STABILITY ANALYSES OF DIFFERENTLY SHAPED SALT CAVERNS
FOR UNDERGROUND NATURAL GAS STORAGE

A Thesis in
Energy and Mineral Engineering

by
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ABSTRACT

The primary purpose of underground storage for natural gas is to balance the variable demand for gas in high consumption seasons against the constant supply by production. There are three basic types of underground storage including depleted reservoirs, aquifers and salt caverns. Construction and use of salt cavern storage has expanded significantly during the past decades because it has a rapid cycling ability with to meet daily even hourly variations in customer needs. Cavern stability is the most important consideration for storage cavern design. Main factors for the structural stability of caverns in salt formation are local geology, rock properties, cavern depth, cavern geometry and cavern locations. In this study, impact of different design parameters on cavern stability and possible deformation characteristics such as displacement, shear and volumetric strain are investigated. For this purpose, numerical modeling using finite element method (FEM) was used. The FEM modeling program Phases© version 7.0 by RocScience was utilized for stability analyses. This program provides useful data on stress distribution, ground displacement and strains as a function of parameters such as in-situ stress ratio, cavern depth and salt properties. A parametric study was performed to evaluate the sensitivity of the program output and results to rock properties, in-situ stresses, and cavern design parameters. The effect of each design factor on the cavern stability with different shapes was studied. The objective of the modeling was to provide optimum cavern design for the given geological conditions. Three specified cavern shapes including cylindrical, tapered cylinder and teardrop was considered in this parametric study. The modeling was performed for three different scenarios. First, single cavern design was studied and behavior of different shaped single caverns was investigated. This effort provided a basis for selection of the most suitable cavern design for underground natural gas storage. The result of modeling showed that the cylindrical design with domed ceiling and floor is the most stable shape and the deformations were below 2% diameter, which is considered to be a reasonable rate for prevention of failure in underground structures. The 2nd step was to study the impact of excavating multiple caverns and the resulting stress, deformation, and stability issues. For multiple caverns, the cavern interaction was the main consideration to evaluate the effects of the spatial configuration of the caverns on deformation of neighboring caverns. The distance of two times the diameter of larger caverns is determined to eliminate mutual interactions between caverns. The third step was to assess the influence of depth of cavern within the salt formation or salt thickness on cavern design. Sufficient salt should be left above the cavern to provide the safe redistribution of stresses. The optimum distance between cavern top and salt formation is investigated and distance of at least one diameter seem to be sufficient to prevent negative interference from the overburden or cap rock.
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NOMENCLATURE

Latin and Greek Letters

D  Diameter of Cavern, m

$e_a$  Permanent Strain

h  Depth Below the Surface, m

H  Cavern Height, m

k  In-situ Stress Ratio

$X$  Ultimate Failure

$\nu$  Poisson’s Ratio of the Material

$\gamma$  Weight Density of the Overlying Material, MN/m$^3$

$\sigma_C$  Critical Stress

$\sigma_H$  Horizontal Virgin In-situ Ground Stress

$\sigma_V$  Vertical Virgin In-situ Ground Stress
**Abbreviations**

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<td>BOTAS</td>
<td>Petroleum Pipeline Corporation</td>
</tr>
<tr>
<td>Bcf</td>
<td>Billion Cubic Feet</td>
</tr>
<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
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<td>International Energy Agency</td>
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<td>UGS</td>
<td>Underground Gas Storage</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

Always an expression is addressed to commemorative people during a grand period of time. Here I want to take this opportunity to express my indebtedness to Dr. Luis Ayala- mentor and advisor both of this thesis and my life at Penn State. I am deeply thankful for his guidance, support, encouragement and patience in my progress of academic learning and exploration. I would like to express my gratitude to Dr. Jamal Rostami for his erudition, instructive suggestion, invaluable and insightful comments that enhanced this work and thesis. I also want to thank Dr. John Yilin Wang for being part of my thesis committee.

I am exceedingly grateful to my sister and my parents who stand behind me from the first day of my life journey and encourage me in every step.

While I am close to a finishing point, I am standing on another starting point of the life cycle.
Chapter 1

INTRODUCTION

Energy is essential to our life and growing economy. It is fundamental for everything from fueling our cars to heating our homes to powering the appliances we use daily. The growing population, economic developments, and technological improvements change the scope of energy use. In a positive sense, it leads to energy-efficiency and cleaner fuels. Energy efficiency is critical for extending the life-time of our energy supplies and reducing the amount of greenhouse gases being emitted. In addition, the technological developments lead us towards exploring additional energy sources and make energy more affordable. This is very important to create new jobs and improve trade around the world.

The world’s population is expected to expand by 2 billion by the year of 2040 (ExxonMobil 2013). This means that there are more transportation requirements, growing electricity needs for homes and other facilities, and more energy supply for power industry. Demographics is one of the most important factors for energy demand. The young working population leads to a stronger economy and more energy consumption. Supplying energy in a safe, reliable and affordable way helps with the growing economy needs and the social development. However, economic growth and improved living standards require more energy than ever. It is estimated that the global economy will grow at annual average rate of 2.8% from 2010 to 2040 (ExxonMobil 2013).

The improvements in the world will cause to increase in energy need for homes, industry, transportation, electricity generation and other vital services. By 2040, residential and commercial energy demand will increase by 30% (ExxonMobil 2013). Energy demand in transportation is expected to rise by 40% over the next 30 years due to the growing economies and international trade (ExxonMobil 2013). The need of industrial energy will continue to increase since it is essential for new jobs, stable economies, daily goods and services. Computers, cell phones, home appliances all depend on electricity to work. The need of power grows up significantly while the number of homes and businesses in the world increase. It is expected to rise by 55% in the fuel for electricity generation (ExxonMobil 2013).
1.1 Energy Consumption by Source

Energy sources can be divided into three main groups:

a) Fossil Fuels (Coal, Natural Gas, Petroleum)

b) Nuclear Power

c) Renewable Energy (Hydroelectric Power, Geothermal, Solar, Wind, Biomass)

Table 1.1 presents data of primary energy consumption by source. The last five year average of energy consumption was about 100 Trillion cubic feet (Tcf). Fossil fuels have an important role for energy demand. Figure 1.1 illustrates the primary energy consumption by source. They account for 80% of overall energy consumption in 2011.

Table 1.1: Primary Energy Consumption by Source in the US (Tcf) (EIA)

<table>
<thead>
<tr>
<th>Year</th>
<th>Coal (Tcf)</th>
<th>Natural Gas (Tcf)</th>
<th>Petroleum (Tcf)</th>
<th>Nuclear Power (Tcf)</th>
<th>Hydroelectric Power (Tcf)</th>
<th>Geothermal (Tcf)</th>
<th>Solar (Tcf)</th>
<th>Wind (Tcf)</th>
<th>Biomass (Tcf)</th>
<th>Total (Tcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>22.749</td>
<td>23.663</td>
<td>39.774</td>
<td>8.455</td>
<td>2.446</td>
<td>0.186</td>
<td>0.076</td>
<td>3.474</td>
<td>101.296</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>22.385</td>
<td>23.843</td>
<td>37.280</td>
<td>8.427</td>
<td>2.511</td>
<td>0.192</td>
<td>0.089</td>
<td>3.489</td>
<td>99.275</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>19.692</td>
<td>23.416</td>
<td>35.403</td>
<td>8.356</td>
<td>2.669</td>
<td>0.200</td>
<td>0.098</td>
<td>0.721</td>
<td>94.559</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>20.971</td>
<td>24.256</td>
<td>36.010</td>
<td>8.434</td>
<td>2.539</td>
<td>0.208</td>
<td>0.126</td>
<td>0.923</td>
<td>97.664</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>19.663</td>
<td>24.757</td>
<td>35.465</td>
<td>8.269</td>
<td>3.103</td>
<td>0.213</td>
<td>0.158</td>
<td>1.168</td>
<td>97.365</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1.1: Primary Energy Consumption by Source in the US (%) (EIA)
1.2 Importance of Natural Gas

Natural gas is an abundant, widespread energy source that will have the highest growing rate of major fuel to 2040. The International Energy Agency (IEA) announces that there is 28,000 Tcf of gas sources in the world (ExxonMobil 2013). This is a sufficient source for the current demand levels for more than 200 years. It is reliable, efficient and affordable. A switch towards gas will provide many benefits for consumers and the environment since it is the least carbon-intensive of energy source. It emits up to 60% less carbon dioxide (CO$_2$) than coal for electricity generation.

The trend of energy source to power our world is changing due to technological developments. It is estimated that natural gas will be the first source for electricity generation by 2040. Gas supply in the world rises by 65% over the next 30 years (ExxonMobil 2013). This increase is a result of modern technology to explore the new resources, which once was difficult to extract.

Gas plays an important role in the energy supply and demand chain, while new technology helps to explore this abundant, clean energy source. For example, in Figure 1.1, the portion of natural gas in overall consumption was about 23% in 2007, while this rate increased to 25% in 2011. Therefore, it is expected that gas will have a significant role over the next 30 years.

1.3 Use of Natural Gas by Sector

There are five basic consumption groups in natural gas as residential, commercial, industrial, transportation and electric power. Table 1.2 presents data of gas consumption by sector. Industrial and electric power sectors have the largest share in gas consumption. Figure 1.2 illustrates the share of gas consumption by sector. They account for 65% of overall gas consumption in 2011.

Table 1.2: Natural Gas Consumption by Sector in the US (Bcf) (EIA)

<table>
<thead>
<tr>
<th>Year</th>
<th>Residential</th>
<th>Commercial</th>
<th>Industrial</th>
<th>Transportation</th>
<th>Electric power</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>4,722</td>
<td>3,013</td>
<td>7,881</td>
<td>646</td>
<td>6,841</td>
</tr>
<tr>
<td>2008</td>
<td>4,892</td>
<td>3,153</td>
<td>7,890</td>
<td>674</td>
<td>6,668</td>
</tr>
<tr>
<td>2009</td>
<td>4,779</td>
<td>3,119</td>
<td>7,443</td>
<td>697</td>
<td>6,873</td>
</tr>
<tr>
<td>2010</td>
<td>4,787</td>
<td>3,102</td>
<td>7,800</td>
<td>700</td>
<td>7,387</td>
</tr>
<tr>
<td>2011</td>
<td>4,729</td>
<td>3,164</td>
<td>8,103</td>
<td>716</td>
<td>7,574</td>
</tr>
</tbody>
</table>
1.4 Need of Underground Natural Gas Storage

Gas storage is primarily processed to balance the variable demand that is defined as consumption against supply. And supply is described as production and import by both pipelines and liquefied natural gas (LNG). Table 1.3, 1.4 and 1.5 present gas production, import and consumption by month, respectively. These data are essential to understand the importance of gas storage.

