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Omission of Wellbore Block for Computational Efficiency in Big Hill Strategic Petroleum Reserve Model

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ABSTRACT: Oil leaks were found in two wellbores of the Big Hill Strategic Petroleum Reserve site. According to the field observations, two instances of casing damage occurred at the depth of the interbed between the caprock bottom and salt top. A three-dimensional finite element model, which contains wellbore blocks at the center of the caverns and allows each cavern to be configured individually, was constructed to investigate the wellbore damage mechanism. The causes of the damaged casing segments are a result of vertical and horizontal movements of salt dome top. To assess how much the wellbore impedes the movement of the salt top, a comparison of the analyses' results from meshes with and without the wellbore blocks was performed. This paper shows models that omit the wellbore blocks could be used for as an acceptable simplified simulation of Strategic Petroleum Reserve sites.

1 INTRODUCTION

The United States (U.S.) Strategic Petroleum Reserve (SPR) stores crude oil in 62 caverns located at four different sites in Texas and Louisiana. The reserve currently contains over 700 million barrels (MMB). Most of the caverns were solution mined by the U.S. Department of Energy (DOE).

Oil leaks were found in wells of two caverns, Caverns 105B and 109B, at the SPR Big Hill (BH) site in southeastern Texas (Ehgartner 2010, Ehgartner 2011). The Cavern 105B leak started after December 3, 2009, and had progressed to 8600 barrels by May 14, 2010. The Cavern 109B leak started on October 8, 2010 and the total amount of oil leaked is estimated to be 2700 barrels. The locations of both leaks were found to be close to the interbed between the caprock and the salt dome. The wells of BH 114A and 114B were found to be in danger of starting to leak from interpretation of multi-arm caliper survey data (Wynn 2012).

The causes of the damaged casing segments are a result of vertical and horizontal movements of the interbed between the caprock and salt dome. The salt top subsides because the volume of caverns below the salt top decrease with time due to salt creep closure, while the caprock subsides at a slower rate because the caprock is thick and stiffer. This discrepancy produces a deformation of the well casings at the depth of the interbed (Park 2014 a).

From a perspective of modeling, the thicknesses of steel casings and cement annuli are very small relative to the global model size. This size difference produces a poor quality mesh shape. To improve the mesh shape quality, the blocks would have to be divided into smaller sizes of elements. Then, the number of elements in the mesh would be more than tens of millions. A mesh with such a large number of elements would consume an extraordinary amount of computer CPU time. If the wellbore stiffness does not affect the movement of salt top, we can omit the blocks for the computational efficiency. How the wellbore impedes the movement of the salt dome top will be described in this paper.

2 PREVIOUS WORK

This paper describes a series of three-dimensional geomechanical simulations of the BH SPR (Park 2014a, Park 2014b, Park et al. 2014). Park (2014a) developed a three-dimensional finite element model, which allows each cavern to be configured individually as shown Figure 1. The model contained interfaces between each lithologic unit and a shear zone to examine the interfaces behavior in a realistic manner. The results from that analysis indicated that the casings of Caverns 105 and 109 failed by shear stress that exceeded the casing shear strength due to the horizontal movement of the top of salt relative to the caprock, and tensile stress due to the downward movement of the top of salt from the caprock. However, that model did not consider the stiffness of the well casings which could impede the movement of the top of the salt dome. That model also did not calculate the resultant displacement of the salt dome top relative to the caprock bottom either, i.e. the horizontal and vertical displacements were calculated separately. For a more realistic simulation, two new models will be constructed: a global model which includes representations of the wellbore casings for all the caverns to calculate large-scale displacements, and a single-cavern wellbore model to evaluate the effect of those displacements on the as-built casing designs. In this paper, the model and the analyses results from the global model are described.

