Cyclic Loading of a Rock Mass for Underground Gas Storage Applications

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The use of Underground Gas Storage (UGS) is expected to increase considerably in the near future due to various factors. Many of the UGS wells require sand control. Expandable Sand Screens (ESS) have many advantages as a completion option in UGS wells. But there has always been a concern on the effects on ESS due to cyclic loading. The paper deals with the changes in the borehole that would be caused during annual injection and production cycles from the storage reservoir. Specifically, the interest is in whether or not the deformation levels out to a constant or whether the damage continues evolving. Cycles can be either annual (production in winter / storage in summer) or far more frequent due to Peak shavering (production to cover peak usage, followed by top-up). Abaqus/Standard FEA Numerical modelling has been carried out on a rock sample with an 8.5" diameter wellbore that is lined with a 7" Expandable Sand Screen. The ESS was represented by a simple representation, a plain pipe, rather than a fully slotted system. The rock material has been assigned properties which weaken due to continuing cycles. Stresses were cycled to simulate a great number of years production and injection. The deformation of the ESS stabilised after a number of years. This shows that ESS is a viable completion option in UGS wells.

Keywords: include Geomechanics, Soil-Structure Interaction and Wellbore

1. Introduction

The objective of this study is to establish, using Abaqus/Standard Finite Element Analysis (FEA), the effect of cyclic loading on Expandable Sand Screens (ESS™), caused by alternating production and storage, in an Underground Gas Storage (UGS) reservoir.

The extraction of gas from a gas storage well causes a reduction in the reservoir pressure. This increases the effective stress on the rock formations and may lead to rock failure. Depending on circumstances, such as depth or extraction rates, the change in reservoir pressure can be of the order of 10-20MPa (1450-2900psi).

Reservoirs for gas storage wells need to have relatively high porosity and permeability. This type of formation can store high quantities of gas and have a high deliverability. However they also tend to be weak and have a propensity to fail and granulate during the pressure cycles inherent in the injection and extraction of the gas.

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The solids produced during formation failure can have severe consequences such as erosion of surface facilities and loss of containment, well productivity impairment, especially during injection cycles and can lead to the complete loss of the well.

Many methods are available to deal with the produced solids and they fall into two broad categories, either surface handling or downhole retention. For gas wells, especially high rate gas wells, retaining the solids downhole is the preferred method. There are a range of downhole sand control options; stand alone screens, gravel packing, frac-packing and ESS. ESS is a filtration screen which is expanded and swaged onto the wellbore. The ESS has several advantages, it supports the wellbore which limits rock failure, it has a large open inflow area which gives a high potential deliverability and it is easy to install and clean up prior to production. ESS has been used successfully in UGS applications. *SPE 122135* describes a successful application of the ESS technology in Austria.

An example of the ESS is showed in Figure 1. The ESS consists of three parts, 1. the slotted basepipe or expandable slotted tubular (EST), 2. the woven metal mesh which retains the sand and 3. an outer shroud which protects the mesh during deployment.

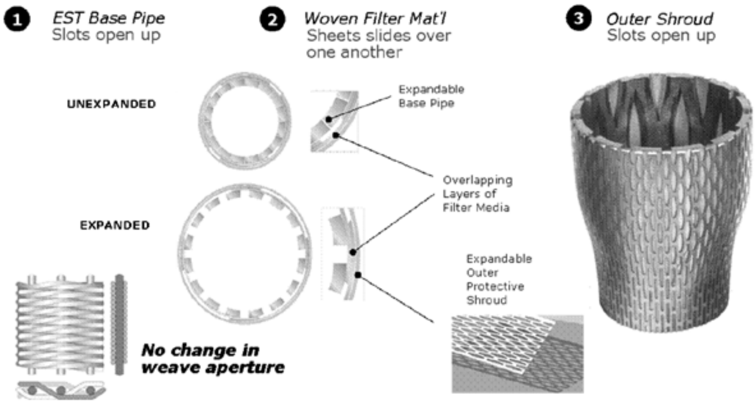


Figure 1 Details of the Construction of ESS

The ESS has been used successfully in a wide range of applications. To ensure success in a given application it is important to model the interaction of the ESS with the rock formations. Weak formations can cause excessive deformation of the ESS which might lead to a loss of sand control. In UGS applications there is the additional complexity of the cyclic loading and its effect on ESS deformation.