### Table 1.3: Natural Gas Production by Month in the US (Bcf) (EIA)

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>1,576</td>
<td>1,444</td>
<td>1,625</td>
<td>1,552</td>
<td>1,643</td>
<td>1,590</td>
<td>1,625</td>
<td>1,634</td>
<td>1,598</td>
<td>1,654</td>
<td>1,633</td>
<td>1,693</td>
</tr>
<tr>
<td>2008</td>
<td>1,686</td>
<td>1,591</td>
<td>1,723</td>
<td>1,662</td>
<td>1,717</td>
<td>1,681</td>
<td>1,769</td>
<td>1,744</td>
<td>1,489</td>
<td>1,675</td>
<td>1,679</td>
<td>1,744</td>
</tr>
<tr>
<td>2009</td>
<td>1,782</td>
<td>1,624</td>
<td>1,786</td>
<td>1,699</td>
<td>1,756</td>
<td>1,707</td>
<td>1,741</td>
<td>1,755</td>
<td>1,652</td>
<td>1,729</td>
<td>1,674</td>
<td>1,717</td>
</tr>
<tr>
<td>2010</td>
<td>1,750</td>
<td>1,611</td>
<td>1,794</td>
<td>1,723</td>
<td>1,791</td>
<td>1,712</td>
<td>1,817</td>
<td>1,832</td>
<td>1,785</td>
<td>1,849</td>
<td>1,792</td>
<td>1,877</td>
</tr>
<tr>
<td>2011</td>
<td>1,880</td>
<td>1,674</td>
<td>1,921</td>
<td>1,884</td>
<td>1,945</td>
<td>1,881</td>
<td>1,944</td>
<td>1,951</td>
<td>1,910</td>
<td>2,008</td>
<td>1,971</td>
<td>2,031</td>
</tr>
</tbody>
</table>

### Table 1.4: Natural Gas Import by Month in the US (Bcf) (EIA)

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>393.14</td>
<td>372.87</td>
<td>401.78</td>
<td>386.84</td>
<td>380.21</td>
<td>381.47</td>
<td>418.58</td>
<td>426.53</td>
<td>361.38</td>
<td>347.22</td>
<td>340.61</td>
<td>396.95</td>
</tr>
<tr>
<td>2008</td>
<td>389.65</td>
<td>349.66</td>
<td>366.81</td>
<td>322.12</td>
<td>297.15</td>
<td>286.92</td>
<td>322.81</td>
<td>328.66</td>
<td>313.87</td>
<td>321.33</td>
<td>320.25</td>
<td>364.86</td>
</tr>
<tr>
<td>2009</td>
<td>356.75</td>
<td>321.52</td>
<td>325.17</td>
<td>321.85</td>
<td>265.79</td>
<td>281.97</td>
<td>316.72</td>
<td>336.85</td>
<td>307.03</td>
<td>273.12</td>
<td>294.92</td>
<td>349.68</td>
</tr>
<tr>
<td>2010</td>
<td>384.59</td>
<td>324.12</td>
<td>318.77</td>
<td>298.46</td>
<td>297.80</td>
<td>282.26</td>
<td>328.66</td>
<td>304.90</td>
<td>281.52</td>
<td>294.74</td>
<td>273.17</td>
<td>351.77</td>
</tr>
<tr>
<td>2011</td>
<td>370.96</td>
<td>307.97</td>
<td>314.26</td>
<td>278.25</td>
<td>270.65</td>
<td>265.21</td>
<td>292.54</td>
<td>279.28</td>
<td>253.27</td>
<td>280.92</td>
<td>247.47</td>
<td>295.17</td>
</tr>
</tbody>
</table>
Table 1.5: Natural Gas Consumption by Month in the US (Bcf) (EIA)

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>2,476</td>
<td>2,567</td>
<td>2,129</td>
<td>1,810</td>
<td>1,559</td>
<td>1,555</td>
<td>1,660</td>
<td>1,896</td>
<td>1,590</td>
<td>1,628</td>
<td>1,835</td>
<td>2,399</td>
</tr>
<tr>
<td>2008</td>
<td>2,734</td>
<td>2,503</td>
<td>2,278</td>
<td>1,824</td>
<td>1,576</td>
<td>1,604</td>
<td>1,709</td>
<td>1,683</td>
<td>1,461</td>
<td>1,636</td>
<td>1,869</td>
<td>2,400</td>
</tr>
<tr>
<td>2009</td>
<td>2,730</td>
<td>2,333</td>
<td>2,171</td>
<td>1,741</td>
<td>1,504</td>
<td>1,528</td>
<td>1,658</td>
<td>1,736</td>
<td>1,575</td>
<td>1,667</td>
<td>1,776</td>
<td>2,492</td>
</tr>
<tr>
<td>2010</td>
<td>2,783</td>
<td>2,456</td>
<td>2,117</td>
<td>1,667</td>
<td>1,591</td>
<td>1,624</td>
<td>1,800</td>
<td>1,853</td>
<td>1,612</td>
<td>1,639</td>
<td>1,947</td>
<td>2,685</td>
</tr>
<tr>
<td>2011</td>
<td>2,876</td>
<td>2,434</td>
<td>2,226</td>
<td>1,826</td>
<td>1,663</td>
<td>1,649</td>
<td>1,874</td>
<td>1,872</td>
<td>1,640</td>
<td>1,746</td>
<td>2,006</td>
<td>2,515</td>
</tr>
</tbody>
</table>

The need of gas peaks during winter months and market demands exceed supply. Therefore, the gas is withdrawn from the storage facility to compensate the difference. During non-heating seasons, the consumption starts to decline, the supply exceeds the market demand and the gas is injected into the facility. Figure 1.3 demonstrates gas storage operations by month in regard to this procedure.

Figure 1.3: Natural Gas Underground Storage Net Withdrawal by Month in the US (Tcf) (EIA)

Table 1.6 presents data of gas storage operations by month. Negative values exhibit the injection of gas into the facility during non-heating seasons. Positive values exhibit the withdrawal of gas from the facility during winter months.
Table 1.6: Natural Gas Underground Storage Net Withdrawal by Month in the US (Bcf) (EIA)

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>683.25</td>
<td>731.86</td>
<td>50.41</td>
<td>-119.72</td>
<td>-459.54</td>
<td>-389.47</td>
<td>-313.61</td>
<td>-126.64</td>
<td>-298.19</td>
<td>-256.54</td>
<td>121.32</td>
<td>568.96</td>
</tr>
<tr>
<td>2009</td>
<td>705.06</td>
<td>371.56</td>
<td>92.81</td>
<td>-250.81</td>
<td>-466.98</td>
<td>-385.63</td>
<td>-338.20</td>
<td>-274.37</td>
<td>-295.16</td>
<td>-167.39</td>
<td>-33.47</td>
<td>693.84</td>
</tr>
<tr>
<td>2010</td>
<td>810.85</td>
<td>619.47</td>
<td>30.86</td>
<td>-359.50</td>
<td>-410.29</td>
<td>-321.24</td>
<td>-226.67</td>
<td>-185.78</td>
<td>-358.60</td>
<td>-355.32</td>
<td>74.03</td>
<td>665.19</td>
</tr>
<tr>
<td>2011</td>
<td>798.70</td>
<td>584.28</td>
<td>145.04</td>
<td>-212.30</td>
<td>-397.99</td>
<td>-340.34</td>
<td>-244.20</td>
<td>-244.43</td>
<td>-398.27</td>
<td>-385.41</td>
<td>-37.21</td>
<td>383.62</td>
</tr>
</tbody>
</table>

Figure 1.4 illustrates gas volume in the facility by month in terms of demand versus supply. As expected, in winter months, market demand exceeds the supply and this need is compensated by the storage facility. During non-heating seasons, the supply exceeds the demand and the gas is injected into the facility for storage.

Figure 1.4: Natural Gas Underground Storage Volume by Month in the US (Tcf) (EIA)
Chapter 2

SCOPE AND OBJECTIVE OF THE THESIS

2.1 Statement of the Thesis

The primary goal of this thesis research is to demonstrate underground natural gas storage concepts in salt caverns. Salt cavern storage is defined as the storage of a pressurized fluid in a thick-walled underground container with the walls of salt. The cavern can meet daily even hourly variations in customer needs since it has a rapid cycling ability.

The main objective of this thesis is to investigate the stability of salt caverns for underground natural gas storage. Before starting the final design, parametric study will be performed. It is essential for the sensitivity analysis of cavern design parameters. It will be expected to observe the effect of each design factor on cavern stability. Also, it will provide optimum conditions for the final design. After the results of parametric study, the final design will be started for cavern stability. The thesis research will have three main focus areas for this issue. First, single cavern design will be developed. The behavior of different shaped single caverns will be studied. This effort will provide the most stable cavern shape for underground natural gas storage. Then, multiple caverns design will be developed. The cavern interaction is the basic consideration for multiple caverns to investigate the effects on deformation of neighboring caverns. The optimum distance will be determined to eliminate mutual interactions between caverns. Finally, salt thickness analysis will be performed. Salt thickness between cavern top and salt formation is a critical factor for cavern design. The purpose of this effort is to determine the optimum distance between cavern top and salt formation to remove mutual interactions for more stable cavern designs. By accomplishing the above considerations, the thesis work would contribute to a fundamental understanding of salt cavern in underground natural gas storage.

2.2 Organization of the Thesis

The contents of this thesis are presented in six chapters. Chapter 1 provides a review of energy sector, the importance of natural gas and the need of underground natural gas storage.

Chapter 2 presents the scope and objective of the thesis.
Chapter 3 extensively explains the background of natural gas storage. The first part of Chapter 3 provides the introduction of underground natural gas storage. It consists of the main reasons of storage, the basic considerations for storage, the principal volumetric terms in storage and the brief description of basic storage facilities. The second part of Chapter 3 describes the salt cavern storage concepts. It includes solution mining process and properties of salt.

Chapter 4 demonstrates the system description of the thesis. It provides the deformation and failure characteristics of salt. Also, site geology of real field from Turkey is presented.

Chapter 5 presents the numerical analysis of cavern stability. First, parametric study is performed on three different cavern shapes. The design parameters are described and investigated. Then, single cavern design is developed with three different cavern shapes. The effect of cavern shape on stability as a function of depth is studied. Also, multiple caverns design is described and analyzed. Finally, salt thickness analysis between cavern top and salt formation is explained.

Chapter 6 covers the conclusions of this thesis. The future work to extend the current thesis research is also suggested and briefly explained.
Chapter 3

BACKGROUND

3.1 Introduction to Underground Natural Gas Storage

Underground natural gas storage provides an inventory management tool, seasonal supply back-up and prevents imbalances between receipts and deliveries on pipeline network (EIA 2007). Gas storage facilities are important to maintain the reliability, integrity and capability of gas transmission and distribution network. Storage development is essential for the markets that are distant from production areas. So, these storage facilities will allow these markets to maintain service reliability and control commodity price volatility with cost-effectiveness for consumers. Steady need for natural gas seldom occurs. Gas storage is located near the market to balance the variable market demand against the constant supply of gas from long distance pipelines. The location of facility is considered by both serving market and pipeline capacity for necessary withdrawal rates.

Severe cold winters, large population areas, existing gas pipeline systems and suitable geology are crucial factors for storage development in the region. Storage reservoirs store natural gas in times of low demand and provide a ready supply of gas in times of high demand. When pipeline capacity exceeds market demand, the gas is injected into storage reservoir. When market demands exceed pipeline supply, the gas is withdrawn from storage reservoir as a supply with pipelines. During non-heating season, natural gas is transported and injected into storage facility. In this time, consumers do not need all the contracted capacity for the consumption requirements. Inventory levels are at their annual peak by the beginning of heating season. Working gas is withdrawn during periods of peak demand.

Underground storage field operations consist of injection/withdrawal wells, water/brine disposal wells, gathering lines, dehydration units, gas measuring units and compressors. Accessing to major transportation pipeline networks is a strict requirement to receive/deliver gas (FERC 2004).

3.2 Main Reasons of Storage

Underground storage is essential due to following reasons:

- Storage is essential to meet gas demand peaks that exceed both production and pipeline capacity. When the demand is more than domestic production and imports, stored gas is withdrawn to balance to difference.
- It is necessary for an efficient and reliable interstate gas transmission and distribution network. The size and content of transmission system are significantly influenced by the storage capacity.
- Pipeline companies tend to operate their systems with full capacity to maximize their revenues. However, there are some factors that prevent to reach 100% of utilization rate. The main issues are:
  - Scheduled/unscheduled maintenance.
  - Temporary decreases in market demand.
  - Weather limitations for operations.

Integrating storage capacity into pipeline network is an efficient way to increase utilization rates. This also provides balancing flow levels throughout year.

- Storage facilities are also used to store excess production instead of serving as a supply source for local markets. This stored production provides a stable flow rate despite various demand fluctuations.
- Gas prices increase with the decline in production. Production mainly depends on the level of demand. Increasing production with demand reduction provides supply to meet demands, even during peak periods, without remarkable price volatility. Also, decreasing production cannot significantly be influenced by the demand and price fluctuations can be controlled due to the availability of gas storage. A storage facility is an effective way to prevent commodity price volatility in higher level.
- Prevent imbalance penalties and control daily/hourly changes and emergency situations.
- Meet peak demand in winter months at constant supplies.
- Increase the level of working gas in inventory.
- Support electric generation loads.
- Balance the system flow to keep sufficient pipeline pressures, and therefore maintain operational integrity.
- Provide a seasonal supply source and back-up for winter peak day gas demands.

3.3 Basic Considerations for Storage

Geology is one of the most important considerations for the location of underground storage facility (FERC 2004). Tight sand geology causes a very low level of injection and withdrawal rates, so this kind of storage facility is primarily used as a pipeline system support. Geological and engineering properties of
potential storage reservoir, the size and base gas requirements must be specified as the first step of storage development. It also considers the access to transportation pipeline network, production area and consuming markets.

There are some basic requirements for underground gas storage (Aminian, Mohaghegh 2009),

- A structure overlain by caprock is an impermeable strata above the reservoir that prevents gas migration toward the surface. Water in caprock seals the tight rock from penetration by gas phase and prevents it from rising vertically. It also leads to accumulation of gas in storage zone below the caprock.
- Sufficient depth for gas storage under pressure.
- A high porosity and permeability zone under caprock for gas storage and flow.
- Water below storage zone to confine the stored gas.

