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Abstract

The three-dimensional finite element mesh capturing realistic geometries of 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 with 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 not only various civil and geological structures but also biological applications such as artificial limbs.

Key words: Caverns for Liquid Storage, Computer Modeling, Hexahedral Finite Element, Rock Mechanics

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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 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 located along the Gulf Coast. The reserve contains approximately 695 million barrels (110 MMm^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 in Louisiana (Figure 1).

Geotechnical concerns arise due to the close proximity of the some of the caverns to each other (e.g., Caverns 15 and 17) or to the edge of salt (e.g., Cavern 20) (Park, et al. 2006). 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 (Cavern 7) in 1954 and another (Cavern 4) which is believed to be in a quasi-stable condition. 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 (Park, 2014). 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 (Park and Ehgartner, 2011). 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 (FE) mesh capturing realistic geometries of 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. CUBIT, an automated mesh generation program developed by Sandia, was used to mesh the site. CUBIT is a full-featured software toolkit for robust generation of two- and three-dimensional finite element meshes (grids) and geometry preparation (Sandia, 2015). 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 percent 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 FE 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 to other modeling. These techniques are also applicable to commercial mesh generation programs that have similar functionalities of CUBIT.

2. Site Descriptions

The BC salt dome, located in south-central Louisiana near Baton Rouge (Figure 1), was discovered in 1926. Since then over three hundred 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 twenty brine wells on the dome. In 1976, the Department of Energy (DOE) purchased eleven of these leached caverns and was storing approximately twenty two million barrels of crude oil in three of the caverns (numbered 15, 18, and 19), forming part of the SPR Program (Hogan, 1980).

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 (Neal et al., 1993). The UTP caverns have gone through changes in ownership. So it was 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. Figure 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 Figure 3.

The surface and near surface sediments overlying the BC dome are of Pleistocene through 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 (Hogan, 1980).

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

[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".

generally more clay than gypsum. The GAZ is predominantly gypsum-anhydrite with minor amounts of clay, sand and gypsum (Hogan, 1980).

The top of the BC salt dome lies between 600 and 700 ft below the surface. The east flank dips gently downward to 1,500 feet where the dip increases to approximately 80º between 2,000 and 6,000 ft. The west flank of the dome is overhung between 1,000 and 5,000 ft. Below 6,000 to 8,000 ft, the slope of the salt surface diminishes to about 60º (Hogan, 1980).

The lithology surrounding the salt dome contains up to 30,000 ft 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 (Hogan, 1980).

The stratigraphy near the BC salt dome is shown in Figure 3. The top layer of overburden, which consists of sand, silts, and clays, has a thickness of 500 ft. The caprock, consisting of gypsum, anhydrite, and sand, is 160 ft thick. The bottom of the deepest cavern (Cavern 27) is at a depth of 6,280 ft. 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 6,400 ft below the surface. All SPR caverns are located below 2,000 ft.

The faults shown in Figures 2 and 3 will be ignored in the FE model because the faults did not extend to the deep salt thus the faults could not affect the structural behavior of the SPR caverns. And, by ignoring the shear zone, the model of overburden and the cap rock layers are able to be simplified.

Figure 1. Bayou Choctaw SPR site location map

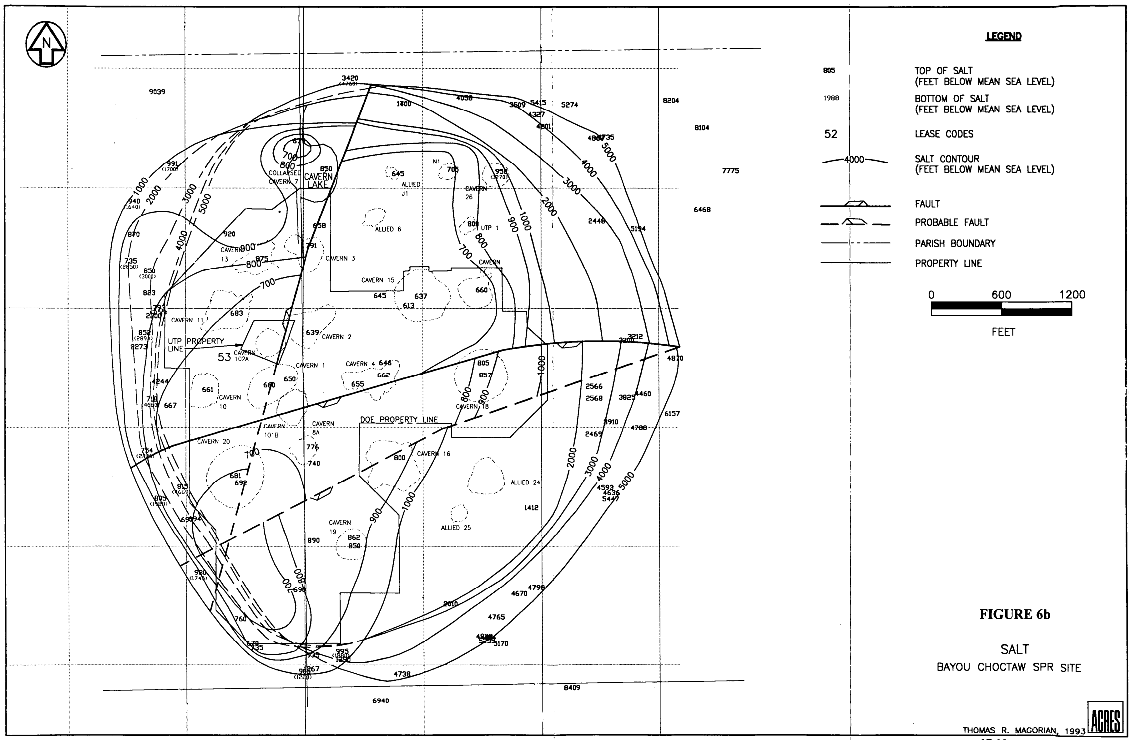

Figure 2 Bayou Choctaw site plan view (Neal et al., 1993)