It has been shown experimentally (*Ray S.K. et al 1998*) that a cycling load will initially cause a decline in material strength, but this reduction levels off after a few tens of cycles and, in fact, after a certain point the cycling load has no effect at all. Our interest is in how the addition of ESS will improve the wellbore stability, on top of what has been established experimentally, on the way in which a rock weakens during cyclic loading. Based on the FEA simulations that were performed, it is seen that, initially, the wellbore ratchets inwards rapidly in a plastic manner, but subsequently, the wellbore deformation levels out to a more elastic behaviour after a few tens of cycles. This therefore gives confidence that a wellbore complete with ESS, for use in a UGS system, will function correctly for many years in an annual cyclic loading scenario.

2. Background

The use of Underground Gas Storage (UGS) is expected to increase considerably in the near future, due to a variety of factors, including security of supply (whether due to technical or political issues). There are several geological structure types for storing gas underground; Figure 2 salt caverns (either natural or manmade), Figure 3 porous rock in depleted gas or oil reservoirs, and finally aquifers, where there would be an impermeable cap rock, with water filled rock strata below, with the injected gas displacing the water.

There are also two main exploitation strategies for UGS:-

1. Annual winter/summer cycling, where there would be just one injection and production cycle per year (production in winter / storage in summer). This strategy by its very nature involves few, but very large, pressure cycles (in the order of tens of cycles).

2. Peak shavering, involving many injection and depletion cycles per year (production to cover peak usage which isn't handled by existing infrastructure, followed by injection top-up when necessary). This strategy involves many, but small, pressure cycles (in the order of hundreds or thousands).

This paper describes some of the work done recently using the Abaqus/Standard package (numerical modeling) on the annual cyclic loading scenario in a depleted gas or oil reservoir.

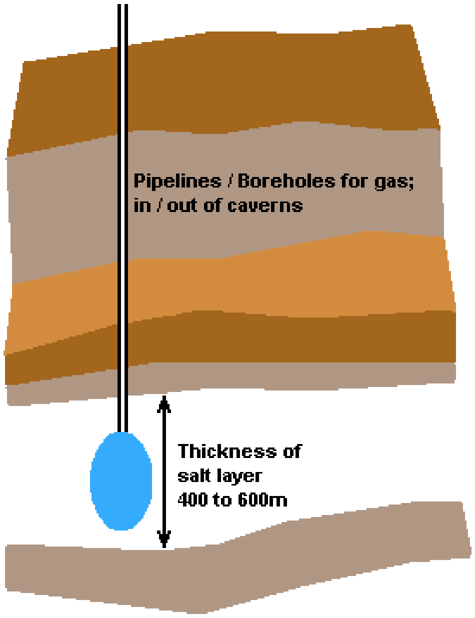


Figure 2 salt cavern UGS

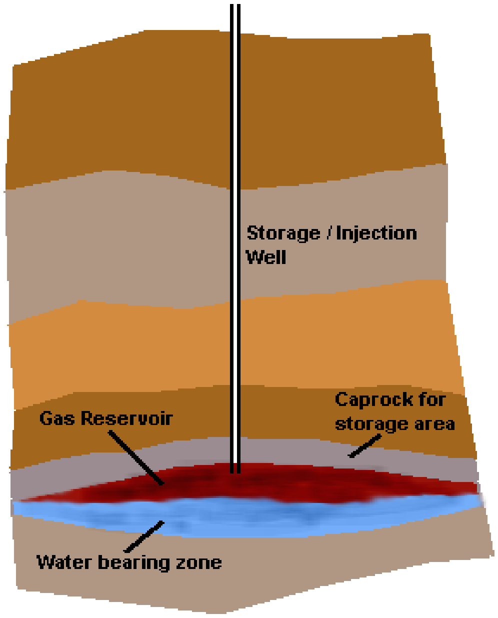


Figure 3 depleted gas reservoir UGS

3. Development of the Model and Material

A model was built to simulate an annual winter/summer cycling UGS application. The rock mass, Figure 4, was set up with the dimensions 1m x 1m x 2m deep, complete with an 8.5" diameter wellbore running through the centre. The model represents a horizontal well, which are commonly used for UGS applications