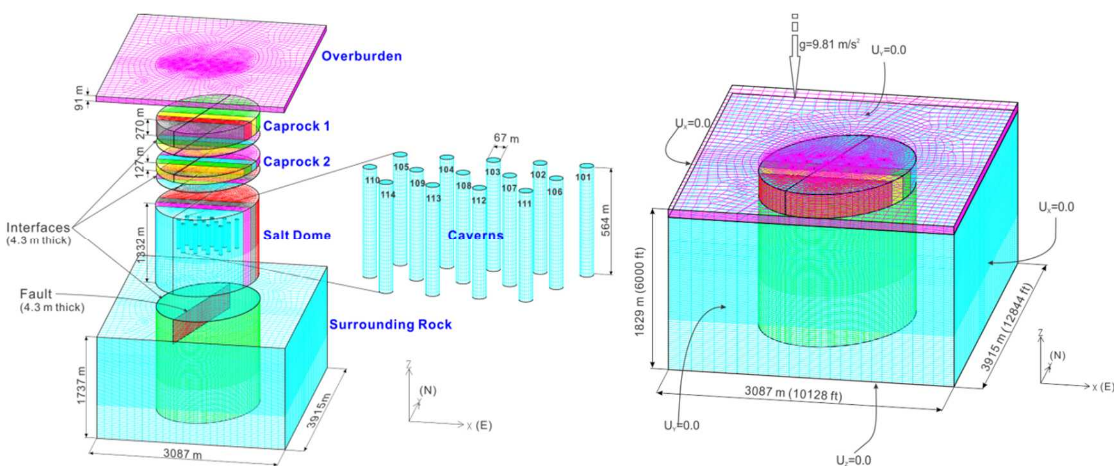

Figure 1. Overview of the finite element mesh of the stratigraphy and cavern field (left), and boundary conditions (right) at Big Hill SPR site.

3 MODEL DESCRIPTION

3.1 Geomechanical and Cavern Models

As mentioned above, this paper describes a series of numerical simulations of the BH SPR. The site description, stratigraphy, and salt dome and cavern geometries are unchanged from the original baseline model and identical to those described by Park (2014a). The constitutive models and material properties used in this analysis for salt, lithologies around the salt dome, interfaces, and fault are also identical to those described by Park (2014a). The model history such as internal pressure change in each cavern and thermal conditions are the same as the original baseline (Park 2014a) also. This paper emphasizes response of the wellbores of each cavern at the interbed between the caprock bottom and salt top.

3.2 Wellbores Model

The steel casings are made of K55 steel, which was modeled with an elastic-plastic constitutive model. The elastic-plastic model used here is based on a standard von Mises type yield condition and uses combined kinematic and isotropic hardening, in the most general case. Taylor and Flanagan (1989) provide details of the model, as implemented within SNL codes.

The cement annuli were modeled with the Kayenta constitutive model, a generalized cap-plasticity model. The Kayenta model includes features and fitting functions appropriate to a broad class of materials including rocks, rock-like engineered materials such as concrete, ceramics, and metals. The cement material response in the calculations was modeled using the parameters given in Brannon et al. (2009).

The more information about the wellbores such as the well configuration and the material properties used in this analysis were provided in Park (2014b).

4 MESH

Figure 2 shows an overview of the finite element mesh of the stratigraphy and cavern field. This mesh contains the wellbore block at the center of each cavern. The mesh has been separated to show the individual material blocks. The X-axis of the model is in the East direction, Y-axis is along the North direction, and Z-axis is the vertical direction, up being positive. The mesh consists of eleven material blocks. Five material blocks used are Overburden, Caprock 1, Caprock 2, Salt Dome, and Surrounding Rock. Three material blocks are used for the interfaces, and one material block is used for the fault. Two material blocks are used for steel casings and cement annuli.

All caverns are idealized as cylinders 564 m height and 67 m in diameter. The top of the caverns is 201 m down from the top of salt (698 m below the surface). The thicknesses of Caprock 1 and 2 are 270 m and 127 m, respectively. The thicknesses of interfaces are 4.3 m. The thickness of the fault (shear zone) is also 4.3 m. The strike direction and dip of the fault are N 18º E and 90º, respectively. The fault runs between Caverns 103 and 104, Caverns 108 and 109, and Caverns 113 and 114. The fault is assumed to extend down to the top of Salt Dome from the surface.

The same boundary conditions as shown in Figure 1 are applied. The salt dome is modeled as being subject to a regional far-field stresses acting from an infinite distance away. The Surrounding Rock block encircles Caprock 1, Caprock 2, and Salt Dome. The lengths of the confining boundaries are 3915 m (two times the dome's major diameter) in the N-S direction and 3087 m (two times the dome's minor diameter) in the E-W direction. The mesh consists of 1,050,760 nodes and 1,012,932 elements with 37 element blocks, 5 node sets, and 28 side sets. The mesh was created using CUBIT[1] version 13.1.

[1] A mesh generation software copyrighted by Sandia Corporation.