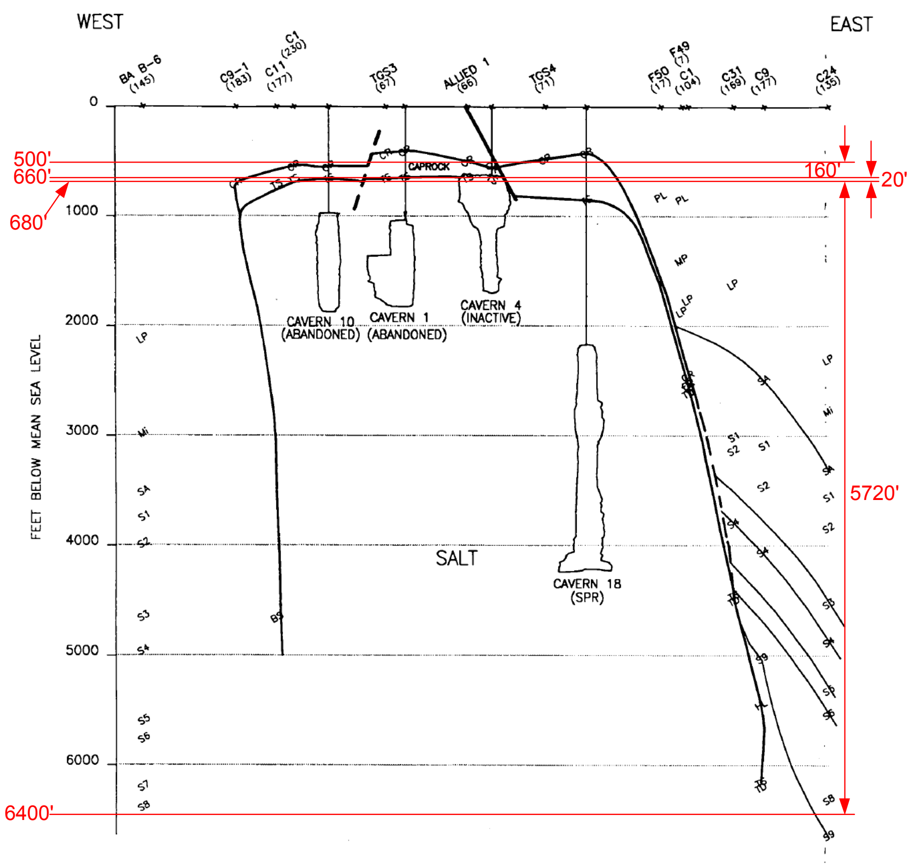

Figure 3 Stratigraphy near the Bayou Choctaw salt dome (Neal et al., 1993) and the thickness of each layer used for modeling.

3. Model Construction

3.1. Basic Rule

Finite element codes such as Sierra/Adagio[2] are designed to conduct simulations with finite elements that are either tetrahedral or hexahedral. Two constitutive models, i.e. power law creep (PLC) model and multi-mechanism deformation (M-D) model, are coded as material models to represent the salt behavior in Adagio. These two material models are programmed in Sierra/Adagio assuming eight-node hexahedral elements. Therefore, the mesh for the BC SPR site has to be constructed with hexahedral elements. Hexahedral elements include 6 convex quadrilateral sides, or facets, with the nodes for these facets being the eight nodes for the element. The cavern boundaries such as the ceiling, wall, and floor are obtained from sonar measurements, and the irregular geometries of these boundaries ultimately require various shapes of facets. Similarly, the geometry of the flank of the salt dome, obtained from seismic measurements, also consists of complicated shapes of facets. To construct a mesh with convex hexahedral elements for a geological volume keeping the complicated geometry as much as possible, the following rules were established and followed:

1. Each perimeter (cavern and dome) consists of the same number of vertices at each depth interval
2. Reference distance between vertices on a perimeter is:
    a. about 20 ft for caverns
    b. about 80 ft for dome
3. The vertical thickness of an element level is kept constant at 20 ft
4. 15% cavern volume increase for each drawdown leach

Figure 4 shows the meshed volume of BC-20 with the sonar image as an example. The circumference at each elevation varies. The average circumference is calculated from averaging the diameter obtained from the sonar data at each elevation. The number of intervals on a circumference is calculated to be 90 by dividing the average circumference by 20 ft, and then kept constant for each vertical layer. Thus the interval size between two vertices varies with elevation. The cavern volume consists of 90 lines from the ceiling to the floor as a blue line in Figure 4. The thickness of each element level is kept constant at 20 ft. Using this rule, coordinates of each vertex are resampled from the sonar image (will be described in Chapter 3.3).

Modeling of the leaching process of the caverns is performed by deleting a pre-meshed block of elements along the walls of the cavern so that the cavern volume is increased by 15 percent per drawdown. The 15% volume increase is typical for a standard freshwater drawdown, although salt quality can vary that amount. Also, typical leaching processes tend to increase cavern radius more at the bottom of the cavern than at the top, with very little change to the roof and floor of the cavern. For the purposes of this modeling effort for Bayou Choctaw, leaching is assumed to add 15% to the volume of the cavern, and is assumed to occur uniformly along the entire height of the cavern, with no leaching in the floor or roof of the caverns. Each leaching layer, or onion skin, is built around the perimeter of the meshed cavern volume using the same rules stated previously.

The X-axis of model is in the E-W (East-West) direction, Y-axis is in the N-S (North-South) direction, and Z-axis is the vertical direction. To realize the leaching process in the mesh, the coordinates of a vertex (X_1, Y_1) in Figure 5 have to be calculated for the first drawdown:

The coordinates of the center at each element level are:

$$X_c = \frac{\sum_{i=1}^{N} X_i}{N}, Y_c = \frac{\sum_{i=1}^{N} Y_i}{N} \quad (1)$$

where, N = number of vertices = 90 for BC-20, X_i, Y_i are shown in Figure 4.

The distance between the center point and a vertex (X_0, Y_0) on the perimeter of original cavern volume:

$$L_0 = \sqrt{(X_C - X_0)^2 + (Y_C - Y_0)^2} \quad (2)$$

[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.

The distance between the center point and a vertex (X_1, Y_1) on the perimeter of one drawdown leached volume:

$$L_1 = L_0\sqrt{1 + R_v} \tag{3}$$

where, $R_v =$ volume increase rate = 15% for BC salt

Then, the coordinate of a vertex (X_1, Y_1) on the perimeter of one drawdown leached volume are calculated as:

$$X_1 = X_C + (X_0 - X_C) \cdot \frac{L_1}{L_0},\ Y_1 = Y_C + (Y_0 - Y_C) \cdot \frac{L_1}{L_0} \tag{4}$$