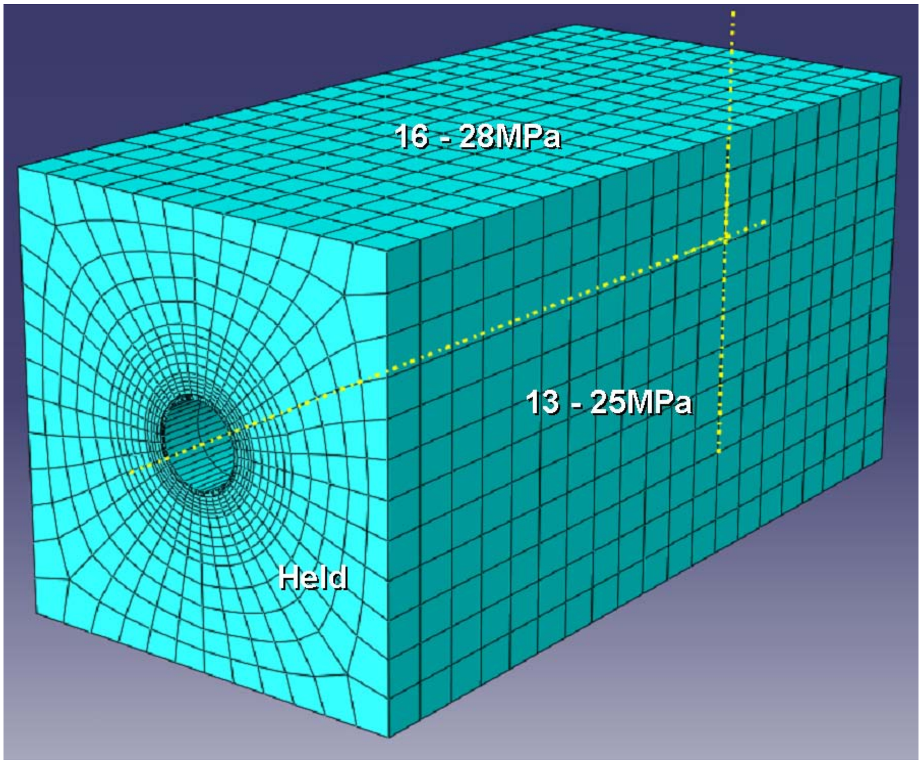


Figure 4 mesh detail for wellbore and plain pipe (equivalent ESS) also showing the cycling load values

For ease of computation, an equivalent plain pipe (with an OD matching the ID of the wellbore as ESS is a compliant system with no annulus between completion and wellbore), rather than a fully slotted system which would then be expanded in place, was used. The material property values were ascertained from existing full scale tests and previous FEA analysis simulations for a fully slotted system. This used methods described in a paper presented at the Simulia Customer Conference - SCC2009 (*Watson and Jones 2009*). From Ray et al 1998, the material properties (UCS or uniaxial compressive strength) of the given rock will decrease by a certain amount over a number of cycles during cyclic loading, but once a certain level is reached, the UCS will remain relatively constant, having no further noticeable decrease in strength, Figure 5.

Development of the Model and Material cont'd

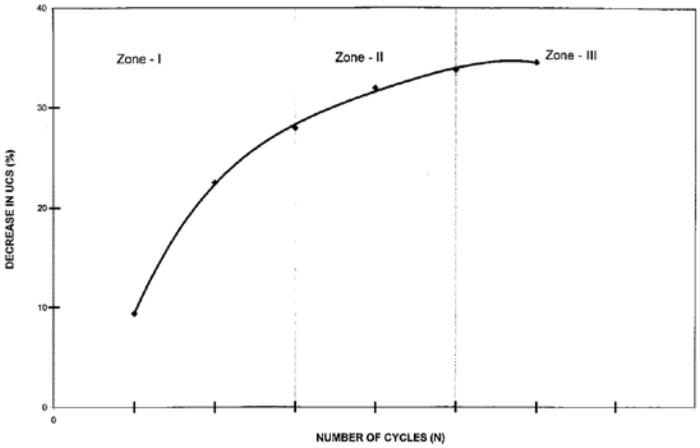


Figure 5 showing the decrease in UCS versus number of cycles

From this graph, it was decided that for a multi-step (cycling) analysis, the first ten cycles would have properties reducing, then for the following cycles, the properties would remain constant, Figure 6.