Injected gas must stay in reservoir for a long time period. Gas does not leave the storage system and unexpected gas movement is prevented by a monitoring system. Containment is the ability of storage field to prevent gas migration from storage horizon. Gas migration causes reduction of deliverability due to gas losses. It primarily depends on the pressure in storage facility. Therefore, storage top pressure must be smaller than initial reservoir pressure to prevent any gas to escape from storage reservoirs by caprock. After the confidence of injected gas containment, the design can be started.

Storage wells operate during many years and the stress is continually cycled from minimum to maximum pressure. Temperature fluctuations from hot gas injection to high withdrawal rates of gas that is cooled at the sand face lead to additional stress to production strings and the cement behind pipe. However, production wells experience maximum pressure only once in a lifetime, but storage wells have this situation every cycle (Knepper 1997). This is one of the most important considerations for storage wells during long operation times.

3.4 Principal Volumetric Terms

Storage fields traditionally are created for peak seasonal demands. However, storage facilities are strongly expected to meet dramatic daily or even hourly changes in today’s world. Thus, high injection/withdrawal cycles become the popular demand for storage operations. Storage operators are trying to improve the performance of existing storage facilities as a result of this need. It is performed to increase working gas capacity and reduce base gas requirements for higher delivery rates.
There are some basic volumetric measures to quantify fundamental characteristics of storage facilities.

### 3.4.1 Base (Cushion) Gas

Base (cushion) gas is the volume of stored gas in a reservoir as the permanent inventory and provides sufficient drive pressures and deliverability rates during withdrawal periods.

Cushion gas can be classified into three categories. It is possible to withdraw some limited cushion gas in heavy demand if all working gas is produced. This kind of cushion gas is the ‘economically recoverable gas with existing equipment.’ The remaining cushion gas is not recoverable with existing equipment and can be divided into two parts. The first is physically recoverable but requires expensive surface equipment, so this is not economical. However, the second is physically non-recoverable because the gas is dispersed in small quantities and then becomes immobile.

### 3.4.2 Working (Top) Gas

Working (top) gas is the volume of stored gas in the reservoir above the level of base gas. It is regularly injected and withdrawn during each cycle. It is used for market conditions change, system balances and peak demands in the near future. It is available to the market place.

Working gas capacity is the difference between total gas capacity and base gas level in place. It depends on reservoir type, local geology and economics (EIA 2006). However, it is mainly dependent on supply availability. If there is enough gas supply during injection season with lowest storage pressure, the gas is injected at the highest rates and ready for the withdrawal season. Increase in reservoir pressures leads to increasing gas volume and decreasing injection rates. Therefore, injection rate is the highest at the beginning of the injection period and the lowest at the end of the injection period. Withdrawal rate is the highest at the end of the injection period with the highest reservoir pressure.

### 3.4.3 Storage Capacity

Underground natural gas storage capacity, which is defined as the summation of base gas and the working gas capacity, fluctuates within a very narrow range. It is the maximum volume of stored gas in a facility.

Total gas in storage is the volume of gas in a facility at a particular time. It is minimum at the end of the withdrawal period and is maximum at the end of the injection period.
Figure 3.1 exhibits the example of changes of volumetric measures in a typical facility by months.

![Figure 3.1: Volumetric measures of the storage facility (EIA 2004)](image)

3.4.4 Deliverability

Deliverability is the measure of gas which can be delivered from the storage facility on daily basis. It mainly depends on the amount of gas in the reservoir at a particular time, pressure, compression capacity and content of surface facilities for connecting pipeline networks. It principally changes with the amount of working and base gas in the reservoir. It is at the highest level when the reservoir is full at the end of the injection period and decreases with the withdrawn working gas.

There are many factors that influence deliverability of wells. One of the most important is water conning. A high pressure drawdown leads to a larger pressure difference at the bottom of well between the gas and the underlying water during withdrawals. Then, water rises and reaches to the bottom of the well, which in turn reduces the deliverability. This depends on the pressure level during withdrawals, thickness of gas sand between the well depth and the underlying water and permeability of the formation between the gas and the underlying water. It is proven that storage wells lose their deliverability capabilities over time due to damages. The average reduction of deliverability is 5% per year (Aminian, Mohaghegh 2009). The major damage factors are bacteria, inorganic elements, organic
residues and plugging for gas storage wells. Bacteria cause damages at the sand face in the bottom of the wellbore. Inorganic elements such as iron compounds block the sand face. Organic residues are resulting from compressor oil, lubricants and chemicals for corrosion control, and therefore they can plug the sand face. Remedial operations are more economical than drilling additional wells to increase well deliverability. There are many techniques to restore well deliverability which should be specified under field conditions. Some of them are acidizing, fracturing, hydroblasting and perforating (Aminian, Mohaghegh 2009).

3.5 Brief Description of Storage Facilities

There are two types of storage facilities in operation as base-loading and peak-shaving. Base-loading facilities are used to provide constant seasonal market demands with sufficient volume of gas capability. Their injection/withdrawal cycles are long and turning over gas once a year. Depleted reservoirs and aquifers are classified as base-loading facilities. Peak-shaving facilities are used to be turned over several times in a year for short term demands. They can hold less gas than base-loading facilities. Salt caverns are the most common type.

There are three basic types of underground storage sites as depleted reservoirs, aquifers and salt caverns. Each type of storage has its own physical characteristics such as porosity, permeability, retention capability and economics as site preparation costs, deliverability rates, cycling capability for the suitability for particular applications.

There are currently 411 natural gas underground storage facilities in operation in the US (EIA). Depleted reservoirs are the most common type with 331 facilities (81%). There are 43 aquifer reservoirs (10%), and 37 salt caverns (9%). All of the requirements are met in underground reservoirs because hydrocarbons are trapped below the caprock and confined by the underlying water for millions of years. That is the reason why many depleted reservoirs are converted into storage facilities.

Depleted reservoirs have the largest share of gas storage capacity and with the aquifer storage are used primarily to meet seasonal demands. However, most of the new storage facilities created since 2007 are salt caverns (EIA 2011). They represent a rapidly growing share of gas storage deliverability in the US. Salt cavern storage currently represents 23% of the total deliverability compared with 16% in 2005 and 11% in 1998 (EIA 2006). Higher deliverability rates and flexible deliverability options are the most important issues for natural gas consumers such as industrial users, electric generation plants and
domestic users. Rapid cycling capability and ability to respond to daily, even hourly variations in customer needs make salt caverns very attractive option.

Increasing base gas results in the reduction of the working gas capacity. The base gas cost of storage is the most important economic issue. Depleted reservoirs typically require 50% base gas. For aquifers, this is between 50-80% base gas. Base gas requirement is only 25% for salt caverns. However, there are leaching and brine disposal costs for salt caverns. Table 3.1 presents the basic gas storage facility operations for each type.

Table 3.1: Gas Storage Facility Operations (FERC 2004)

<table>
<thead>
<tr>
<th>Type</th>
<th>Cushion to Working Gas Ratio (%)</th>
<th>Injection Period (days)</th>
<th>Withdrawal Period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depleted Reservoirs</td>
<td>50</td>
<td>200-250</td>
<td>100-150</td>
</tr>
<tr>
<td>Aquifer</td>
<td>50-80</td>
<td>200-250</td>
<td>100-150</td>
</tr>
<tr>
<td>Salt Cavern</td>
<td>20-30</td>
<td>20-40</td>
<td>10-20</td>
</tr>
</tbody>
</table>

3.5.1 Depleted Reservoirs

Depleted reservoirs are the most commonly used storage sites because of their wide availability. They are relatively easy to convert for storage and close to consumption centers and existing pipelines. Figure 3.2 represents the basic depleted reservoir for underground gas storage.

![Depleted Reservoir for Underground Natural Gas Storage](Intragaz)
They have already been tapped of all their recoverable hydrocarbons, so the formation is geologically suitable for natural gas holding. Also, extraction and distribution equipment is left over from the field. This provides significant cost reduction for converting a depleted reservoir into a storage facility. They are also attractive because the geological characteristics of formation are already known, so no more time is required for this preliminary geological analysis. Therefore, depleted reservoirs are the cheapest and the easiest type for storage development.

For depleted reservoirs that are converted into storage facilities, the maximum pressure depends on reservoir depth and geometry, caprock properties and the associated water. However, the minimum pressure does not have an effect on overall structural stability. The pressure range in a depleted reservoir for the operating cycle is essential for safe upper limit of reservoir pressure, wells flow capacity and compression requirements during injection/withdrawal. The highest reservoir pressure provides the maximum storage capacity and the highest flow capacity of the wells. Therefore, required storage deliverability primarily depends on storage pressure and gas-in-place volumes. Working gas must be recycled properly because it tends to move from high-pressure areas to low-pressure areas in the field. This puts the gas into tight formations, which results in an increase for cushion gas requirements or gas losses.

Depleted reservoirs are pressurized back to their original discovery pressure for gas storage. A top storage pressure can be higher than discovery pressure with the complement caprock. This provides larger storage capacity and higher flow rates. If the caprock is thin, storage pressure should be lower than the discovery pressure.

3.5.2 Aquifers

Aquifers are underground permeable rock formations which are known as natural water reservoirs. Figure 3.3 illustrates the basic aquifer for underground gas storage. They are only used in areas with no depleted reservoirs, because they are very expensive to develop as gas storage facilities. They are the least desirable and most expensive type of gas storage due to following reasons: The geological characteristics of aquifer formation must be discovered and the suitability as a storage facility must be determined. This process is expensive and time consuming. Also, the base gas requirement is much higher than other types.
Suitable natural aquifers are converted into natural gas storage facilities. First, water-bearing formation must be overlaid with an impermeable cap rock. They require more base gas and complicated monitoring of injection/withdrawal operations. The geology of aquifers is similar to the depleted production fields.

In aquifer storage, gas is stored in reservoirs which originally contain all or mostly water. These reservoirs are similar to gas/oil reservoirs, but included very little or no hydrocarbons. If the reservoir is suitable for development, there are some concerns associated with water movement in the reservoir and water production with gas withdrawal. Some amount of injection gas can be trapped by water and becomes unavailable for recovery. Thus, higher level of base gas is required. Water movement near the wellbore can generate deliverability problems such as freezing in wellbore and wellhead, so water-removal equipment is installed.

Gas is injected into an aquifer and this creates a ‘gas bubble’ within the porous rock to expand and displace the water. Maximum pressure mainly depends on aquifer geometry, caprock properties and the behavior of associated water. The associated water is more important for aquifer storage since water provides the primary horizontal containment. The minimum pressure has very little effect on overall stability, but it is considered for efficient operations of the facilities. Aquifer storage pressure must be larger than the initial value to displace water and create the gas reservoir.
The injection period (non-heating season) includes the months of April through October and the withdrawal period (heating season) includes the months of November through March for aquifers and depleted reservoirs. At the beginning of injection cycle, water moves in since gas pressure is lower than the aquifer pressure. The gas pressure increases with added gas and pressure balance is obtained between gas and the aquifer, which in turn stops the water movement. Finally, the gas pressure exceeds aquifer pressure and the water starts to move out. This leads to expansion of gas volume and increase in pressure. At the beginning of withdrawal cycle, gas pressure is larger than aquifer pressure and water moves out. The gas pressure decreases during withdrawal period and gas and aquifer reach the pressure balance which stops the water movement. The gas pressure falls below the aquifer pressure and water begins to move in. This causes decrease in gas volume and in pressure.

3.5.3 Salt Caverns

Saline formations are deep sedimentary rocks and saturated with water or brine, which have high concentrations of dissolved salts (Benson, Cook 2005). Underground salt formations are suitable for gas storage, because they prevent the gas from escaping. The cavern walls have the structural integrity of steel, which prevents reservoir degradation.

X-ray diffraction analysis and dissolution analysis are used to determine mineralogic and chemical properties of the formation. It provides the mineralogic composition of samples. Halite is the principal mineral (70-97.5%) and small amounts of quartz (SiO$_2$), magnesite (MgCO$_3$), kieserite (MgSO$_4$.H$_2$O) are generally encountered (Istvan et al. 1997). The quantity of the insoluble material is calculated by chemical analysis. Sodium and chloride are the most dominant ions in the solution. Calcium, magnesium and potassium are minor dissolved elements (Istvan et al. 1997). Finally, the insoluble residue is tested by bulk X-ray diffraction analysis for mineralogic composition.