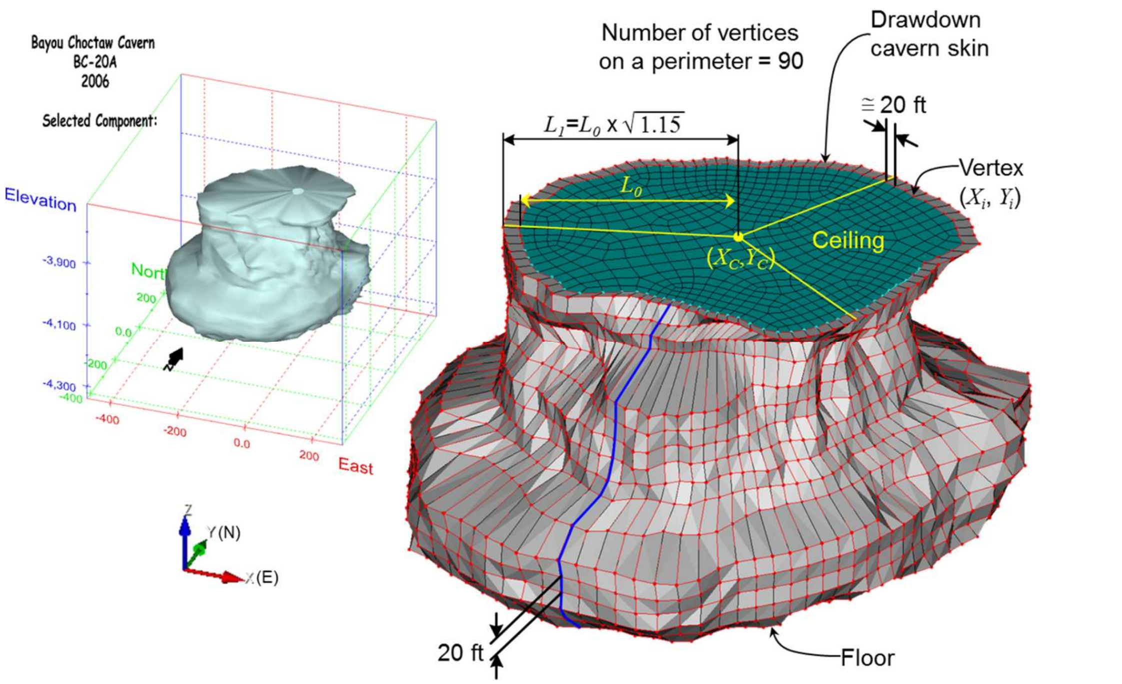

Figure 4. Sonar image (left) and meshed volume of Bayou Choctaw Cavern 20 with one drawdown cavern skin

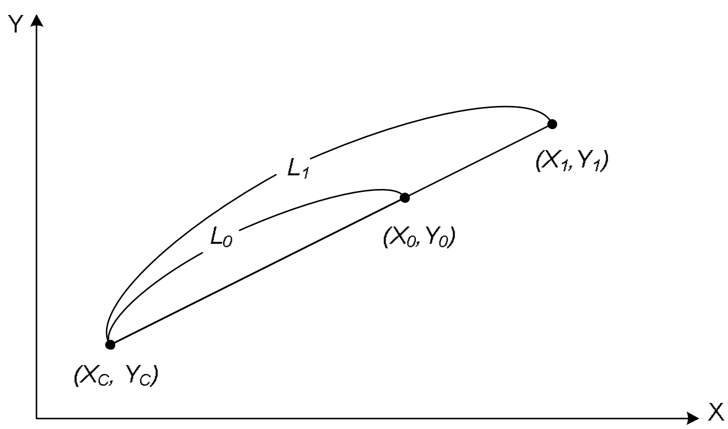

Figure 5. Calculation of coordinates of a vertex for the 1st drawdown cavern skin

3.2. Work Flow

Figure 6 shows the overall work flow to construct a mesh capturing realistic geometries of the Bayou Choctaw site. The BC 3D seismic data was shot in 1994 for petroleum exploration. The sonar surveys on BC caverns were performed on the dates as listed in Table 1. The cavern numbers are also defined in Table 1 to use in the CUBIT input journal. The top and bottom elevations of each cavern are calculated in the resampling step will be mentioned in Section 3.3. The data from the surveys are manipulated in the MVS[3] geologic modeling software suite. This step is necessary to provide a full three-dimensional surface model of the sonar and seismic data.

The vertices output for the geomechanical simulations need to be at specific depth intervals which may not correspond to the actual sonar sampling locations. Continuous three-dimensional surface models of the survey data are created, which allows sampling at any needed depth. This resampling step is performed through an algorithm coded using Python. Then, the resampled node coordinates data sets for the dome and caverns are generated as the output in this step.

The resampled nodal data are converted into CUBIT vertices data through MS Excel manipulation. 3D hexahedral element meshes for 26 caverns, salt dome, caprock, overburden, interbed, and interface between the dome and surrounding rock of BC SPR site, are constructed using various functions in CUBIT. Mesh quality is checked for each block in CUBIT. All meshes are combined into one Genesis hexahedral FE mesh using GJOIN[4]. The solver, Adagio, will be executed with the mesh to calculate the geomechanical behavior of caverns, dome and surrounding lithologies.

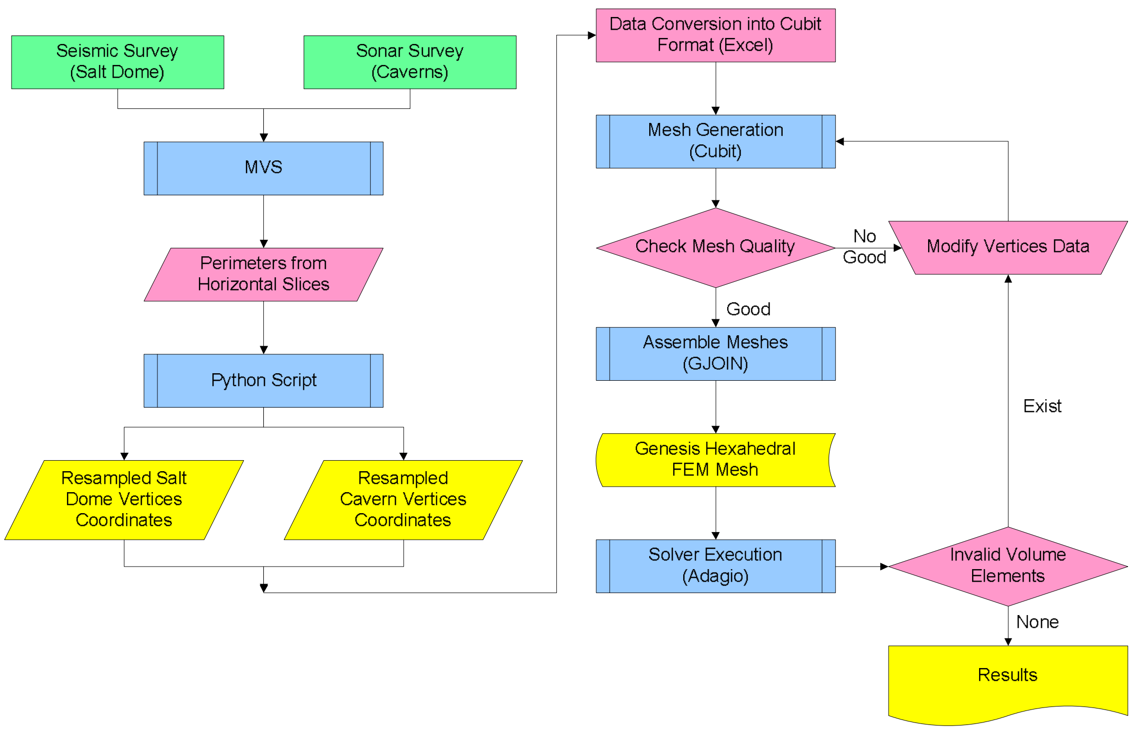

Figure 6. Work flow for the simulation using finite element mesh capturing realistic geometries of Bayou Choctaw site.