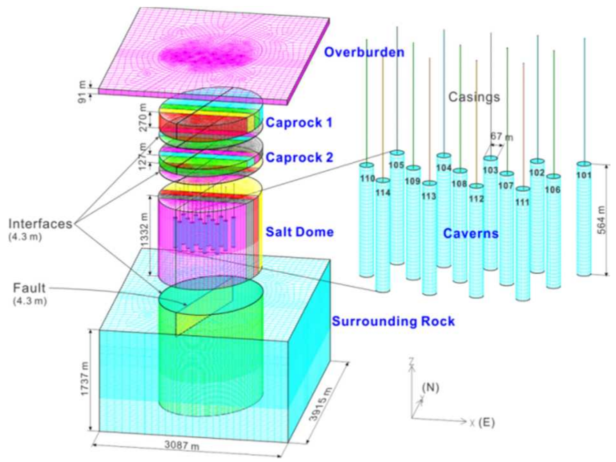

Figure 2: Overview of the components of the finite element mesh of the stratigraphy and cavern field at Big Hill.

5 ANALYSIS RESULTS

The displacements in X-, Y-, and Z-directions are calculated at Nodes N_{CM}, N_{CI}, N_{SI} and N_{SM} in Figure 3 for all fourteen wellbores. To determine the relative movement between the salt dome top and the caprock bottom above the center of each cavern, the displacements at Nodes N_{CI} (caprock bottom) and N_{SI} (salt dome top) are calculated over time. The displacement history data at Nodes N_{CM} and N_{SM}, which will correspond to the top and bottom of the wellbore model, respectively, will be applied to the wellbore model as prescribed boundary conditions for each cavern well. The detailed as-built double steel casing and cement annuli behaviors will be calculated through the wellbore analysis using the displacement data obtained in this simulation in the next stage (not in this paper).

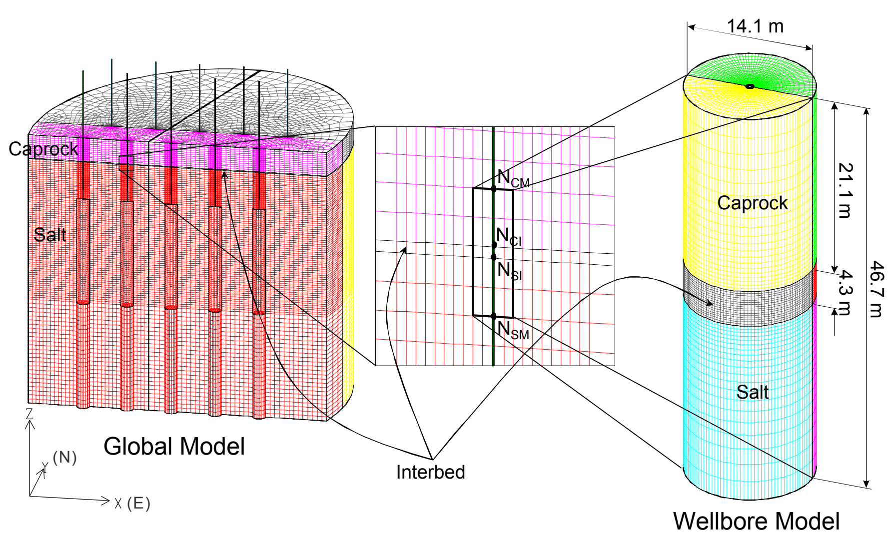

Figure 3: Configuration at the intersection of a wellbore and interbed to show the locations for calculating the predicted displacements and relationship between global model and wellbore model.

To assess how the wellbore impedes the movement of the salt dome top, a comparison of the results from meshes with and without the wellbore blocks is conducted. Figures 4 and 5 show the predicted relative displacements between N_{CI} and N_{SI}, and N_{CM} and N_{SM} for BH105 and BH109 as a function of time, respectively. The solid and dashed lines indicate the results from the model with and without wellbore blocks, respectively. The predicted relative displacements at inside nodes N_{CM} and N_{SM} (21.1 m apart from the top and bottom of interbed, respectively) are almost identical, while those at nodes N_{CI} and N_{SI} (on the top and bottom of interbed, respectively) show only a slight difference. We recognize the stiff wellbore blocks impede the movement of the salt top some, however the amount that the displacement is restricted is very small. The predicted relative displacements for fourteen cavern wells are provided in Park (2014b).