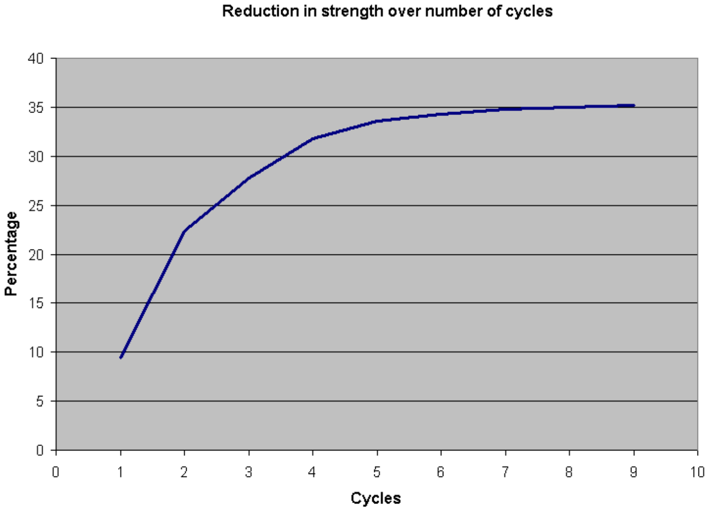
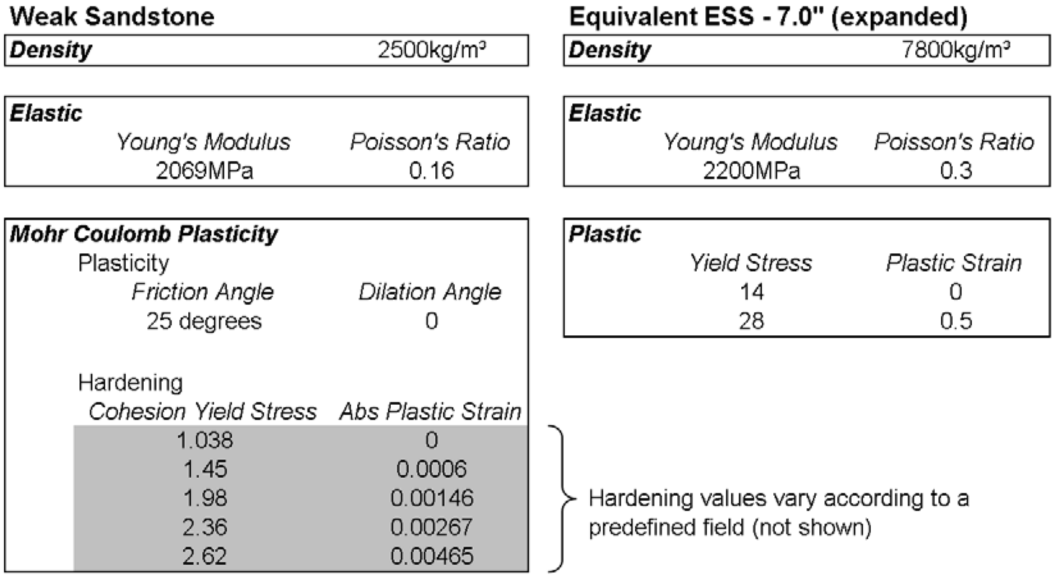


Figure 6 showing the percentage decrease in Cohesion Yield Stress

Development of the Model and Material cont'd

The tables below, Figure 7, give more detail for both the rock properties (a typical weak sandstone) and the equivalent ESS (*Watson and Jones 2009*) that was used for lining the wellbore.



Weak Sandstone

Density	2500kg/m³

Elastic		
	Young's Modulus	*Poisson's Ratio*
	2069MPa	0.16

Mohr Coulomb Plasticity		
Plasticity		
	Friction Angle	*Dilation Angle*
	25 degrees	0
Hardening		
	Cohesion Yield Stress	*Abs Plastic Strain*
	1.038	0
	1.45	0.0006
	1.98	0.00146
	2.36	0.00267
	2.62	0.00465

Hardening values vary according to a predefined field (not shown)

Equivalent ESS - 7.0" (expanded)