Halite has innate characteristics for oil and gas storage and toxic wastes isolation from the environment. It is almost impermeable to gases and liquids (Langer 1993). This provides a sealing for caverns and prevents the product from rising vertically. Also, it deforms in a plastic manner with a wide range of pressure, temperature and deformation rates.

There are three basic parts in salt cavern development: a drilling pilot well for obtaining geological data, core samples for the leaching process and numerical simulation for the cavern stability (Hoelen et al. 2006). The brine pumping station is necessary to provide sufficient pressure for leaching process at
the desired depth with sufficient leaching capacity. Gas is compressed to the caverns for storage. The gas is cooled down before injection since compression leads to increase in temperature. It is necessary to prevent thermal stresses in the cavern.

Suitable geology and economy are basic factors for cavern storage development (Pb-Kbb Inc. 1998). High delivery rates and multiple cycles are preferred for storage operations. First, suitable region is selected for cavern construction. Then, market conditions are investigated for economic concerns. The ratio between working gas and cushion gas volumes is maximized for storage economy (DeVries 2003).

In cavern storage, gas is not stored within the pore space of formation. An excavated cavern within the structure is used for storage. Caverns are relatively small in total capacity which is up to 5 or 6 Bcf due to high creation costs, but they have very high deliverability rates. Most caverns can deliver 10% of the top gas in a day (Knepper 1997).

Salt cavern storage has developed significantly during the past decades, because it has a rapid cycling ability to meet daily even hourly variations in customer needs. Storage operations of salt caverns are not restricted by seasonal needs as back-up gas. They are directly functions of customer needs. Recently, the needs of the energy market have changed towards more aggressive operations. Therefore, it is necessary to apply high frequency cycling operation on salt caverns. They typically are emptied in 10 days and refilled in 30 days (Berest 2011). Cavern construction is more costly than depleted field conversions but performing several cycles significantly reduces operation costs.

Cores from the field are analyzed to determine factors such as the content of insoluble, solution rates, number and thickness of interbeds, creep rates and mechanical strength. Large thickness and high level of halite at suitable depths are very desirable properties for gas caverns (Axel 2007). Also, it is highly preferred that non-salt layers in whole salt formations are at the lowest thickness level. With these experimental data, computer models provide the most suitable cavern design for size, shape, operating pressure range and leaching process to create caverns. One very large diameter well is used to create caverns for leaching, dewatering and operating conditions.

Salt cavern storage has several advantages such as,

- They operate under very high pressures, so they can quickly inject/deliver large amount of gas. This enables to meet aggressive short term changes in supply and demand.
- They provide more cycling, usually up to 6-12 cycles per year (EIA 2011). The gas is injected in summer and withdrawn in winter for seasonal storage in traditional method of depleted reservoirs and aquifers.
- They require less base gas and have higher proportions of working gas. This significantly decreases capital costs associated with base gas.
- Salt walls and cap of caverns are impermeable under high pressures. Also, storage caverns are self-healing with geologic pressures at certain depths for any cracks that may occur to seal quickly.

Although salt cavern storage has many advantages, one serious limitation is to be highly sensitive to the minimum storage pressure for structural stability (Hardy 1982). For salt cavern storage, the gas does not flow through porous rock into the wellbore unlike both depleted reservoirs and aquifers, so it can be produced very quickly when needed and the cavern can be refilled in periods of low demand. The suitable salt geology, a sufficient water supply for solution mining process and the reasonable brine disposal methods are necessary for storage development. There are two basic salt formations for gas storage: salt domes and salt beds. Salt beds contain thin non-salt layers such as shale, anhydrite, dolomite, limestone, which lead to serious problems in cavern development. Salt domes are generally huge, vertical cylinders of circular or oval cross-section with rounded caps. They have caprocks that are composed of calcites, anhydrites to cover the top of the dome. They are highly suitable for storage development since they have a nearly pure rock salt formation.

### 3.6 Solution Mining Process

As illustrated in Figure 3.4.A, when a cavern is developed in salt formation, one well is generally drilled. Pipe is cemented from the top of the salt layer to the surface, and a string of smaller piping is placed inside the outer pipe. Fresh water is injected to the inner pipe into the salt formation to dissolve the salt. The resulting brine is removed through the outer pipes. Then, the cavern is dewatered by injecting gas through the outer annulus and the brine is thrown out by inner pipe. As shown in Figure 3.4.B, the cavern becomes ready for gas storage.
Fresh water is injected into the salt deposit for dissolution process and the resulting brine is withdrawn through wells in solution mining (leaching) techniques. They are classified as direct or reverse circulation (Hardy 1982). In direct circulation, water is injected through tubing and brine is withdrawn through the annulus; in reverse circulation, fresh water is injected through the annulus and brine is produced through the tubing. The bottom of the cavern primarily depends on the location of the inlet in the direct circulation and the outlet in the reverse circulation. The top of the cavern is controlled by the level of inert fluid blankets such as oil, gas or air. Also, the blanket fluid level is controlled by additional pipes. The approximate volume of the cavern is usually estimated from the brine production data. However, sonar surveys are necessary to obtain the desired final cavern design with accurate shape and volume.

### 3.6.1 Basic Solution Mining Modes

There are two basic solution mining modes for cavern development, direct (tubing) and reverse (annulus) injection (Hardy 1982). As shown in Figure 3.5.A, the water goes down through the inner casing and the brine goes up through the annulus during direct injection mode. Cavern structure is usually wider at the bottom and narrower at the top. The sump is necessary to collect the insoluble which fall to the cavern bottom. Conversely, as illustrated in Figure 3.5.B, the water is down through the
annulus between the inner and outer casings during reverse injection mode. The resulting cavern shape is controlled by the vertical separation between the outer and inner casings and the depth of the protective roof blanket. Small casing separations with significant distances above the injection depth generate cavern shapes similar to those produced by the indirect injection mode. This is also known as modified reverse injection modes shown in Figure 3.5.C.

Salt dissolution is endothermic and the rock mass around the cavern becomes cooler after leaching (Brouard et al. 1997). This generates a small reduction of cavern creep.

The development phase depends on dissolution parameters such as pipe-hole size and spacing, injection rate of fresh water and insoluble content (Bauer et al. 1998). The length of horizontal caverns principally depends on insoluble content. This provides to estimate cavern cross-sectional aspect ratio, cavern volume and width, brine production rate and specific gravity, insoluble volume and level, and ceiling level at fresh water injection for various times during the leaching process. Also, fresh water injection rate and insoluble contents are the main parameters for cavern development in salt formation.

Debrining process, which is defined as removing brine from the cavern after the leaching process, is also used for removal of the brine that is leftover in the cavern by gas pressure at the end of the solution mining (Healy 2008). Gas is injected into the cavern and pushes the brine out. Then, the brine is generally sent out for appropriate disposal.

Moisture occurs during storage and it must be removed before gas delivery for efficient operations. If dry injected gas stays in the cavern for a short period of time, it cannot reach saturation and hydrates will not occur. This is one of the important advantages for high deliverability salt caverns to prevent hydrates (Healy 2008).
3.6.2 Geometry of Cavern Design

The cavern shape is controlled by adjusting the inner and outer casings and by the injection mode during solution mining. The specific cavern development requires different adjustments in the flow directions and the depth of the casing. These are necessary for the desired cavern structure. A sump is primarily generated for settlement of the insoluble in bedded salt deposits. Therefore, the sump volume is dependent on the amount of insoluble and the thickness of shale layers. Figure 3.6 represents the geometry of an idealized cavern design for use in bedded and domal salt.
3.7 Properties of Salt

The mechanical behaviors of cavern depend on both material properties of salt/non-salt surrounding the cavern and the material properties of the fluids inside the cavern. There are three basic operations during cavern development: cavern excavation by solution mining, cavern dewatering and gas service cycles (DeVries et al. 2005). The cavern is filled by saturated brine before dewatering. Then, it is filled by natural gas during the dewatering process.

Rock salt is favorable medium for storage since it is a viscoplastic material, so it does not fail under moderate levels of confining pressure. Circumventing states of stress that lead to salt dilation must be determined for the integrity of host salt formation. Dilation is defined as a volumetric expansion that occurs by microfracturing of the material (DeVries et al. 2005). Mechanical properties are investigated for horizontal stress that leads to fracture pressure (Bruno, Dusseault 2012). Rock salt is permeable to gas and brine even far from caverns (Cosenza et al. 1999). Salt behaves like liquid since it can flow under very small deviatoric stresses (Berest et al. 1999). Furthermore, rock salt has favorable geomechanical properties. It can stay stable for a long time without any support. Stress deformation states are very important for cavern integrity. The host rock provides load-bearing against changes in rock stress during cavern construction (Langer 1993).

Salt cavern storage can be defined as the storage of a pressurized fluid in a thick-walled underground container with the walls of salt. This container is loaded internally by stored fluid pressure and externally by in-situ ground stresses in use (Hardy 1982). Therefore, the mechanical stability of such a container depends on the internal pressure, the in-situ stress field, the geometry of the container and the mechanical properties of the salt. There are minimum and maximum critical pressure levels that need to be considered in such storage facilities. This critical minimum pressure increases since the pressure induced by the storage fluid provides cavern stability by balancing the effects of the in-situ ground stress. However, below the critical minimum pressure, the in-situ stress field might overcome the strength of the surrounding salt, so cavern closure and failure can occur.

First, the strength and deformation characteristics of the salt/non-salt formation around the cavern should be analyzed. Despite the extended literature on material properties, varying outcomes might come up during operations due to site specific salt behaviors. Therefore, salt responses for all possible states of stress in the field must be considered. Triaxial extension and compression states of stress are main issues to determine the strength and deformation characteristics of salt under the stress states.
Laboratory testing is necessary for strength and deformation characteristics of salt formation to investigate cavern stability. Geological analyses are applied to determine salt bed thickness, depth, numbers and overlying rock properties for the storage formation. It provides the characteristics of strength and deformation of the rock salt under different possible states of stress. There are three main laboratory tests: confined compression tests, constant mean stress dilation tests and creep tests (DeVries et al. 2005). The confined compression tests are used to determine compressive strength, Young’s modulus and Poisson’s ratio. These are elastic and strength properties of the material. The constant mean stress dilation tests provide stress conditions which cause dilation of the salt. The creep tests are necessary for time-dependent behaviors of the salt.

Bedded salt formations occur in different thickness, depths and other interbedded rock layers. The height of bedded salt caverns depends on the thickness of the salt beds. It is generally much smaller than salt domes. Therefore, their diameters are much greater than the heights for sufficient storage volume. They are generally layered with non-salt materials such as mudstone, shale, anhydrite, limestone and dolomite (Bruno, Dusseault 2012). Also, the salt layers contain some impurities. Therefore, they are more complicated than salt domes in development and operations. Some main concerns are layered, heterogeneous lithology, different deformation characteristics, slipping between layers and larger lateral dimensions in caverns. Also, large roof spans are generated in bedded salt formation and this must be supported by the geological formation to prevent roof instability. Stored gas can escape along the interface of interlayers (Huang, Xiong 2011).

Salt domes provide massive cavern area for gas storage. Caverns are generally cylindric and their heights are considerably greater. They are selected as cylindric shaped to provide the maximum possible storage capacity in salt dome formation (Sharifzadeh, Ghasr 2009). In salt domes, in-situ principal stresses are nearly equal in magnitude, so hydrostatic condition can be reached more easily. This is very favorable for cavern pressure range during operations. However, in salt beds, in-situ principal stresses might be very different from each other. For example, maximum horizontal principal stress might be much higher than minimum horizontal principal stress. Allowable maximum pressure is very important to prevent seal failures or formation fractures. Minimum allowable internal pressure is necessary to avoid spalling from the walls of cavern (Staudtmeister, Rokahr 1997). Furthermore, multiple well leaching is used to increase the efficiency of the leaching process in bedded salt. However, this leads to unexpected horizontally extended caverns.
Water content is crucial because if the water is not fully saturated with salt, some of the salt from cavern walls can be dissolved, and therefore the cavern extends unexpectedly (U.S. Department of Energy 1999). The weight of overlying rock leads to deformation of the salt formations surrounding the cavern and large pressure against walls. Then, salt slowly flows into the cavern. This results in volume reduction in the cavern that is also called as salt creep.