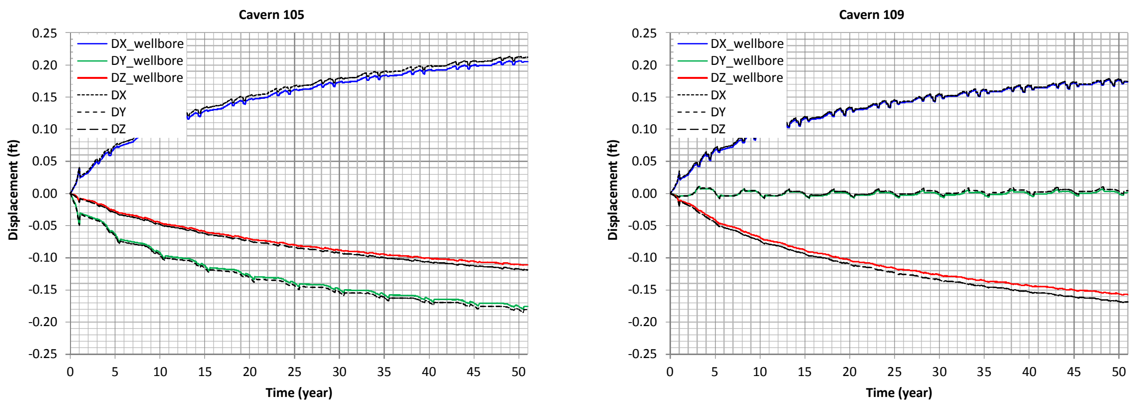

Figure 4. Predicted relative displacement between N_{CI} and N_{SI} in Figure 3 for BH105 and BH109 as a function of time.

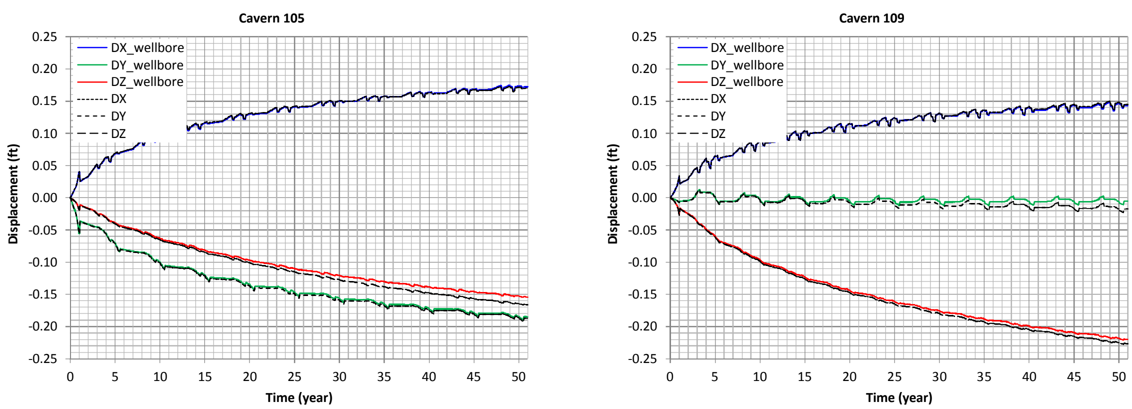

Figure 5. Predicted relative displacement between N_{CM} and N_{SM} in Figure 3 for BH105 and BH109 as a function of time.

6 CONCLUSIONS

The SPR stores crude oil in 62 caverns located at BH and Bryan Mound (BM) in Texas and Bayou Choctaw (BC) and West Hackberry (WH) in Louisiana. The caverns were solution mined in the salt domes. Oil leaks were found in the wells of BH caverns could have been caused by interbed movement induced by cavern volume closure due to salt creep. A leak at the interbed could inject a large amount of oil into the discontinuity or layer making up the interbed. The leaked oil could flow out past the dome boundary to the surrounding rocks and possibly into nearby aquifers. This could become a significant source of environmental contamination. Therefore, remediation of the well casings needs to be performed before the occurrence of an oil leak.

An advanced model to predict the leak date of each well for the remediation plan was developed. It was noted that by including the wellbore material blocks in the model, in order to obtain a mesh with a good shape quality, the number of elements would have to be extremely large and its solution would consume an extraordinary amount of computer CPU time. This paper shows the stiff wellbore blocks do indeed impede the movement of the salt top some; however, the amount is quite small and can be considered not significant. Therefore, a model omitting the wellbore blocks is sufficient as an acceptable simplification of the simulation. A model without wellbores would reduce the effort needed to construct the mesh and save on computer run time, and the result would be not much different from the result from the model containing wellbore blocks. This result suggests that the models for BC, BM, and WH, whose geometries are more complicated, could omit the wellbore material blocks.

ACKNOWLEDGEMENTS

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