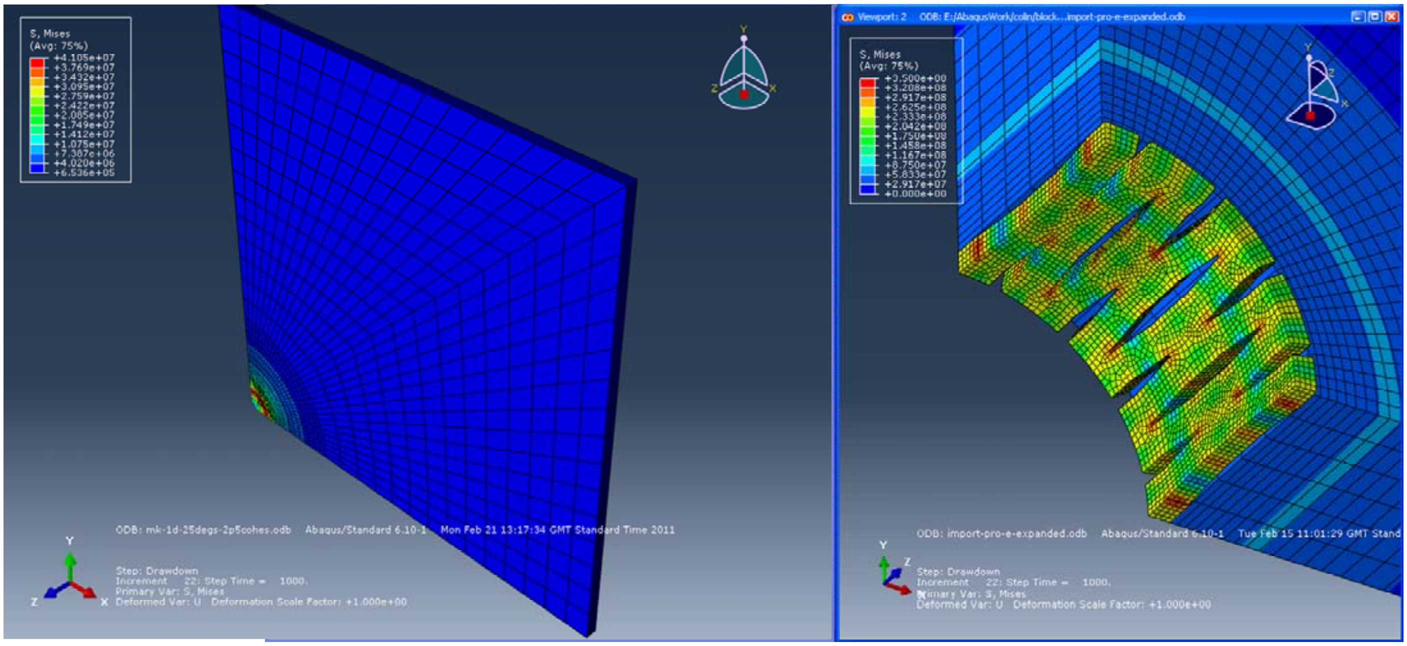

Figure 12: Model Configuration

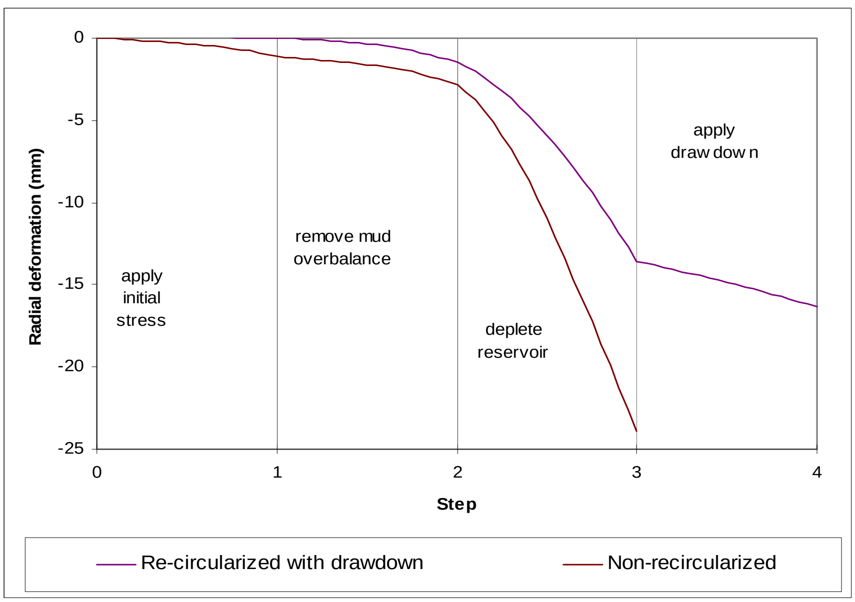

Figure 13: Example of simulation of the full life cycle of ESS including recircularisation

Depth	1900m
Vertical Stress	35MPa
Horizontal stress	32MPa
Initial Reservoir Pressure	19.2MPa
Final Reservoir Pressure	6.9MPa
Mud Overbalance	3.5MPa

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 4: Reservoir and rock properties