There are three distinct phases in the salt model. First, the material response is linearly elastic until predefined pressure dependent damages the surface. The material is still compact and returns to the unstressed state by complete unloading during the elastic phase. Therefore, there is no permanent damage in the elastic phase. The second phase is described by permanent microcracks and corresponding volumetric dilation. The material cannot return to the natural stress-free state by unloading. Finally, after certain amounts of cracks are formed, the material fails and the strength becomes zero (Bruno 2005).

3.7.1 The Influence of Cavern Depth

Natural gas is stored in solution-mined caverns by domal or bedded salt formation. Salt caverns provide flexible gas storage services. Thick salt formations are always preferred for cavern development. There is a minimum 50 m thick salt layer and 300 m depth for salt cavern development (Bruno 2005). However, the exact cavern depth depends on local geology and salt dissolution. Salt caverns can be located 2,500 m below the surface (Sharifzadeh, Ghasr 2009). At shallow depths, the pressure range is relatively small since the maximum pressure must be below the overburden pressure. Therefore, very large caverns or many caverns together are required for sufficient storage volume. In contrast, large pressure ranges are possible for deeper caverns. This is less desirable since the cost of wellbore casing and surface compression equipment increases dramatically with depth. Thus, moderate depths are determined with respect to site specific properties and economic conditions. Thick non-salt beds are detrimental during leaching process and prevent the upward development of caverns.

Sufficient depth is essential for caverns to prevent surface erosion and dissolution by circulating ground water. Also, the plastic flow rate of rock salt from overburden pressure increases with depth. Cavern depth should be as low as possible to reduce the effect of in-situ temperature since it increases with depth. In general, temperature increase leads to disproportionally larger increases in volume closure (Hardy 1982).
Elastic deformation and thermal expansion behaviors do not vary considerably from site to site, while inelastic deformation, creep properties and damage behaviors are highly site specific (Bruno 2005). The mechanical behavior of salt is influenced by stress, temperature, moisture content and anisotropy. The deformation rate mainly depends on stress difference and temperature. The stress in the salt outside the cavern is a function of overburden weight. The pressure inside the cavern is equal to the operating gas pressure. Therefore, potential risks of cavern deformation, creep and salt damage increase with depth since stress and temperature increase with depth.

3.7.2 The Influence of In-situ Stress Ratio (k)

The integrity of the walls and roof of cavern mainly depends on deviatoric stress state that is generated by in-situ stress and the forces on cavern walls by the cavern fluid. Therefore, in-situ stresses are essential for storage caverns.

Principal in-situ stresses are defined with a coordinate system as vertical and horizontal exponents. The magnitude of vertical principal stress is equal to overburden weight. The mean stress in salt formation increases with higher depths due to additional overburden. Shear stress distribution occurs primarily around the cavern roof and bottom corners while salt damage occurs mainly around the cavern sidewall (Bruno 2005). In salt domes, in-situ principal stresses are generally equal in magnitude. However, in bedded salt formation, the magnitudes of principal stresses are not equal due to regional faulting or active tectonics. The failure of shale beds basically depends on initial stress states. However, this is very difficult to determine in-situ stress of non-salt units since the large variety of horizontal principal stresses. Thus, isotropic initial states of stress are assumed in numerical simulations.

The vertical and horizontal virgin in-situ stresses at the cavern site are respectively $\sigma_v$ and $\sigma_h$ as shown in Figure 3.7.A. The horizontal virgin stress field is isotropic in the horizontal plane, so horizontal stresses are independent of direction. These stresses are functions of depth and any orogenic conditions. Also, they are generally homogeneous (constant) along a horizontal line such as A-B. However, when a single cavern is developed, as illustrated in Figure 3.7.B, the homogeneous virgin stress field is distorted and stresses along a line such as C-D vary with distance from the cavern. Therefore, the stresses become the following, $\sigma'_h \neq \sigma_h$ and $\sigma'_v \neq \sigma_v$. A similar distortion of the stress field occurs at all locations around the cavern with changes of stresses at different points from the original virgin values depending on location. However, the stresses can again reach the virgin values at distances of four to five times the maximum cavern dimension (Hardy 1982).
Virgin in-situ stresses below the ground are linear functions of depth. They can be obtained by the following equations based on the earth that is considered a linear-elastic sphere:

\[
\sigma_V = \gamma h \quad (\text{Eq. 3.1})
\]

\[
\sigma_H = m \sigma_V \quad (\text{Eq. 3.2})
\]

\[
m = \left(\frac{v}{1-v}\right) \quad (\text{Eq. 3.3})
\]

where \(\sigma_V\) and \(\sigma_H\) are vertical and horizontal virgin in-situ ground stresses, respectively. The \(\gamma\) is the weight density of the overlying material, \(h\) is the depth below the surface and \(v\) is the Poisson’s ratio of the material. However, the horizontal stress component differs significantly from the actual field studies. In such cases, \(\sigma_H\) is calculated from the following relationship:

\[
\sigma_H = k \sigma_V \quad (\text{Eq. 3.4})
\]

where \(k\) is defined as the ground stress ratio.
The stress ratio at any point in the structure can also be defined as the stress concentration factor (SCF). Even though they might be either positive or negative (compressive or tensile stresses), the virgin stress field is generally compressive. This mainly depends on the specific location and the geometry of the cavern.

When in-situ stress ratio \( k \) is equal to one, the vertical and horizontal in-situ stress components are equal and this is defined as a hydrostatic stress field. Also, values of \( k > 2 \) are observed due to the presence of geological anomalies (dikes, faults), tectonic movements or residual stresses by prior geological processes (salt dome formation) (Hardy 1982). Stress distribution along the cavern wall for different ratio values of far field stresses is essential for cavern development and stability analysis during long term operations (Cristescu, Paraschiv 1995).

### 3.7.3 Types of Cavern Instabilities

There are some possible types of mechanical instabilities that occur in solution mined storage caverns during and after their development. These are shown in Figure 3.8 and 3.9 as subsurface subsidence and subsequent surface subsidence, closure, local fracture and block flow, deep fracturing and various combinations (Hardy 1982). The occurrence of the noted instabilities is rare with the exception of closure even though small scale instabilities of most types occur frequently. However, as larger and more sophisticated cavern facilities are constructed, careful site selection, more detailed design techniques and instability detection methods are necessary for long term cavern stability.

![Figure 3.8: Subsurface and Surface Subsidence for Cavern Instability (Hardy 1982)](image)
Subsidence shown in Figure 3.8 generally occurs during the development stage of storage caverns or in caverns developed for brine production (Hardy 1982). The risk of potential surface subsidence is more for shallow cavern depths. This might happen due to poor cementing of production casing, lack of necessary blanket control or high stress concentrations in the upper region of the cavern. Initial parts of the cavern roof are destroyed by dissolution or fracturing with high localized stress concentrations. Then, the damaged roof begins to fracture and the fractured region extends upwards. The fracture region extends over the surface that leads to gentle surface subsidence or large, aggressive piping subsidence with extensive sink hole development.

Salt cavern closure is simply defined as the shrinkage of the cavern volume. This is generally due to the presence of high in-situ stress, low cavern pressure or elevated temperature. Figure 3.9.B demonstrates the closure fact. The original cavern size decreases with time. It is observed that salt storage caverns sometimes experience 5-10 percent closure during the first year; however, this might be up to 20 percent or more with respect to field characteristics and operation conditions (Hardy 1982). Such incidents are also called as facility failures. Since cavern closure is a stress dependent instability, it is directly related to cavern depth and possibly the orogenic stresses. They might have little effect on the closure of caverns in bedded salt deposits, but they are very important for caverns in salt domes.

High stress regions due to cavern geometry or stress field heterogeneities lead to localized failure as shown in Figure 3.9.C (Hardy 1982). Parts of the cavern wall and roof fracture, eventually break away and fall to the cavern bottom. It might also turn into extensive subsurface subsidence and at shallow cavern depths even failure to surface. Conversely, local fracture might modify the cavern shape to a more stable geometry, reduce the stress concentration factors and delay the fracturing process. This
type of instability usually occurs in shallow caverns where lower internal cavern pressures are presented. Under these conditions, salt behaves in more brittle, elastic form. However, for deeper caverns, the higher storage pressures lead to the inelastic salt behavior.

Deep fracturing shown in Figure 3.9.D might occur in salt caverns under certain conditions (Hardy 1982). A condition similar to hydrofracturing occurs with some massive fractures at the cavern wall, extending into the salt surrounding the cavern. Such fracturing depends on the cavern geometry, internal pressure as well as the direction and magnitude of the in-situ stress field. However, the most common type of instability of salt caverns is cavern closure. Also, certain data such as stress distributions around different cavern shapes and mechanical properties of salt is applicable to the study of other types of cavern instabilities. Therefore, it is necessary to have a detailed understanding of the basic mechanical behavior of salt, the possible instability types associated with in-situ stress conditions, cavern geometry and cavern pressure for economic and stable design of salt storage caverns.
Chapter 4

SYSTEM DESCRIPTION

Under room temperatures and confinement, most rocks behave as brittle, elastic materials. The knowledge of their failure strength and elastic properties are sufficient to determine their characteristics under mechanical loading. However, salt is more complex since it exhibits yield strength, initiation of plastic behavior, and time-dependent strain behaviors at stress level significantly below its failure strength. Therefore, it must be considered as an inelastic material.

4.1 Deformation and Failure Characteristics

When a solid body is stressed, some changes occur in the dimensions and geometry. Such changes are called strains. Figure 4.1.A represents a series of typical stress-strain curves (Hardy 1982). Below a critical stress level ($\sigma_C$), these strains are elastic in nature and the body returns to the original shape when the applied stress is removed as shown in curve 1. However, at stresses above the critical level (curve 2), the material cannot maintain the elastic nature and permanent strain ($e_a$) stays when the applied stress is removed. Such behavior is called as inelastic. The stress level for the first inelastic behavior is as low as 40-50 percent of the ultimate strength for many geological materials. However, the critical level is less than 25 percent for salt. Inelastic behavior leads to time-dependent deformation (creep) and plastic deformations. Salt only behaves elastically at very low stress level. At higher stresses, it becomes inelastic and exhibits plasticity, viscoelasticity and creep behaviors.

![Stress-Strain Behavior](image)

Figure 4.1: Typical Stress-Strain Behavior for Solid Material Under Stress (Hardy 1982)
It is sufficient to determine the simple elastic moduli (Young’s modulus and Poisson’s ratio) of the material for the deformation characteristics of many materials. However, some materials such as salt are more complex, so the elastic and inelastic properties need to be defined. Many materials exhibit a typical brittle type stress-strain curve when stressed to failure as shown in Figure 4.1B. The stress-strain curve is almost linear, but it deviates from linearity as approaching ultimate failure (X). Conversely, salt exhibits a typical ductile behavior, it has a limited linear region at very low stress levels. In many materials, the observed deviation from linearity is assumed to illustrate the initiation of inelastic behavior. This point in metals represents the yield strength or elastic limit which the metal starts to exhibit plastic deformation behavior. Although it can be applicable for salt cavern designs, stress-strain curves for salt are generally in non-linear form even in the elastic region.

4.2 Time-Dependent Inelastic Strain (Creep)

Time-dependent inelastic strain, generally called creep, occurs in geologic materials when the applied stress is higher than the critical level. The yield-point of salt is relatively low and salt exhibits creep at very low stress levels. The typical stages of creep tests are illustrated in Figure 4.2 (Hardy 1982). The strain in the region A-B is instantaneous and it includes the elastic and permanent (plastic) strains during the load. The region B-C is the transient or primary creep stage, and the strain rate decreases rapidly. The region C-E is the steady-state stage and the majority of the total strain during long-term creep test is observed. In the final or tertiary stage, region E-F, the strain starts to accelerate and failure occurs at point F, in a highly brittle nature. If the applied load is removed during steady-state creep, some amount of the strain (D-G) is instantaneously recovered. After sufficient time, all strain is recovered with the exception of viscous flow strain. Also, when the applied load is removed during the transient stage rather than the steady-state stage, the total strain is recovered for many materials. However, this is generally only observed at very low stress levels.
4.3 Geological Description of the Salt Deposit

The prospective salt deposit of Tuz Golu is of Oligocene to Miocene age (Late Tertiary). Based on detailed core investigation and interpretation of geophysical well logs, the rock salt is rather pure (average content of insolubles of about 7 to 11%, however locally up to 26%). The insolubles consist predominately of disperse distributed anhydrite and fine-grained clay minerals; locally there are also thin, intensively folded anhydrite bands and clay intercalations. There is no indication of the occurrence of polyhalite, kieserite and gypsum within the salt interval. The log data and drilling cores give no indication of high-soluble evaporitic minerals (e.g. sylvine, carnallite) (BOTAS).