[3] MVS (Mining Visualization System) is C Tech's flagship product for state-of-the art analysis and visualization. MVS was designed from the ground up to meet the demanding requirements of underground and surface mining analysis; however, its tools are also used by civil engineers and advanced environmental modelers.
[4] GJOIN is a GENESIS database combinaiton program developed by Sandia.

Table 1. Date of the last sonar survey on BC caverns, cavern number, top and bottom elevations of the caverns

ID	Date of the sonar survey	Cavern/Dome number	Top elevation (ft)	Bottom elevation (ft)
BC-1	05-30-1980	001	-1040	-1820
BC-2	07-28-1983	002	-780	-1520
BC-3	07-13-1977	003	-1020	-1840
BC-4	07-30-2013	004	-640	-1660
BC-6	11-01-2006	006	-1240	-1560
BC-7	Collapsed in 1954	007	0	-1940
BC-8	05-31-1980	008	-1300	-1940
BC-10	09-13-1973	010	-1000	-1880
BC-11	03-10-1978	011	-1120	-1740
BC-13	08-13-1977	013	-1120	-1860
BC-15	04-15-2009	015	-2600	-3260
BC-16	06-28-2004	016	-2620	-3200
BC-17	04-16-2009	017	-2740	-3960
BC-18	01-06-2009	018	-2160	-4160
BC-19	04-14-2009	019	-2980	-4200
BC-20	12-13-2013	020	-3820	-4180
BC-24	04-16-1997	024	-3100	-4320
BC-25	10-30-2007	025	-2580	-5640
BC-26	10-11-1996	026	-2300	-3320
BC-27	10-28-2007	027	-5940	-6280
BC-28	10-29-2007	028	-4700	-6240
BC-J1	07-27-2006	031	-2860	-3900
BC-N1	12-05-2003	032	-1920	-3480
BC-UTP	10-14-2006	033	-2380	-3480
BC-101	04-14-2009	101	-2580	-4780
BC-102	02-22-2012	102	-2640	-5220
Salt Dome	Seismic survey in 1994	999	-680	-6400

3.3. Sonar and Seismic Data Resampling

3.3.1. Vertical Resampling

Representations of the BC caverns based on sonar data were incorporated into the geomechanical model to provide a more realistic depiction of the caverns. To facilitate this, the cavern sonar data were resampled to a nodal spacing more appropriate for the geomechanical model. This process was implemented using a custom Python script which operated on ASCII files containing representations of the sonar data. The output from the script was an ASCII file containing X, Y, and Z locations of the newly determined nodal sites. The details of this process are provided below.

The actual sonar data is delivered from the sonar contactors. An additional processing code SONAR7[5] was used to turn these contractor files into a format compatible with the MVS geologic modeling software suite. This is a mature process which has been used for many years at Sandia. This step is necessary to provide a full three-dimensional surface model of the sonar data. The nodal

[5] A data conversion program developed by Sandia. SONAR7 converts sonar data sets with various formats provided by different vendors into the extended file format (EFF) and other MVS compatible formats.

output for the geomechanical simulations needs to be at specific depth intervals which may not correspond to the actual sonar sampling locations. By creating a continuous three-dimensional surface model of the sonar data, we can resample the model at any depth desired.

This general process is shown in Figure 7 which shows a portion of a typical cavern. The left hand image shows the original sonar data as a mesh of three-dimensional points which create a continuous surface. The right hand image shows the same sonar surface overlaid by blue lines representing the desired sampling interval for the geomechanical simulations. This demonstrates how the original sonar data points do not necessarily line up with the desired vertical sampling interval, and how the continuous three-dimensional surface allows sampling at any needed depth.

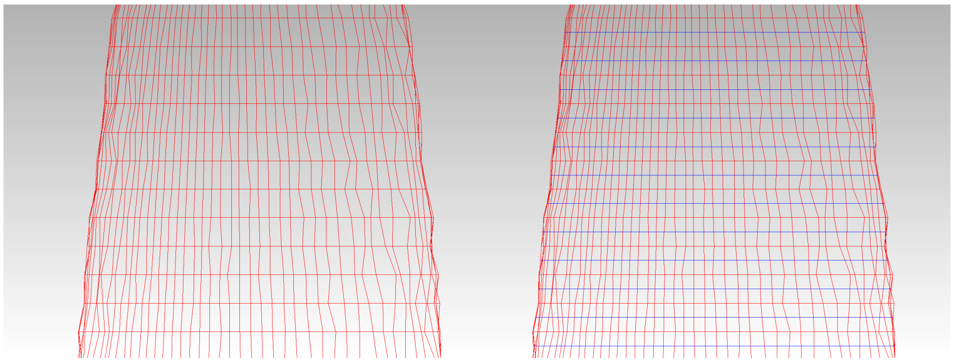

Figure 7. Comparison between original sonar data (left) and desired surface contour sampling shown by blue lines (right)

The blue line in Figure 7 represent contours of the cavern surface falling at the desired depth spacing. An example of this is shown in Figure 8. These contours of the cavern are then forwarded as ASCII files for use in further processing.

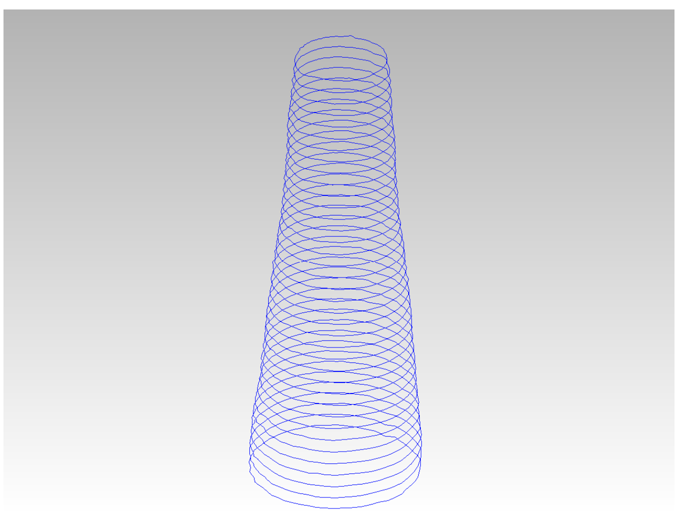

Figure 8. Contours of cavern created from 3D sonar surface

3.3.2. Horizontal Resampling

With the development of the cavern contour files, the cavern sonar data is now resampled to the necessary depth intervals. Now it is necessary to sub-sample the contours to a desired nodal spacing. For this, each ACII contour file is processed using a custom Python script. The Python script reads the contour file for a given cavern, then, at a predetermined depth, computes the number of nodes along the contour given a specific nodal spacing. This happens at a specified “template” depth which was chosen to have the circumference necessary to generate the desired number of nodes at an optimal nodal spacing.