Density	7800kg/m³

Elastic		
	Young's Modulus	*Poisson's Ratio*
	2200MPa	0.3

Plastic		
	Yield Stress	*Plastic Strain*
	14	0
	28	0.5

Figure 7 material properties for (initial) sandstone and equivalent ESS

It was necessary to alter the material properties during the simulation (the Cohesion Yield Stress degrades according to the graph shown at Figure 6). This was done very simply via a field variable, which adds another column to the hardening area of the Mohr Coulomb Plasticity model. A predefined field is then created where the value will increment through zero, one, two etc. This then allows Abaqus/Standard to know which set of hardening values to use at each step.
A cycling load was created;
for the vertical sides, the load varied between **13 and 25MPa** (1885 and 3625psi) and
for the top and bottom the load varied between **16 and 28MPa** (2320 and 4060psi).
These load changes can be viewed as changes in UGS reservoir pressure of **12 MPa** (1740 psi) due to injection and production. The front and back faces had no load, they were held in such a manner (with a simple boundary condition) to limit the rock extruding out, Figure 4.
The stress values are typical of a reservoir at **4000-5000ft** vertical depth.

4. Analysis

The graph, Figure 8, shows the wellbore displacement (complete with equivalent ESS installed) as the cycling load is applied. Although the material properties are only degraded over the first 10 cycles, it can be seen that it took considerably longer (around another 25 cycles) for the displacement to settle down to a reasonably constant value. The reason for this is that during an application of stress the failed zone around the wellbore grows to a certain extent. When the wellbore is reloaded it is slightly weaker due to the extended failed zone from the previous loading cycle, so more rock fails and the failed zone increases slightly. There is a rise in radial stress in the failed zone which strengthens the failed rock due to the friction angle. As the failed zone increases in diameter the radial stress rises until the failed rock is strong enough to withstand the stress changes without further failure. It is important that the deformation stabilises, since excessive formation induced deformation of ESS could restrict access to the well and may ultimately cause a loss of sand control. Extensive testing in a joint industry project showed that 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 joint industry project. The 20% value includes a large safety factor. For the weak sandstone used in this analysis, the extent of deformation prior to stabilisation is seen to be around 12%, which is well within the acceptable limit of 20%. The analysis was completed in a small number of hours on a powerful quad core desktop computer.

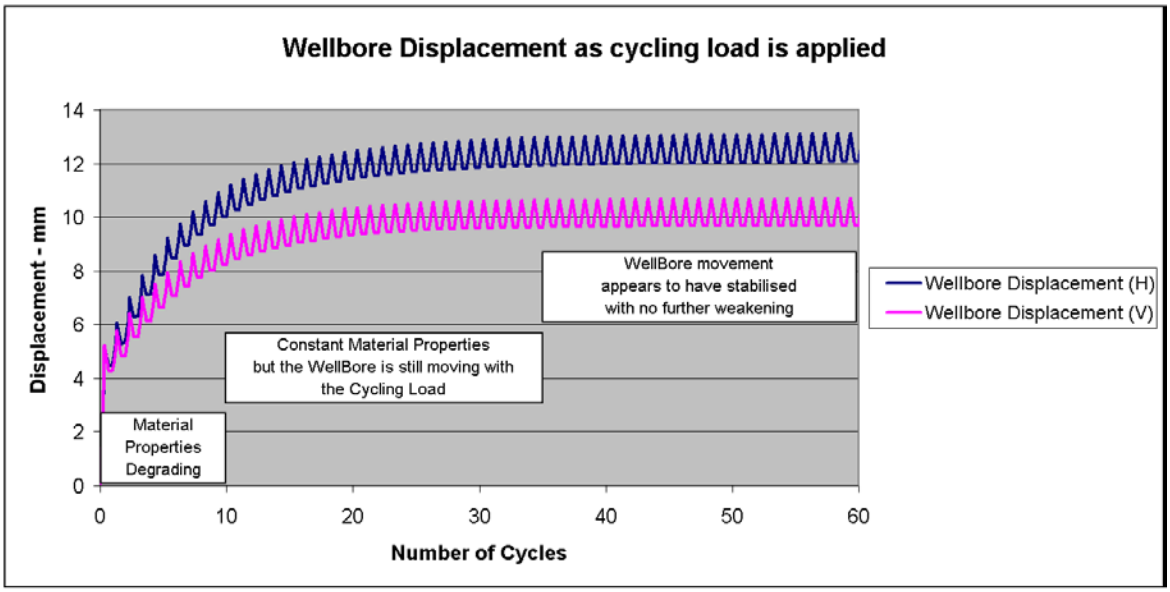


Figure 8 radial wellbore displacement as cycling load is applied showing both Horizontal and Vertical movement