The Tuz Golu salt formation is folded up to an elongated narrow salt wall by post-sedimentary halokinetic processes. Based on seismic data, the salt body exhibits a rather complex and irregular subsurface topography with rather steep dipping flanks. Within the presumed cavern area, the top of salt formation is expected in depth between 595 m and 1,085 m as illustrated in 4.3 (BOTAS).
4.3.1 Stratigraphic Preconditions

Table 4.1 presents general geological and lithological information about the expected drilling profile of the field.

Table 4.1: Stratigraphic Preconditions of the Field (BOTAS)

<table>
<thead>
<tr>
<th>Stratigraphic formation / unit or subunit</th>
<th>Estimated thickness range (m)</th>
<th>General Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cihanbeyli to Kochisar fm.</td>
<td>640 – 1,080</td>
<td>Shale, marlstone, conglomerates and limestones</td>
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<tr>
<td>Caprock</td>
<td>65 – 95*</td>
<td>Anhydrite occasionally with thin intercalations of clay and/or carbonates</td>
</tr>
<tr>
<td>Salt</td>
<td>&gt; 1,000</td>
<td>Rock salt with an average of about 7 to 11% of insolubles (mostly anhydrite), locally up to 26%</td>
</tr>
</tbody>
</table>

*exception: the very low thickness of the anhydrite of only 13.5 m in UGS-1 is possibly caused by a crossed fault with a throw of about 60 m.
**4.3.2 Drilling Locations of Cavern Wells**

Table 4.2 shows the drilling locations and the properties of cavern wells in the salt dome. Figure 4.4 illustrates the different depth of the salt body and the presumed caverns, the planned cavern wells are compiled in a north–south trending cross section.

<table>
<thead>
<tr>
<th>Well</th>
<th>Easting</th>
<th>Northing</th>
<th>Ground level (m)</th>
<th>Depth 20'' casing (m)*</th>
<th>Depth top salt (m)</th>
<th>Depth 13 3/8'' casing (m)**</th>
<th>Top cavern</th>
<th>Base cavern</th>
</tr>
</thead>
<tbody>
<tr>
<td>UGS3</td>
<td>554140</td>
<td>4215370</td>
<td>985</td>
<td>575</td>
<td>615</td>
<td>1,070</td>
<td>1,100</td>
<td>1,400</td>
</tr>
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<td>4215480</td>
<td>1,001</td>
<td>655</td>
<td>675</td>
<td>1,070</td>
<td>1,100</td>
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<td>991</td>
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<td>705</td>
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<td>1,150</td>
<td>1,450</td>
</tr>
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<td>4216040</td>
<td>998</td>
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<td>1,120</td>
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<td>1,450</td>
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</tbody>
</table>

* The surface casing (20'') should be set about 20 m below top of the anhydrite.

** The last cemented casing (13 3/8'') should be set about 30 m above the future roof of the cavern.

Figure 4.4: General Sketch of the Cavern Wells of Tuz Golu Storage Project (BOTAS)
Chapter 5

NUMERICAL ANALYSIS of CAVERN STABILITY

Cavern stability is the most important consideration for storage cavern design. It limits the cavern size, spacing and operation pressure range in salt formations. Also, it is necessary for containment of stored gas and safe operations. Numerical model is used to illustrate the stress and strain fields in host formation around the cavern for stability and long term usage (Heusermann 2003).

The primary objective is to avoid or reduce the amount of failure and provide necessary stability during operations. It is performed to provide a minimal or no failure of the rock surrounding caverns. The effect of cavern shape for possible microcracking in the surrounding rock is a very important factor. These considerations basically depend on depth, states of field stress and properties of host rock.

There are some important factors to investigate for cavern stability. These are stress changes and deformations around caverns, location and amount of tensile/shear damage, determination of high strain/failure areas and cavern volume reduction. The numerical models are necessary to observe pillar stresses in the cavern after excavation and the changes of cavern pillars during operation (Mohanty, Vandergrift 2012). Main factors for the structural stability of caverns in salt formation are local hydrology, local geology, rock properties, cavern operating conditions, cavern depth, cavern geometry and cavern locations. Also, it is well known that these factors are interrelated in development of salt cavern for gas storage. In cavern design, integrity of the salt is essential aspect to provide cavern stability during long-term operations.

Different design parameters are investigated for cavern stability and possible deformation characteristics such as displacement, shear and volumetric strain. The primary objective of this effort is to determine the amount of damage around the cavern wall and roof. Salt deformation primarily occurs around the cavern roof and corners, while salt damage happens mainly around the cavern walls (Han et al. 2006).

There are two basic simulation considerations as a single cavern and multiple caverns. Initially, the behavior of different shaped single caverns is investigated. This effort provides a basis for the most suitable cavern design for underground natural gas storage. It also allows the evaluation of the critical design parameters for salt formations. For multiple caverns, the cavern interaction is the basic
consideration to investigate the effects on damage propagation and deformation of neighboring caverns. The optimum distance is determined to eliminate mutual interactions between caverns. Increasing the number of horizontal caverns provides financial benefits. In such cases, the stability of the cavern array must be high priority. The displacement is selected as a kinematics quantity to observe cavern interactions.

5.1 Parametric Study

When a solution mined cavern is created in salt, a stress field is induced around the cavern that results in displacement and strain.

The RocScience program is utilized for stability analyses that provide useful data on stress distribution, cavern displacement and strains as a function of parameters such as in-situ stress ratio, cavern depth and salt properties. The program is capable of performing plastic analyses to evaluate the effects of varying in-situ ground stress ratio (k), cavern depth and salt properties on the stability associated with different cavern shapes. In order to evaluate the stability analysis, the results of computer-drawn displacement and strain plots are presented. It is developed to observe the displacement and strain in the cavern after excavation process. Also, the highest displacement location can be determined to estimate potential failure around the cavern. Smaller displacements and strains (shear and volume) are preferred to more stable caverns.

Axisymmetric modeling is the most suitable mechanical system for realistic and meaningful results. It allows us to analyze a 3-dimensional excavation which is rotationally symmetric about an axis. The input is 2-dimensional, but the analysis results apply to the 3-dimensional problem.

A storage cavern experiences a higher in-situ stress at the bottom than at the top. Gradient loading assumes that the cavern is subjected to in-situ stresses varying linearly with depth. Therefore, all the analyses in this study utilize gradient loading.

The external boundary conditions are very important for an axisymmetric model and they need to be specified. First, cavern boundaries are free to move with no restriction in any direction. The boundary segments above and below the cavern are restrained in the x-axis, but they are free to move in the y-axis. The boundary segment along the top is free to move in the x-axis. The boundary conditions along the bottom and opposite edge are specified as no movement in any direction.
Analyses are performed with isotropic initial state of stress and homogeneous isotropic structure of salt formation. Mohr-Coulomb model is specified for damage and failure issues. Salt only behaves elastically at very low stress levels, perhaps as low as 10-20 percent of the ultimate strength (Hardy 1982). Therefore, salt is assumed to be a plastic material for numerical analyses.

There are three specified cavern shapes as cylindrical, tapered cylinder and teardrop in this parametric study. Figure 5.1 illustrates the shape of cylindrical cavern, tapered cylinder cavern and teardrop cavern, respectively. In numerical models, it is assumed that the salt formation has 80 m height and 80 m diameter. Each cavern shape has its own specific geometry. The geometric layout of the cylindrical shaped cavern model is 48 m in height and 16 m in diameter. It is described in terms of Diameter/Height (D/H) ratio, i.e. the model has a D/H ratio of 1/3. The excavation area is 338.02 m². The tapered cylinder model is 67 m in height and 14 m in diameter. The excavation area is 334.37 m². The teardrop model is 34 m in height and 30 m in diameter. The excavation area is 333.47 m².

![Figure 5.1: The Shapes of Cylindrical Cavern, Tapered Cylinder Cavern and Teardrop Cavern](image)

(A) Cylindrical  (B) Tapered Cylinder  (C) Teardrop

Figure 5.1: The Shapes of Cylindrical Cavern, Tapered Cylinder Cavern and Teardrop Cavern
Figure 5.2, 5.3 and 5.4 illustrate the geometric layout of cylindrical cavern, tapered cylinder cavern and teardrop cavern in the software, respectively.

Figure 5.2: The geometric layout of cylindrical cavern

Figure 5.3: The geometric layout of tapered cylinder cavern
Parametric study is essential for the sensitivity analysis of cavern design parameters. It is expected to observe the effect of each design factor on the stability of cavern with different shapes. It provides optimum conditions for final cavern design.

Cavern design parameters in this study are:

- Cavern depth (200, 600, 750, 1000 and 1500 m)
- Total in-situ stress ratio, $k$ (0.5, 1.0, 1.5, 2.0 and 3.0)
- Unit weight of overburden (0.010, 0.030, 0.050 and 0.075 MN/m$^3$)
- Young’s modulus of salt (10000, 20000, 30000 and 45000 MPa)
- Poisson’s ratio of salt (0.10, 0.20, 0.30 and 0.45)
- Tensile strength of salt (0.5, 2, 10 and 30 MPa)
- Friction angle of salt (10°, 15°, 25° and 30°)
- Cohesion of salt (0.5, 1.0, 2.5 and 5.0 MPa)
- Dilation angle of salt (5°, 10°, 15° and 17.5°)

Table 5.1 presents description of salt cavern numerical analyses and Table 5.2 exhibits results of salt cavern numerical analyses in this parametric study.
Table 5.1: Description of Salt Cavern Numerical Analyses

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Depth (m)</th>
<th>Total stress ratio (k)</th>
<th>Unit weight of overburden (MN/m²)</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Tensile strength (MPa)</th>
<th>Friction angle(°)</th>
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<tr>
<td>87</td>
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<td>0.0016</td>
<td>-0.0014</td>
</tr>
<tr>
<td>88</td>
<td>0.2562</td>
<td>0.0375</td>
<td>-0.0302</td>
</tr>
</tbody>
</table>
5.1.1 The Study on Cylindrical, Tapered Cylinder and Teardrop Caverns

In this part of the research, a parametric study is performed on cylindrical, tapered cylinder and teardrop cavern are the specified cavern shapes for stability analyses in this study. The objective of this issue is to observe the effect of design parameters on cavern stability. The outputs between each design parameter and cavern stability are figured, and they are shown in Appendix part. Appendix A, B and C present the result of cylindrical, tapered cylinder and teardrop caverns, respectively. In shear strain figures, negative values present compressive strain on the cavern boundaries, and they are observed on the cavern roof. Positive strain values present tensile strain, and they are experienced on the cavern wall.
5.1.1.1 Cavern Depth:

The first study involves differently shaped caverns located at depths of 200, 600, 750, 1000 and 1500 m. It is assumed that there is a hydrostatic in-situ stress field, \( k = 1 \), and the salt has the following properties: Young’s modulus=30,000 MPa, Poisson’s ratio=0.30, Tensile strength: 2 MPa, Friction angle: 15°, Cohesion: 1 MPa and Dilation angle: 15°. The overburden and salt have unit weights of 0.030 and 0.021 MN/m\(^3\), respectively.

Figure A.1, A.2 and A.3 in Appendix A represent the variations of total displacement, shear strain and volumetric strain as a function of cavern depth for cylindrical cavern. Figure B.1, B.2 and B.3 in Appendix B illustrate the variations of total displacement, shear strain and volumetric strain as a function of cavern depth for tapered cylinder cavern. Figure C.1, C.2 and C.3 in Appendix C exhibit the variations of total displacement, shear strain and volumetric strain as a function of cavern depth for teardrop cavern. It is concluded that increasing depth leads to less stable caverns since the amount of displacement and strains increase significantly.

5.1.1.2 Total In-situ Stress Ratio (\( k \)):

The effect of total stress ratio on cavern stability is investigated. There are five different stress ratio (\( k \)) values of 0.5, 1.0, 1.5, 2.0 and 3.0 in this study. The selected cavern depth is 750 m and unit weight of overburden is 0.030 MN/m\(^3\). All other salt properties are constant.

