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Construction of hexahedral finite element mesh capturing realistic geometries of a petroleum reserve☆

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ABSTRACT

The three-dimensional finite element mesh capturing realistic geometries of the Bayou Choctaw site has been constructed using the sonar and seismic survey data obtained from the field. The mesh consists of hexahedral elements because the salt constitutive model is coded using hexahedral elements. Various ideas and techniques to construct finite element mesh capturing artificially and naturally formed geometries are provided. The techniques to reduce the number of elements as much as possible to save on computer run time while maintaining the computational accuracy is also introduced. The steps and methodologies could be applied to construct the meshes of Big Hill, Bryan Mound, and West Hackberry strategic petroleum reserve sites. The methodology could be applied to the complicated shape masses for various civil and geological structures.

1. Introduction

Sandia National Laboratories (hereafter ‘Sandia’) uses large-scale, three-dimensional computational models to model the geomechanical behavior of underground storage facilities consisting of solution-mined caverns in a salt dome. It is not easy to realize the naturally formed cavern, salt dome, and opening in the rocks into some regular geometrical shapes. It is even harder to convert the geometries into the meshed mass consisting of only hexahedral finite elements commonly used in these computational models. The opening excavated using a machine such as tunnel boring machine (TBM) could have a regular shape. However, the geometry of a cavern leached by solution mining in the salt will be irregular. The irregularity of the shape will be compounded if a salt fall occurs within the cavern. The geometries of the salt dome containing caverns and the caprock over the salt dome are also naturally formed and therefore irregular and complex in shape. This paper describes how to realize the geological mass combining artificially and naturally formed geometries into a geomechanical model.

The U.S. Strategic Petroleum Reserve (SPR) stores crude oil in 60 caverns located at four sites along the Gulf Coast. The reserve contains approximately 695 MMbbls (110 Mm^3) of crude oil. Most of the caverns were solution mined by the U.S. Department of Energy (DOE) and are typified as cylindrical in shape. In reality, the geometry, spacing, and depths of the caverns are irregular. Sandia, on behalf of DOE, is evaluating the mechanical integrity of the salt surrounding existing petroleum storage caverns in the Bayou Choctaw (BC) Salt Dome located in Louisiana.

Geotechnical concerns arise due to the close proximity of some of the caverns to each other (e.g., Caverns 15 and 17) or to the edge of salt (e.g., Cavern 20) [3]. In addition to the SPR caverns at BC, eight other caverns exist, which store various hydrocarbons and are operated by private industry. Also, there are nine abandoned caverns, one of which collapsed in 1954 (Cavern 7) and another which is believed to be in a quasi-stable condition (Cavern 4). The integrity of wellbores at the interbed between the caprock and salt is another concern because oil leaks occurred at the interbed in the Big Hill site [5]. When oil is withdrawn from a cavern in salt using freshwater, the cavern enlarges. As a result, the pillar separating caverns in the SPR fields is reduced over time due to usage of the reserve. The enlarged cavern diameters and smaller pillars reduce underground stability [4]. It is necessary to establish a limit for the remaining pillar thickness between caverns without threatening the structural integrity of the caverns.

The three-dimensional finite element mesh capturing realistic geometries of the BC site has been constructed using the sonar and seismic survey data obtained from the field. The mesh has to consist of hexahedral elements because the salt constitutive model, which will be used in the numerical simulation using this mesh, is coded for using hexahedral elements. The site was meshed with CUBIT, an automated mesh generation program developed by Sandia. CUBIT is a full-featured software toolkit for robust generation of two- and three-dimensional finite element meshes (grids) and geometry preparation

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[8]. The mesh contains the interbed between the caprock and salt top and the interface between the salt dome and surrounding in situ rock stratigraphy. Modeling of the leaching process of the caverns is performed by deleting elements along the walls of the cavern so that the cavern volume is increased by 15% per a drawdown.[1] An additional layer of elements is considered on the outside of every cavern to check the analysis results at the cavern wall, roof, and floor.

This paper provides various ideas and techniques to construct finite element mesh capturing artificially and naturally formed geometries. Techniques to reduce the number of elements as much as possible to save on computer run time while maintaining the computational accuracy are introduced. The detailed steps and program command scripts are provided so people who are familiar with CUBIT can duplicate the method and apply it to other modeling. These techniques are also applicable to commercial mesh generation programs that have similar functionalities of CUBIT. The detailed methodologies provided by Park and Roberts [6] are summarized because of the page limitation of this journal paper.