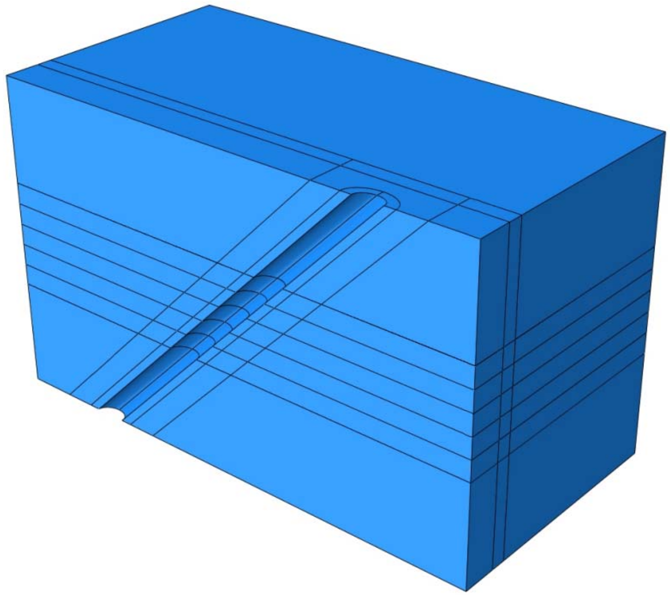

Figure 14: Inclined borehole model

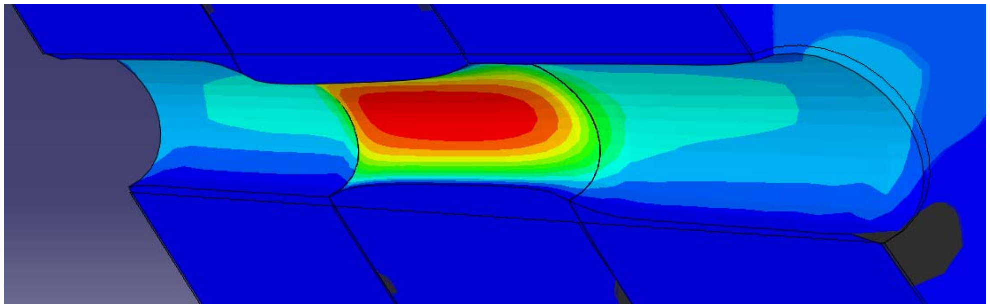

Figure 15: Deformation in a sand-shale sequence

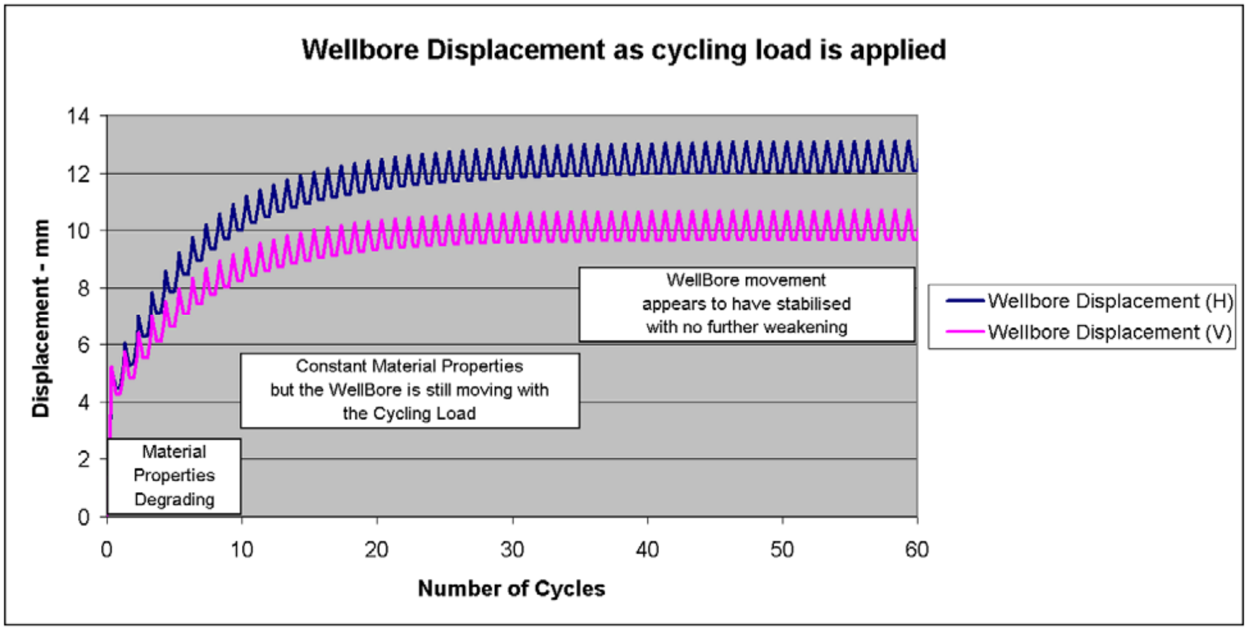

Figure 16: Predicted deformation during multiple cycles of production and injection

Discussion

The PEA 182 tests show that the ESS can withstand large stresses in unconsolidated sands and sandstones, but that there may be excessive deformation in very weak shales. The FEA models can predict the deformation for any application if the stress and formation properties are known. The FEA model also predicts large deformations in weak shales. The main aim of the extensive testing programme and subsequent development of analytical and numeric models is to ensure tools and methods are available to verify suitability of ESS for a given application. If there are risks that the deformation will be excessive (i.e. exceeding the 20% safe limit) then sensitivity studies can be easily performed to evaluate impact of changes to well inclination, azimuth, mud overbalance and changes in ESS metallurgy. If ESS deformation is still too excessive, then either the weak rocks will need to be isolated behind blank pipe, or an inner perforated support string deployed to strengthen the ESS completion. If neither of these contingencies is deemed viable, then ESS should not be used.

Inner strings have been proposed for a number of recent applications; they limit the deformation and impart more strength. Recent testing shows that the inclusion of a 5 ½” predrilled basepipe into the 7” ESS more than doubles the stress that the ESS can withstand before buckling.

Conclusions

- Extensive large scale triaxial thick wall cylinder tests have confirmed that ESS inside a rock formation can withstand very large stress changes, with only small deformations induced.
- A simple analytical model (EWBS) has been developed to screen all applications for excessive deformation.
- A more accurate FEA representation has been developed to address more complex geological settings and a wider range of geomechanical phenomena. This multi-step modeling technique is used to screen applications out with the scope of the EWBS model.
- ESS deformation in sandstone-shale sequences has been studied using FEA models, demonstrating that ESS deformation can be greater in the shales, but that the sandstone supports the shale at the interface and limits its deformation.
- Cyclic loading of ESS in gas storage wells has also been successfully studied within an FEA environment, with simulations predicting that ratcheting reduction of ESS ID is not an issue.
- ESS deformation in shales remains an issue, but modeling tools, techniques and methodologies have been developed to verify suitability of ESS for a given application. If such due-diligence studies indicate that ESS deformation will be too excessive, then either the shales will need to be isolated behing blank pipe or an inner perforated string will need to be deployed inside the ESS.

Acknowledgments

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Nomenclature

ESS Expandable sand screen
FEA Finite element analysis
LVDT Linearly variable differential transformer
SAS Stand alone screen

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