Figure A.4, A.5 and A.6 in Appendix A represent the variations of total displacement, shear strain and volumetric strain as a function of in-situ stress ratio for cylindrical cavern. Figure B.4, B.5 and B.6 in Appendix B illustrate the variations of total displacement, shear strain and volumetric strain as a function of in-situ stress ratio for tapered cylinder cavern. Figure C.4, C.5 and C.6 in Appendix C exhibit the variations of total displacement, shear strain and volumetric strain as a function of in-situ stress ratio for teardrop cavern. \( k \)-value should not be extreme such as 2.0 or 3.0. They lead to larger displacement and strains on the cavern boundaries. Therefore, it must be between 0.5 and 1.0 for more stable caverns.

5.1.1.3 Unit Weight of Overburden:

The effect of unit weight of overburden on cavern stability is studied. There are four different values as 0.010, 0.030, 0.050 and 0.075 MN/m\(^3\). The selected cavern depth is 750 m. All other parameters are constant.
Figure A.7, A.8 and A.9 in Appendix A represent the variations of total displacement, shear strain and volumetric strain as a function of unit weight of overburden for cylindrical cavern. Figure B.7, B.8 and B.9 in Appendix B illustrate the variations of total displacement, shear strain and volumetric strain as a function of unit weight of overburden for tapered cylinder cavern. Figure C.7, C.8 and C.9 in Appendix C exhibit the variations of total displacement, shear strain and volumetric strain as a function of unit weight of overburden for teardrop cavern. It is concluded that cavern displacement and strains increase dramatically with higher overburden unit weights. Therefore, it is very favorable to have the lower unit weight of overburden for cavern stability.

5.1.1.4 Young’s Modulus of Salt:

The effect of Young’s modulus is studied for cavern stability. The cavern depth is 750 m, unit weight of overburden is 0.030 MN/m$^3$ and $k$ value is 1. There are four different Young’s modulus values as 10000, 20000, 30000 and 45000 MPa with a constant Poisson’s ratio of 0.30.

Figure A.10, A.11 and A.12 in Appendix A represent the variations of total displacement, shear strain and volumetric strain as a function of Young’s modulus of salt for cylindrical cavern. Figure B.10, B.11 and B.12 in Appendix B illustrate the variations of total displacement, shear strain and volumetric strain as a function of Young’s modulus of salt for tapered cylinder cavern. Figure C.10, C.11 and C.12 in Appendix C exhibit the variations of total displacement, shear strain and volumetric strain as a function of Young’s modulus of salt for teardrop cavern. It is concluded that higher values are preferable for cavern stability since the displacement and strains increase with lower Young’s modulus values.

5.1.1.5 Poisson’s Ratio of Salt:

The effect of Poisson’s ratio of salt on cavern stability is studied. The cavern depth is 750 m, unit weight of overburden is 0.030 MN/m$^3$ and $k$ value is 1. There are four different Poisson’s ratio values as 0.10, 0.20, 0.30 and 0.45 with constant Young’s modulus of 30000 MPa.

Figure A.13, A.14 and A.15 in Appendix A represent the variations of total displacement, shear strain and volumetric strain as a function of Poisson’s ratio of salt for cylindrical cavern. Figure B.13, B.14 and B.15 in Appendix B illustrate the variations of total displacement, shear strain and volumetric strain as a function of Poisson’s ratio of salt for tapered cylinder cavern. Figure C.13, C.14 and C.15 in Appendix C exhibit the variations of total displacement, shear strain and volumetric strain as a function of Poisson’s ratio of salt for teardrop cavern. It is concluded that cavern displacement and strains decrease with
higher ratio values. However, the effect is not significant due to small changes. The results are very close to each other. However, it may be clearly seen by higher ratios. In this study, the ratio of 0.45 provides much more stable caverns.

5.1.1.6 Tensile Strength of Salt:

The effect of tensile strength of salt on cavern stability is investigated. There are four different tensile strength of salt values of 0.5, 2, 10 and 30 MPa in this study. The selected cavern depth is 750 m, total in-situ stress ratio is 1.0 and unit weight of overburden is 0.030 MN/m$^3$. All other salt properties are constant.

Figure A.16, A.17 and A.18 in Appendix A represent the variations of total displacement, shear strain and volumetric strain as a function of tensile strength of salt for cylindrical cavern. Figure B.16, B.17 and B.18 in Appendix B illustrate the variations of total displacement, shear strain and volumetric strain as a function of tensile strength of salt for tapered cylinder cavern. Figure C.16, C.17 and C.18 in Appendix C exhibit the variations of total displacement, shear strain and volumetric strain as a function of tensile strength of salt for teardrop cavern. It is concluded that tensile strength has a slight effect on cavern stability since the amount of displacement and strain are not changed significantly.

5.1.1.7 Friction Angle of Salt:

The influence of friction angle of salt on cavern stability is studied. There are four different friction angle of salt values of 10°, 15°, 20° and 30° in this study. The selected cavern depth is 750 m, total in-situ stress ratio is 1.0 and unit weight of overburden is 0.030 MN/m$^3$. All other salt properties are constant.

Figure A.19, A.20 and A.21 in Appendix A represent the variations of total displacement, shear strain and volumetric strain as a function of friction angle of salt for cylindrical cavern. Figure B.19, B.20 and B.21 in Appendix B illustrate the variations of total displacement, shear strain and volumetric strain as a function of friction angle of salt for tapered cylinder cavern. Figure C.19, C.20 and C.21 in Appendix C exhibit the variations of total displacement, shear strain and volumetric strain as a function of friction angle of salt for teardrop cavern. It is concluded that cavern displacement and strains decrease dramatically with higher friction angle values. Therefore, higher friction angle of salt is much better for cavern stability.
5.1.1.8 Cohesion of Salt:

The effect of cohesion of salt on cavern stability is investigated. There are four different cohesion of salt values of 0.5, 1, 2.5 and 5 MPa in this study. The selected cavern depth is 750 m, total in-situ stress ratio is 1.0 and unit weight of overburden is 0.030 MN/m³. All other salt properties are constant.

Figure A.22, A.23 and A.24 in Appendix A represent the variations of total displacement, shear strain and volumetric strain as a function of cohesion of salt for cylindrical cavern. Figure B.22, B.23 and B.24 in Appendix B illustrate the variations of total displacement, shear strain and volumetric strain as a function of cohesion of salt for tapered cylinder cavern. Figure C.22, C.23 and C.24 in Appendix C exhibit the variations of total displacement, shear strain and volumetric strain as a function of cohesion of salt for teardrop cavern. It is concluded that cavern displacement and strains decrease dramatically with higher cohesion levels. It is very important to have higher values of cohesion for more stable cavern.

5.1.1.9 Dilation Angle of Salt:

The effect of dilation angle of salt on cavern stability is investigated. There are four different dilation angle of salt values of 5°, 10°, 15° and 17.5° in this study. The selected cavern depth is 750 m, total in-situ stress ratio is 1.0 and unit weight of overburden is 0.030 MN/m³. All other salt properties are constant.

Figure A.25, A.26 and A.27 in Appendix A represent the variations of total displacement, shear strain and volumetric strain as a function of dilation angle of salt for cylindrical cavern. Figure B.25, B.26 and B.27 in Appendix B illustrate the variations of total displacement, shear strain and volumetric strain as a function of dilation angle of salt for tapered cylinder cavern. Figure C.25, C.26 and C.27 in Appendix C exhibit the variations of total displacement, shear strain and volumetric strain as a function of dilation angle of salt for teardrop cavern. It is concluded that cavern displacement and strains increase with higher dilation angle levels.

5.1.2 Summary of Parametric Study

The parametric study is very important for the final design in this study to determine the properties of salt formation. It provides sensitivity analysis of each design parameter for stability. The following results are obtained by the parametric study:
Cavern depth is one of the most important concerns for cavern design. It is observed that increasing depth leads to less stable caverns since the amount of displacement and strains increase significantly.

The ground stress ratio (k) has a significant effect on the stress distribution around the cavern. The k-value should not be extreme such as 2.0 or 3.0. It causes larger displacement and strains on the cavern boundaries. Therefore, it must be between 0.5 and 1.0 for more stable caverns.

Unit weight of overburden is a very important parameter for cavern stability. It is concluded that cavern displacement and strains increase with higher overburden unit weights.

Cavern stability is less sensitive to Young’s modulus of salt. It is observed that higher values are favorable for cavern stability since the displacement and strains increase with lower Young’s modulus values. However, the effect is not significant.

Cavern stability decreases with higher Poisson’s ratio of salt values but the effect is not significant due to small changes. The results are very close to each other. However, it can clearly be seen by higher ratios. In this study, the ratio of 0.45 provides more stable caverns.

Tensile strength of salt has a very slight effect on cavern stability since the amount of displacement and strain are not changed considerably.

Friction angle of salt is a very important factor for cavern stability. It is concluded that cavern displacement and strains decrease dramatically with higher friction angle values.

Cohesion of salt influences significantly cavern stability. It is found that cavern displacement and strains decrease dramatically with higher cohesion levels.

Dilation angle of salt has a significant effect on cavern stability. It is observed that cavern displacement and strains increase with higher dilation angle levels.

5.2 Final Cavern Design

The following principals are important for cavern design and development:

- Salt is the most competent rock for the structural stability of the cavern. Therefore, sufficient salt is left above the cavern to provide the safe redistribution of stresses from cavern development.
- A minimum thickness is determined in the overlying salt bed for the cavern roof to balance the overburden stress. Thicker salt roofs provide stiffer and more stable conditions.

- The excavated salt is supported by the salt in the cavern walls since the average wall stresses increase with excavation.

- Overall cavern stability also depends on the salt remaining between caverns for cavern arrays. The redistribution of stresses from cavern development increases the average pillar stress. A thicker pillar has a lower pillar stress, and therefore a lower yield tendency.

- In general, cavern depth is limited by two main factors, economics and salt properties. Storage caverns are not generally designed greater than 1,800 m since the creep rate increases with depth (Hardy 1982). For greater depths, cavern walls and bottom deform at unacceptable rates, so very high cavern storage volume losses are presented.

- The ground stress ratio \((k)\) has a significant effect on the stress distribution around the cavern. Therefore, a better understanding of the virgin state of stress in underground salt formation is highly important for the optimum design of storage caverns.

In final design, it is assumed that the salt formation has 600 m height and 600 m diameter. This dimension of the site for numerical model is determined by real field data from Petroleum Pipeline Corporation in Turkey. In chapter of site geology, Tuz Golu Storage Project is explained and it can provide this realistic site for underground natural gas storage.

It is very important to determine the exact location of the cavern in the salt formation. Table 5.3 presents the location of caverns in the study.

Table 5.3: The Location of Salt Formation/Caverns in the Final Design

<table>
<thead>
<tr>
<th>Cavern</th>
<th>Salt Formation (Top-Base) (m)</th>
<th>Cavern Depth (Top-Base)(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario_1</td>
<td>450-1,050</td>
<td>600-900</td>
</tr>
<tr>
<td>Scenario_2</td>
<td>650-1,250</td>
<td>800-1,100</td>
</tr>
<tr>
<td>Scenario_3</td>
<td>850-1,450</td>
<td>1,000-1,300</td>
</tr>
<tr>
<td>Scenario_4</td>
<td>1,050-1,650</td>
<td>1,200-1,500</td>
</tr>
<tr>
<td>Scenario_5</td>
<td>1,250-1,850</td>
<td>1,400-1,700</td>
</tr>
</tbody>
</table>
The properties of salt formation in final design are determined by the results of previous parametric study. It provides optimum and realistic data by sensitivity analyses for the design. Table 5.4 presents the properties of salt formation in this study. Also, the most reasonable conditions are 0.03 MN/m$^3$ and $k=1$ for the values of unit weight of overburden and in-situ stress ratio, respectively.