As the first of a series, this paper describes the construction of a three-dimensional finite element mesh capturing realistic geometries of the BC site using the sonar and seismic survey data obtained from the field. The second paper will describe the model calibration to match the analysis results to the field measurements, and the third paper will provide solutions for the geotechnical concerns and conclusions.

Fig. 1. Bayou Choctaw SPR site location map.

2. Site descriptions

The BC salt dome, located in south-central Louisiana near Baton Rouge (Fig. 1), was discovered in 1926. Since then, over 300 oil and gas wells have been drilled on and around the dome, as well as numerous shallow holes drilled into the caprock. Since 1937, Allied Chemical Corporation has drilled over 20 brine wells on the dome. In 1976, US Department of Energy (DOE) purchased 11 of these leached caverns and was storing approximately 22 million barrels of crude oil in three of the caverns (Caverns 15, 18, and 19), forming part of the SPR Program [1].

Since 1980, SPR Caverns 18, 19, and 20 have been enlarged substantially; Union Texas Petroleum (UTP) Caverns 6 and 26 have been constructed; and Caverns 101 and 102 have been leached by DOE. Cavern 102 was traded to UTP in a swap for Cavern 17, now used for SPR oil storage. In 1992, UTP converted its brine Cavern 24 to natural gas storage. UTP had leached in 1993 along the northeast dome edge [2]. The UTP caverns have gone through changes in ownership: first UTP, then Petrologistics, and now Boardwalk.

Data from the 300 oil and gas wells were used to construct contour maps and cross sections of the salt dome and the overlying caprock. Fig. 2 shows a plan view of the BC site with salt contour lines defining the approximate location of the salt dome edge. The locations of the six SPR caverns, nine Boardwalk caverns, one inactive cavern, and seven abandoned caverns are included. A vertical cross section through Cavern 4 and Cavern 18 provides a geologic representation near the middle of the dome as shown in Fig. 3.

The surface and near surface sediments overlying the BC dome are of the Pleistocene through the Holocene age. The oldest sediments consist of proglacial sands and gravels with some clay layers. These sediments are overlain by alternating sequences of sand, silts, and clays [1].

Two distinct zones are found in the caprock at BC: an upper zone, termed the clay and gypsum zone (CGZ); and the lower zone, called the massive gypsum-anhydrite zone (GAZ). The CGZ is composed of layers of gypsum intercalated with clay. The proportion of clay to gypsum is highly variable, with generally more clay than gypsum. The GAZ is predominantly gypsum-anhydrite with minor amounts of clay, sand, and gypsum [1].

The top of the BC salt dome lies between 600 and 700 ft (183 and 213 m) below the surface. The east flank dips gently downward to 1,500 ft (457 m) where the dip increases to approximately 80° between 2000 and 6000 ft (610 and 1829 m). The west flank of the dome is overhung between 1000 and 5000 ft (305 and 1524 m). Below 6000 to 8000 ft (1,829 to 2438 m), the slope of the salt surface diminishes to about 60° [1].

The lithology surrounding the salt dome contains up to 30,000 ft (9,144 m) of silts, sands, shales, limestones, and evaporites. These sediments were deposited in a variety of sedimentary environments including desert basin, evaporating flat, ocean basin, and delta [1].

The stratigraphy near the BC salt dome is shown in Fig. 3. The top layer of overburden, which consists of sand, silts, and clays, has a thickness of 500 ft (152 m). The caprock, consisting of gypsum, anhydrite, and sand, is 160 ft (49 m) thick. The bottom of the deepest cavern (Cavern 27) is at a depth of 6,280 ft (1914 m). For the vertical direction constraint at the bottom of the model, sufficient thickness between the lowest cavern bottom and the model bottom is necessary to not affect the structural reaction by the bottom boundary. Therefore, the depth of the salt dome is considered up to 6400 ft (1951 m) below the surface. All SPR caverns are located below 2000 ft (610 m).

The faults shown in Figs. 2 and 3 will be ignored in the finite element model because the faults did not extend to the deep salt. Thus, the faults could not affect the structural behavior of the SPR caverns. By ignoring the shear zone, the model of overburden and the cap rock layers are able to be simplified.

3. Model construction

3.1. Basic rule

Finite element codes such as SIERRA/ADAGIO[2] are designed to

[1] "Drawdown" is when the crude oil is withdrawn from the cavern. Fresh water injection is used to withdraw the crude oil. Because the cavern enlarges due to salt dissolving from the cavern walls, it is called a "drawdown leach".

[2] ADAGIO is the most recently Sandia-developed 3D solid mechanics code. It is written for parallel computing environments, and its solvers allow for scalable solutions of very large problems. ADAGIO uses the SIERRA Framework, which allows for coupling with other SIERRA mechanics codes.