Using this template contour as a polygon, the circumference length and desired node spacing is used to compute the total node count for this depth contour. This value is then used to calculate the angular displacement between radial rays originating at the center of the contour polygon, radiating outwards, and intersecting the polygon. These intersections define the locations of the nodes for that depth contour. Figure 9 shows an example of this.

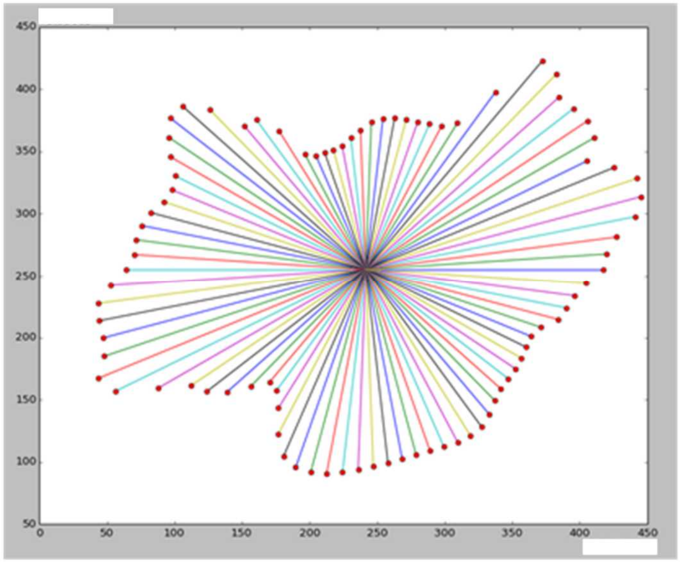

Figure 9. Example of radial rays propagating from center of contour polygon to each circumference nodal location

The process of propagating rays from the center of the contour polygons is repeated for each depth contour. During this process the same nodal count is maintained for each depth level. This allows for the connection of the node locations during the meshing procedure.

An example of the final nodal configuration from this process is shown in Figure 10. These final node locations are then written to an ASCII file for incorporation into the mesh structure for the geomechanical simulation model. A similar process was applied to the three-dimensional geologic model of the BC salt dome.

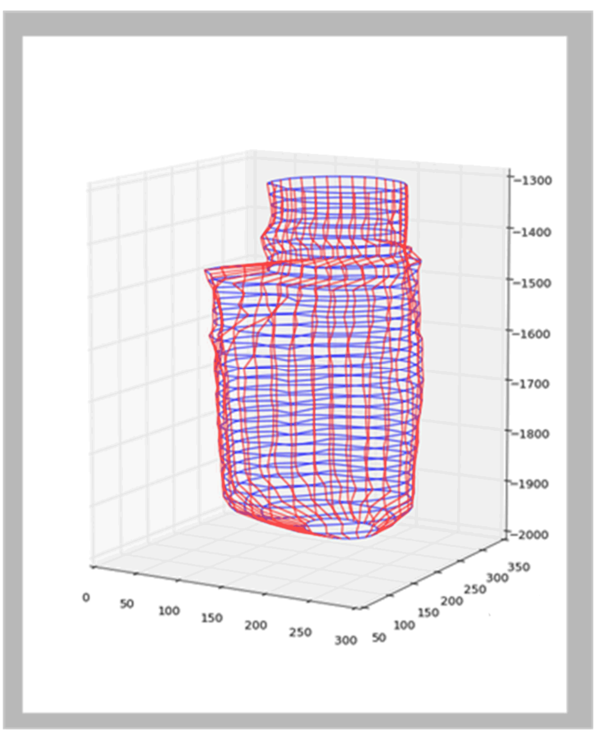

Figure 10. Final node configuration resulting from resampling of cavern sonar data

3.4. Cavern

Figure 11 shows the procedure to create a cavern mesh of BC-20 as an example. The sonar image of the cavern boundary including cavern ceiling, wall, and floor is obtained from the sonar survey. The 3D-coordinates of the vertices are resampled from the sonar image. Cavern slice block 20 ft thick layers are generated using the coordinates of vertices. The cavern mesh has to be composed of hexahedral elements. The hexahedral element shape has to be translated from the top through the bottom of the model. Therefore, the upper and lower salt blocks, interbed block, caprock block, and overburden block are needed. The hexahedral element meshes are created in the overburden layer first. The quadrilateral element shapes on the top surface of the overburden block translate to the bottom surface of the block. The element shapes on the bottom surface of the overb urden block transfer to the top surface of the caprock block through merging the surfaces. In the same manner, the hexahedral element shapes of the overburden block are translated through the interbed, upper salt, cavern ceiling, cavern body, cavern floor, and lower salt blocks. Those meshed blocks are assembled into the cavern column. The upper salt block leans to the left (west) because the dome leans to the west (Figure 12). To avoid poor shape elements in the salt between the dome edge and the upper salt block, the upper salt column needs to be parallel to the dome edge as much as possible. In the same manner, the other 25 cavern columns are generated for the remaining 25 caverns.