Analysis cont'd

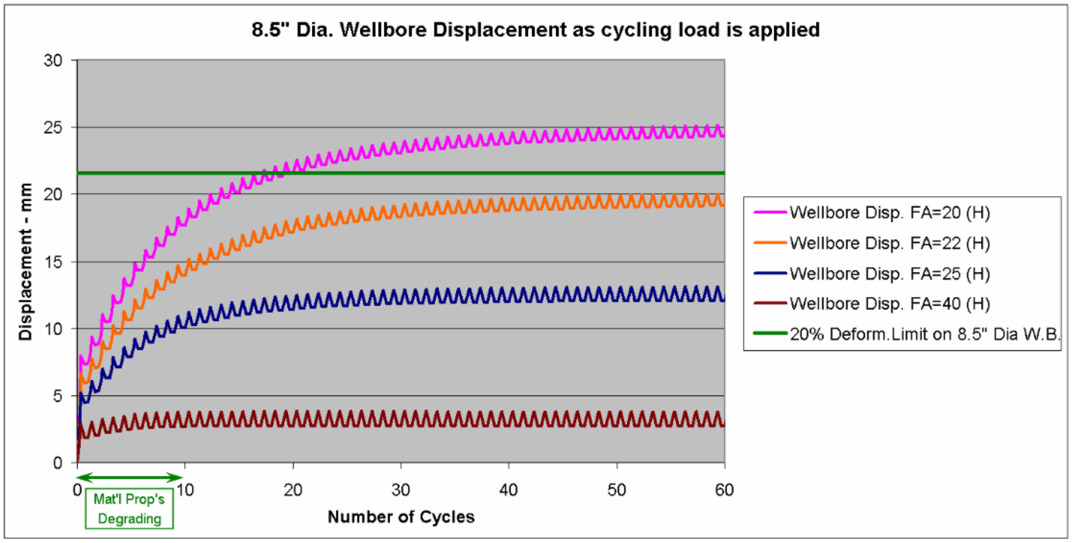


Figure 9 varying the friction angle, radial wellbore displacement as cycling load is applied

Figure 9, shows the wellbore deformation for various of the friction angle values. A deformation limit of 20% (this includes a safety factor) for ESS is acceptable, i.e. there should be no loss of sand control. The friction angle of weak sandstone can typically vary between 20° and 40°. As can be seen from the four trace lines, the weakest sandstone will have too much movement in the wellbore and will minimally pass the 20% limit, however, 22° and upwards, is within the design limits of the ESS. The limit of 22° is for the specific conditions of the modeled reservoir and must be evaluated for each application.

5. Discussion and Conclusions

As the overlying layers of rock etc. have been impervious to gas for millennia already, it is safe to assume that safe storage conditions do exist, and that during extraction of the original gas or oil, the material and stress conditions of the reservoir will be fully defined (through coring and logging in the early life of the well). As such, the highest uncertainties in a UGS system will centre on the wellbore/completion interaction.

From the results shown in the wellbore displacement graph it can be reasonably stated that although there is initial plastic/ratcheting movement in the wellbore, the magnitude of movement does slow down and will tend towards a more elastic behaviour after a few tens of cycles.

For peak shavering, there will be a far greater number of cycles, but the loads will be markedly lower. There may still be a material strength degradation due to the cycling production and injection load, but it would be realistic to say that the peak shavering gross behaviour of the wellbore/ESS would be similar to that of the annual cyclic scenario, in that the plastic/ratcheting movement would happen over a few years (rather than cycles) followed by a steady state elastic behaviour after a few tens of years. It is also likely that the deformation would be less.

As UGS systems become more common, an efficient high productivity sand control completion is advantageous. ESS has many benefits, including ease of installation and long term high productivity. This study shows that in a UGS application, which involves cycling stressing of the reservoir rock, the ESS stays within its design limits and will provide reliable sand control over the feasible life of the UGS well. A similar screening study should be performed on all potential applications.

6. References

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