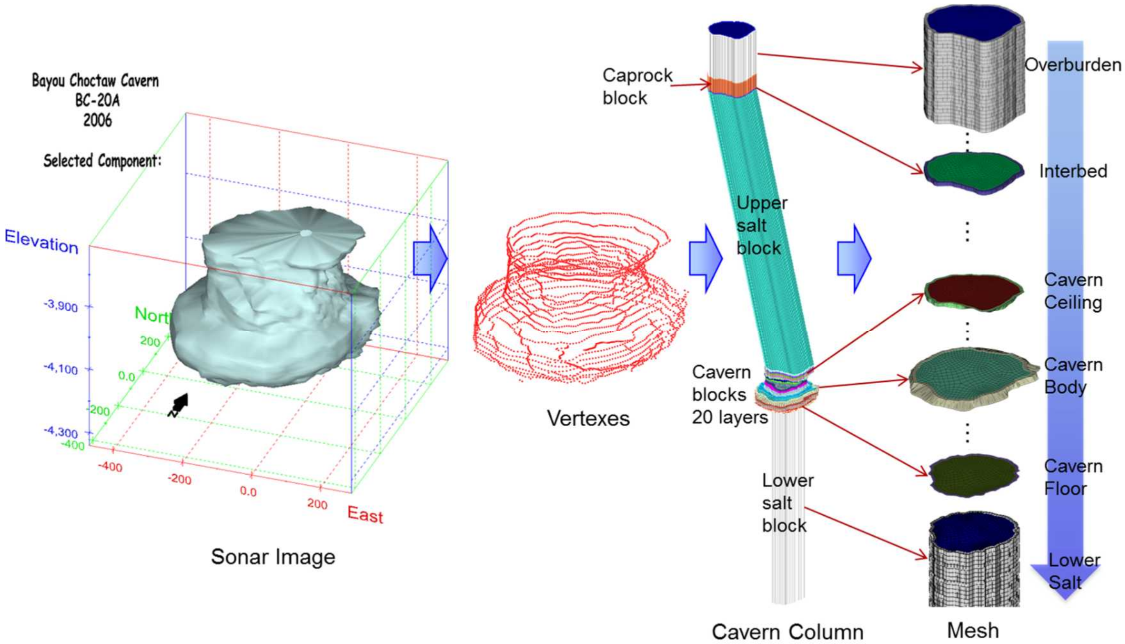

Figure 11. Work flow to create Bayou Choctaw Cavern 20 mesh

3.5. Dome

Figure 12 shows the procedure to create the BC dome mesh. The image of the dome boundary such as dome top and flank are obtained from the seismic survey in 1994 (Rautman et al., 2009). The 3D-coordinates of vertices are resampled from the seismic image. The real interbed between the salt dome and caprock is not flat. The uneven interbed should create poorly shaped elements. To avoid the poor shape, the vertex data above the elevation of -1320 ft are removed (called 'trimming'). The salt dome leans to the west. The coordinates of vertices at every 20 ft element level from elevations -1320 ft through -680 ft are calculated considering the leaning. The dome centers X-, Y-coordinates at elevations -4000 ft and -900 ft are (-62.50, 134.99) and (-782.10, 16.62). The differences between two coordinates DX, DY, and DH are calculated to be 719.61 ft, 118.37 ft, and -3100 ft, respectively. The leaning is calculated using DX, DY, and DH. In similar, the vertices data below the elevation of -5880 ft are removed (trimming). The vertex data for the lower salt blocks are translated vertically downward from the vertex data of the bottom of trimmed salt dome block (-5880 ft). The leaning slope of dome is not considered for the lower salt block.

The dome mesh has to be composed of hexahedral elements. The hexahedral element shape has to be translated from the top through the bottom of the model. Therefore, the overburden block, caprock block, interbed block, upper salt blocks, and lower salt blocks have to be generated first. The vertex data for the upper salt blocks are translated upward from the vertex data of the trimmed salt dome top. The upper salt block leans to the west to match the trend of the trimmed salt dome body. The vertex data for the interbed, caprock, and overburden blocks are translated vertically upward from the vertices data of the top of upper salt blocks. 283 dome slice blocks with 20 ft thickness are created using the coordinates of vertices. Finally, the dome column consists of 286 slice blocks including the overburden block 500 ft thick, caprock block 160 ft thick, and bottom salt dome block 100 ft thick. The interbed block will be separated from the caprock block with 20 ft thick.

Each block is punched with 26 cavern columns which were generated in the previous section. The vertices data of each hole in the dome layer blocks are transferred from the cavern columns. The mesh will be created with the vertices of each hole and dome perimeter.

The hexahedral mesh in each block will be translated from over/under block. The cross-section areas of each cavern column and dome column are varied with depth. Considering the cross-sectional areas of the pillars between caverns; caverns and dome edge, the optimum base layer block is selected to avoid creating poor shape elements, so creating the number of poor shape elements in every layer block is as little as possible. The hexahedral element meshes are created at the base slice block which bottom is located at -2760 ft below the surface with 20 ft thick. The quadrilateral element shapes on the top of the base slice block translate upward through the top of the dome column, and the element shapes on the bottom of the base layer block translate downward through the bottom of the dome column. 286 meshed layer blocks are assembled into the dome column which consists of 320 element levels (the height of dome column is 6400 ft). The dome leans to the west as shown in Figure 12.

3.6. Surrounding rock

Figure 13 shows the procedure to create the BC surrounding rock (far field) mesh. To represent the far field surrounding the BC dome, a rectangular brick, whose widths in E-W and N-S directions are approximately two times the maximum widths of dome in the E-W and N-W directions, respectively, is created at -6400 ft depth. The rectangular brick is the base surrounding rock slice block whose thickness and bottom elevation are 100 ft and -6400 ft, respectively.

The bottom salt dome skin block, which was created in the previous section, is inserted into the base block and punched with the bottom salt dome skin block. The vertices data of the dome perimeter are transferred from the salt dome skin block. The number of intervals on E-W and N-S sides of the block is 20 which is selected as a balance number between the total number of elements and element shape. The number of intervals is one of key factors to determine the total number of elements in the model. Larger number of elements consumes more computer running time, but makes better mesh quality. The hexahedral element mesh is constructed with the vertices and the intervals. The thickness of each element layer sets up 20 ft in this model. The mesh has five element levels vertically because the thickness of the base block is 100 ft.

In the similar manner, a rectangular block is created right above the base block. The top surface of the base block becomes the bottom surface of the new block. New blocks are constructed over the base block upward to the surface. Each layer block is assembled as the surrounding rock.

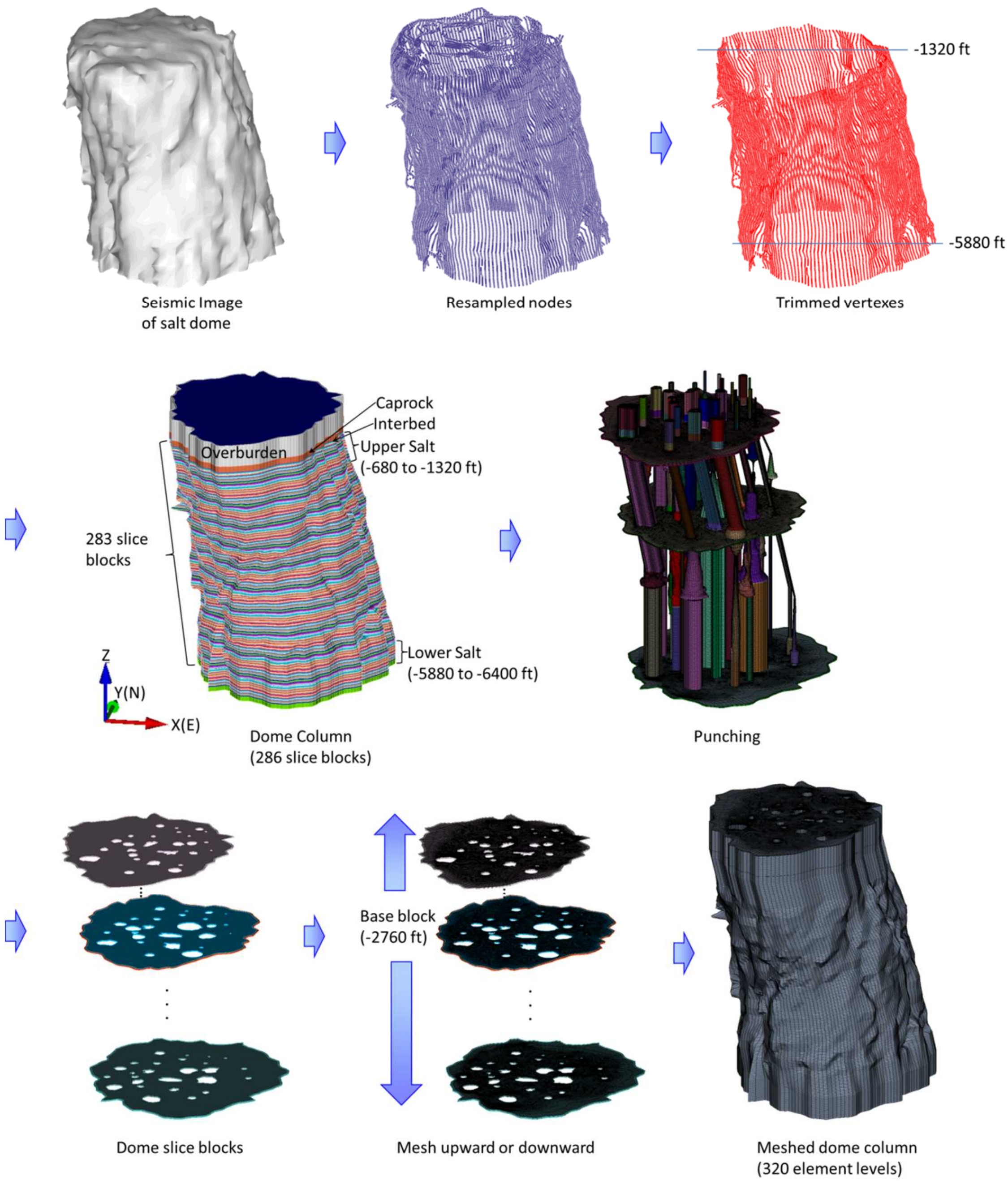

Figure 12. Work flow to create Bayou Choctaw dome mesh

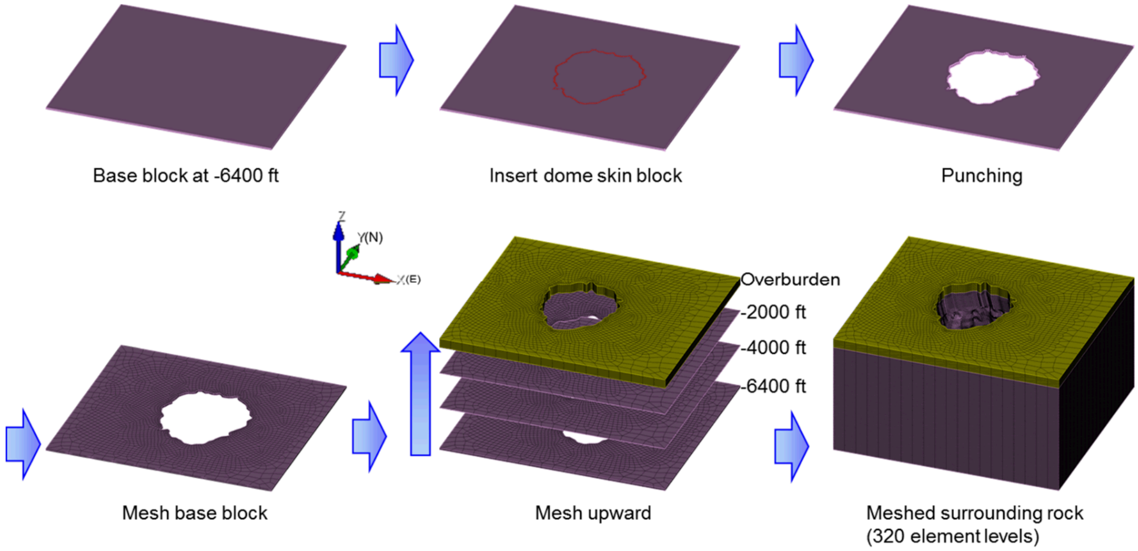

Figure 13. Work flow to create Bayou Choctaw surrounding rock (far field) mesh

3.7. Assemble

26 cavern columns and dome column created in Sections 3.4 and 3.5 are combined into the BC-dome as shown Figure 14 through the GJOIN process. The BC-Dome and surrounding rock column created in Section 3.6 are combined into the entire BC-model as shown Figure 15 through the GJOIN process. The geologic temperature data will be added into the entire model. Figure 16 shows the overview of the hexahedral finite element mesh of the stratigraphy and cavern field at BC SPR site. The mesh consists of 7,796,127 nodes and 7,758,720 elements with 170 element blocks, 3 node sets, and 55 side sets.

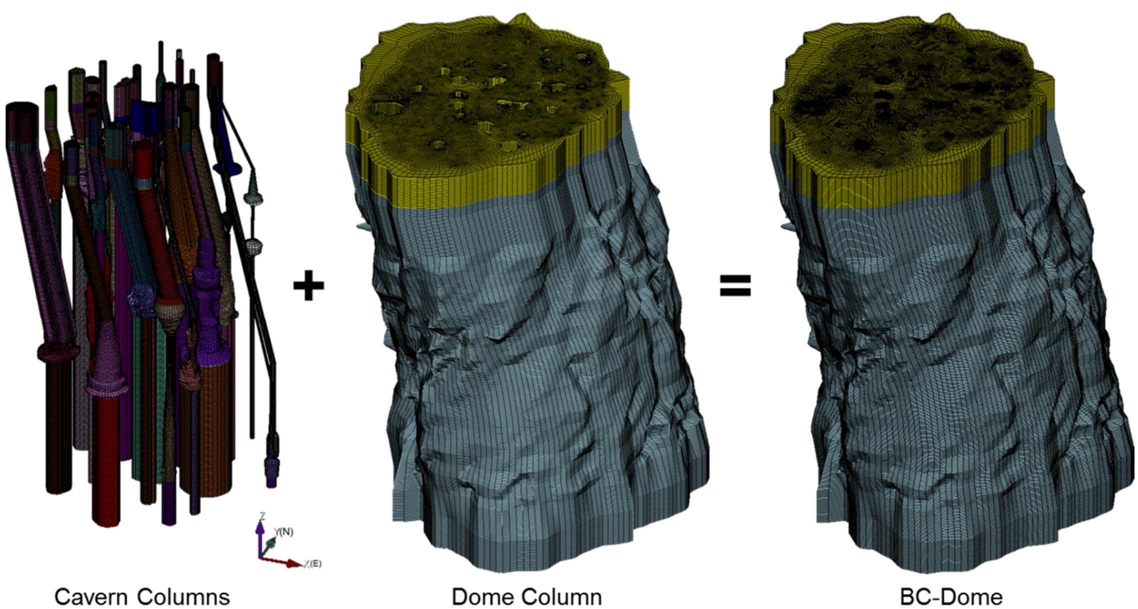

Figure 14. Cavern columns and dome column are combined into BC-Dome

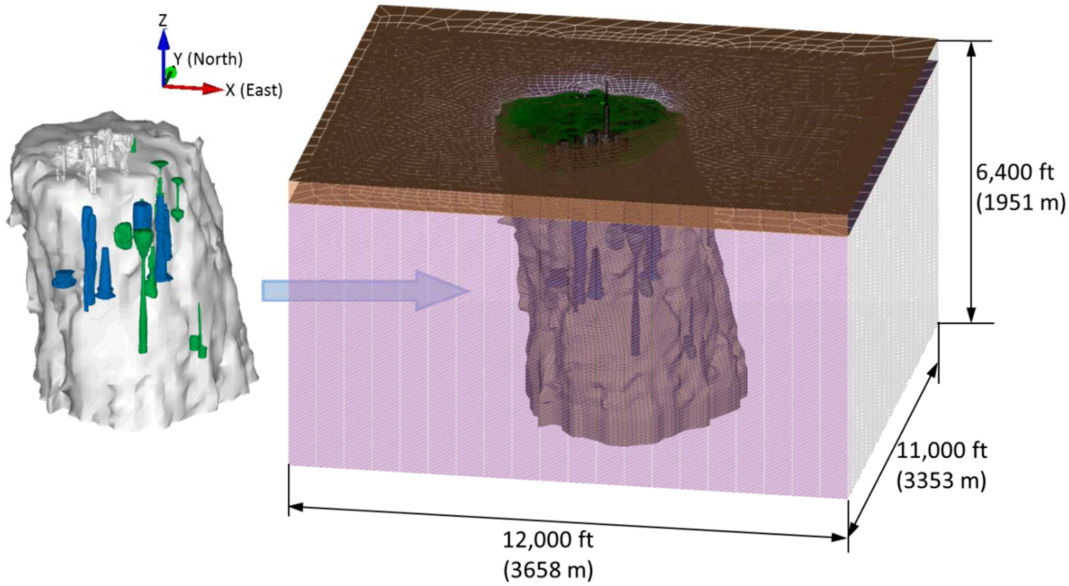

Figure 15: The images of salt dome and caverns obtained from the seismic and sonar surveys, respectively (left) and the hexahedral elements mesh capturing realistic geometries of Bayou Choctaw Strategic Petroleum Reserve.

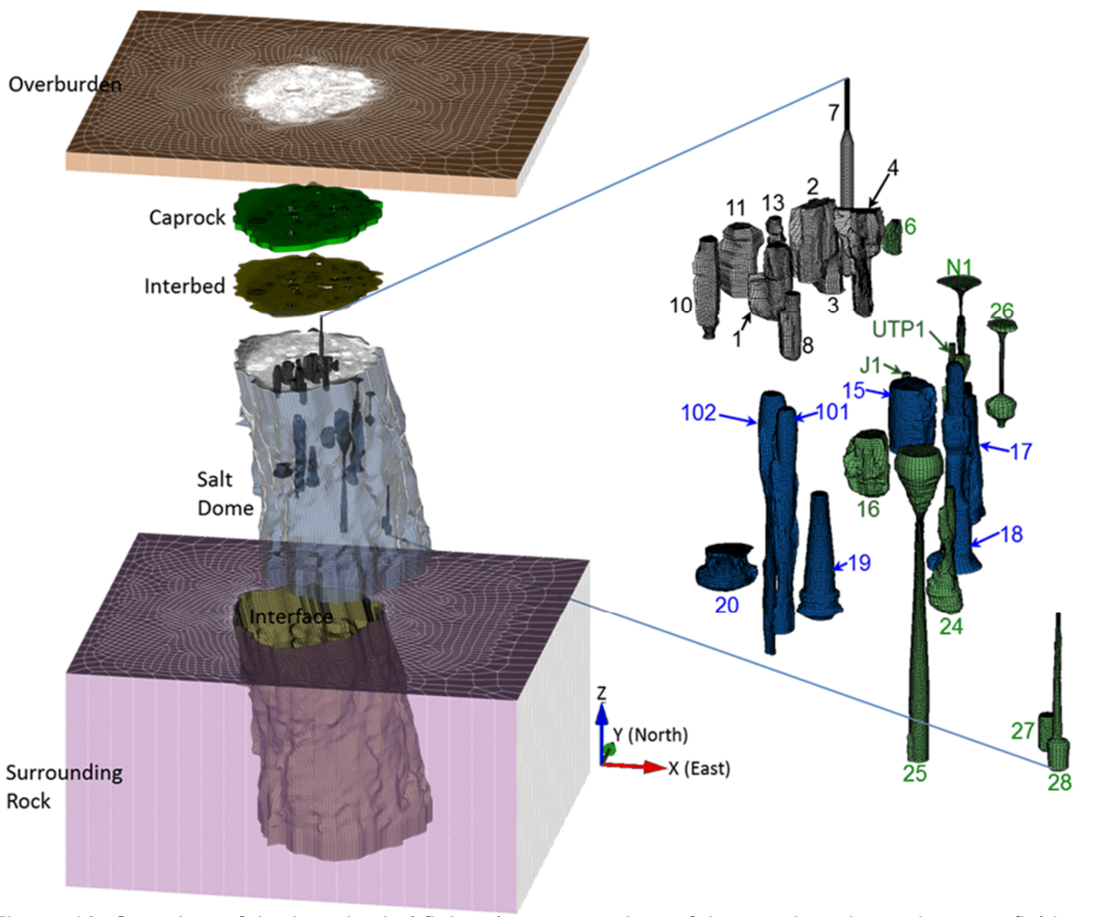

Figure 16: Overview of the hexahedral finite element meshes of the stratigraphy and cavern field at Bayou Choctaw. The U.S. Strategic Petroleum Reserve stores crude oil in the seven blue caverns. Green shows privately owned caverns, and grey depicts abandoned caverns. The cavern ID numbers are also shown.

4. Conclusions

The three-dimensional FE mesh capturing realistic geometries of Bayou Choctaw site has been constructed using the sonar and seismic survey data obtained from the field. Various ideas and techniques to construct the mesh capturing artificially and naturally formed geometries are introduced. The steps and methodologies in this paper are being applied to construct the meshes of Big Hill, Bryan Mound, and West Hackberry SPR sites. The newly developed mesh documented in this paper is currently being used in large-scale numerical simulations of the geomechanical behavior of the Bayou Choctaw oil storage facility. The analyses using this new mesh will allow for a new, detailed examination of the mechanical stability of BC-20 and the caprock over BC-4, as well as the effects of close-proximity, undercutting domal walls near a cavern.

These ideas and techniques could be applied to various cases. For example, the caverns and salt dome in this paper are tall (vertically long), so the volumes are divided by horizontal slice blocks 20 ft thick. A tunnel or horizontally long structure in mountains or subsurface can be divided by vertical slice blocks with any thickness. The methodology could be applied to the complicated shape masses for not only various civil and geological structures but also biological applications such as artificial limbs.

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