Table 5.4: The Properties of Salt Formation in Final Design

<table>
<thead>
<tr>
<th>Initial element loading</th>
<th>Field stress &amp; body force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight (MN/m$^3$)</td>
<td>0.021</td>
</tr>
<tr>
<td>Elastic type</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Young's modulus (MPa)</td>
<td>30,000</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.30</td>
</tr>
<tr>
<td>Failure criterion</td>
<td>Mohr-Coulomb</td>
</tr>
<tr>
<td>Peak tensile strength (MPa)</td>
<td>2</td>
</tr>
<tr>
<td>Residual tensile strength (MPa)</td>
<td>2</td>
</tr>
<tr>
<td>Peak friction angle (*)</td>
<td>15</td>
</tr>
<tr>
<td>Peak cohesion (MPa)</td>
<td>2.5</td>
</tr>
<tr>
<td>Material type</td>
<td>Plastic</td>
</tr>
<tr>
<td>Dilation angle (*)</td>
<td>10</td>
</tr>
<tr>
<td>Residual friction angle (*)</td>
<td>15</td>
</tr>
<tr>
<td>Residual cohesion</td>
<td>2.5</td>
</tr>
</tbody>
</table>

5.2.1 Single Cavern Design

There are three specified cavern shapes as cylindrical, tapered cylinder and teardrop in this study. Figure 5.5 illustrates the shape of cylindrical cavern, tapered cylinder cavern and teardrop cavern, respectively. The most common cavern shape is cylindrical for enough storage volume. Also, salt caverns will be created in the project of Tuz Golu as a cylindrical shape which has the ratio of ½ of Diameter/Height. The proposed cavern height is planned to be 300 m. Each cavern shape has its own specific geometry with different cavern roof configurations. To have reasonable comparisons, the cross-sectional area of the caverns must be as close as possible.

The behaviors of different cavern shapes are investigated. The effect of cavern shape on stability as a function of depth is studied. This effort provides a basis for the most suitable cavern design for underground natural gas storage.
First, stress distribution around the cavern and salt formation is studied. Then, total displacement on the cavern boundary is investigated to illustrate the stability. Also, the point of the maximum total displacement in the cavern is determined.

(C) Cylindrical                                (B) Tapered cylinder                                         (C) Teardrop

Figure 5.5: The Shapes of Cylindrical Cavern, Tapered Cylinder Cavern and Teardrop Cavern

5.2.1.1 Cylindrical Cavern Design

The most common cavern shape for underground natural gas storage is cylindrical in the industry since it provides the maximum storage volume. Also, salt caverns will be created in the project of Tuz Golu as a cylindrical shape which has the ratio of \( \frac{1}{2} \) of Diameter/Height. The proposed cavern height is planned to be 300 m. Therefore, it is the first choice in this study.

The geometric layout of the cylindrical cavern model is 300 m in height and 150 m in diameter. The excavation area is 20,097.224 m\(^2\). Figure 5.6 illustrates the geometric layout of cylindrical cavern in this study.
5.2.1.1 Stress Analysis

A storage cavern experiences a higher in-situ stress at the bottom than at the top. Gradient loading assumes that the cavern is subjected to in-situ stresses varying linearly with depth. Therefore, the analysis in this study utilize gradient loading. Unit weight of overburden is specified as 0.030 MN/m$^3$ and the in-situ stress ratio (k) is equal to 1. This ratio describes that vertical and horizontal stress values are equal to each other.

Figure 5.7 illustrates the stress distribution of Scenario_1. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 15 MPa, and at the bottom surface of salt formation, they are up to 30 MPa for Scenario_1.
Figure 5.7: Stress Contour of Scenario_1 for Cylindrical Cavern

Figure 5.8 exhibits the stress distribution of Scenario_2. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 21 MPa, and at the bottom surface of salt formation, they are up to 36 MPa for Scenario_2.

Figure 5.8: Stress Contour of Scenario_2 for Cylindrical Cavern

Figure 5.9 exhibits the stress distribution of Scenario_3. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 27 MPa, and at the bottom surface of salt formation, they are up to 42 MPa for Scenario_3.
Figure 5.9: Stress Contour of Scenario_3 for Cylindrical Cavern

Figure 5.10 illustrates the stress distribution of Scenario_4. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 33 MPa, and at the bottom surface of salt formation, they are up to 48 MPa for Scenario_4.

Figure 5.10: Stress Contour of Scenario_4 for Cylindrical Cavern

Figure 5.11 illustrates the stress distribution of Scenario_5. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 39 MPa, and at the bottom surface of salt formation, they are up to 54 MPa for Scenario_5.
5.2.1.1.2 Total Displacement Analysis

Total displacement is the primary consideration for stability analyses of salt caverns for underground natural gas storage in this study. The effect of cavern depth for stability is investigated. The objective of this effort is to observe the variation of total displacement as a function of cavern depth.

Figure 5.12 illustrates the total displacement contour of Scenario_1. Deformation characteristics of the cavern can be observed as shown in Figure 5.13. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_1. Figure 5.14 exhibits the total displacement values at specified points. Also, the point of maximum total displacement in the cavern is determined and it is shown in a red box.
Figure 5.12: Total Displacement Contour of Scenario_1 for Cylindrical Cavern

Figure 5.13: Deformation Characteristics of Scenario_1 for Cylindrical Cavern
Figure 5.14: Total Displacement Values of Scenario_1 for Cylindrical Cavern at Specified Points

Figure 5.15 illustrates the total displacement contour of Scenario_2. Deformation characteristics of the cavern can be observed as shown in Figure 5.16. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_2. Figure 5.17 exhibits the total displacement values at specified points. Also, the point of maximum total displacement in the cavern is determined and it is shown in a red box.

Figure 5.15: Total Displacement Contour of Scenario_2 for Cylindrical Cavern
Figure 5.16: Deformation Characteristics of Scenario_2 for Cylindrical Cavern

Figure 5.17: Total Displacement Values of Scenario_2 for Cylindrical Cavern at Specified Points

Figure 5.18 illustrates the total displacement contour of Scenario_3. Deformation characteristics of the cavern can be observed as shown in Figure 5.19. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern wall is the most disturbed region for Scenario_3. Figure 5.20 exhibits the total displacement
values at specified points. Also, the point of maximum total displacement in the cavern is determined and it is shown in a red box.

Figure 5.18: Total Displacement Contour of Scenario_3 for Cylindrical Cavern

Figure 5.19: Deformation Characteristics of Scenario_3 for Cylindrical Cavern
Figure 5.20: Total Displacement Values of Scenario_3 for Cylindrical Cavern at Specified Points

Figure 5.21 illustrates the total displacement contour of Scenario_4. Deformation characteristics of the cavern can be observed as shown in Figure 5.22. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern wall is the most disturbed region for Scenario_4. Figure 5.23 exhibits the total displacement values at specified points. Also, the point of maximum total displacement in the cavern is determined and it is shown in a red box.
Figure 5.22: Deformation Characteristics of Scenario_4 for Cylindrical Cavern

Figure 5.23: Total Displacement Values of Scenario_4 for Cylindrical Cavern at Specified Points

Figure 5.24 illustrates the total displacement contour of Scenario_5. Deformation characteristics of the cavern can be observed as shown in Figure 5.25. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern wall is the most disturbed region for Scenario_5. Figure 5.26 exhibits the total displacement
values at specified points. Also, the point of maximum total displacement in the cavern is determined and it is shown in a red box.

Figure 5.24: Total Displacement Contour of Scenario_5 for Cylindrical Cavern

Figure 5.25: Deformation Characteristics of Scenario_5 for Cylindrical Cavern
5.2.1.2 Tapered Cylinder Cavern Design

The second cavern shape for underground natural gas storage is tapered cylinder in this study. The geometric layout of the tapered cylinder cavern model is 300 m in height and 158 m in diameter with different cavern roof configuration. The excavation area is 20,147.734 m$^2$. Figure 5.27 illustrates the geometric layout of cylindrical cavern in this study.
5.2.1.2.1 Stress Analysis

A storage cavern experiences a higher in-situ stress at the bottom than at the top. Gradient loading assumes that the cavern is subjected to in-situ stresses varying linearly with depth. Therefore, the analysis in this study utilize gradient loading. Unit weight of overburden is specified as 0.030 MN/m$^3$ and the in-situ stress ratio (k) is equal to 1. This ratio describes that vertical and horizontal stress values are equal to each other.

Figure 5.28 illustrates the stress distribution of Scenario_1. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 15 MPa, and at the bottom surface of salt formation, they are up to 30 MPa for Scenario_1. The values are very close to the cylindrical cavern design; however, there are some significant differences on the cavern boundary due to specific geometry of each cavern.

Figure 5.28: Stress Contour of Scenario_1 for Tapered Cylinder Cavern

Figure 5.29 exhibits the stress distribution of Scenario_2. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 21 MPa, and at the bottom surface of salt formation, they are up to 36 MPa for Scenario_2. The values are very close to the cylindrical cavern design; however, there are some significant differences on the cavern boundary due to specific geometry of each cavern.
Figure 5.29: Stress Contour of Scenario_2 for Tapered Cylinder Cavern

Figure 5.30 exhibits the stress distribution of Scenario_3. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 27 MPa, and at the bottom surface of salt formation, they are up to 42 MPa for Scenario_3. The values are very close to the cylindrical cavern design; however, there are some significant differences on the cavern boundary due to specific geometry of each cavern.

Figure 5.30: Stress Contour of Scenario_3 for Tapered Cylinder Cavern
Figure 5.31 illustrates the stress distribution of Scenario_4. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 33 MPa, and at the bottom surface of salt formation, they are up to 48 MPa for Scenario_4. The values are very close to the cylindrical cavern design; however, there are some significant differences on the cavern boundary due to specific geometry of each cavern.

Figure 5.31: Stress Contour of Scenario_4 for Tapered Cylinder Cavern

Figure 5.32 illustrates the stress distribution of Scenario_5. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 39 MPa, and at the bottom surface of salt formation, they are up to 54 MPa for Scenario_5. The values are very close to the cylindrical cavern design; however, there are some significant differences on the cavern boundary due to specific geometry of each cavern.
5.2.1.2.2 Total Displacement Analysis

Total displacement is the primary consideration for stability analyses of salt caverns for underground natural gas storage in this study. The effect of cavern depth for stability is investigated. The objective of this effort is to observe the variation of total displacement as a function of cavern depth.

Figure 5.33 illustrates the total displacement contour of Scenario_1. Deformation characteristics of the cavern can be observed as shown in Figure 5.34. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_1. Figure 5.35 exhibits the total displacement values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.
Figure 5.34: Deformation Characteristics of Scenario_1 for Tapered Cylinder Cavern

Figure 5.35: Total Displacement Values of Scenario_1 for Tapered Cylinder Cavern at Specified Points

Figure 5.36 illustrates the total displacement contour of Scenario_2. Deformation characteristics of the cavern can be observed as shown in Figure 5.37. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_2. Figure 5.38 exhibits the total displacement values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.
Figure 5.36: Total Displacement Contour of Scenario_2 for Tapered Cylinder Cavern

Figure 5.37: Deformation Characteristics of Scenario_2 for Tapered Cylinder Cavern
Figure 5.38: Total Displacement Values of Scenario_2 for Tapered Cylinder Cavern at Specified Points

Figure 5.39 illustrates the total displacement contour of Scenario_3. Deformation characteristics of the cavern can be observed as shown in Figure 5.40. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_3. Figure 5.41 exhibits the total displacement values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.

Figure 5.39: Total Displacement Contour of Scenario_3 for Tapered Cylinder Cavern
Figure 5.40: Deformation Characteristics of Scenario_3 for Tapered Cylinder Cavern

Figure 5.41: Total Displacement Values of Scenario_3 for Tapered Cylinder Cavern at Specified Points

Figure 5.42 illustrates the total displacement contour of Scenario_4. Deformation characteristics of the cavern can be observed as shown in Figure 5.43. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_4. Figure 5.44 exhibits the total displacement values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.
Figure 5.42: Total Displacement Contour of Scenario_4 for Tapered Cylinder Cavern

Figure 5.43: Deformation Characteristics of Scenario_4 for Tapered Cylinder Cavern
Figure 5.44: Total Displacement Values of Scenario_4 for Tapered Cylinder Cavern at Specified Points

Figure 5.45 illustrates the total displacement contour of Scenario_5. Deformation characteristics of the cavern can be observed as shown in Figure 5.46. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_5. Figure 5.47 exhibits the total displacement values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.
5.2.1.3 Teardrop Cavern Design

The last cavern shape for underground natural gas storage is teardrop in this study. The geometric layout of the teardrop model is 300 m in height and 180 m in diameter with different cavern roof configuration. The excavation area is $20,114.712 \text{ m}^2$. Figure 5.48 illustrates the geometric layout of teardrop cavern in this study.
5.2.1.3.1 Stress Analysis

A storage cavern experiences a higher in-situ stress at the bottom than at the top. Gradient loading assumes that the cavern is subjected to in-situ stresses varying linearly with depth. Therefore, the analysis in this study utilize gradient loading. Unit weight of overburden is specified as 0.030 MN/m$^3$ and the in-situ stress ratio (k) is equal to 1. This ratio describes that vertical and horizontal stress values are equal to each other.

Figure 5.49 illustrates the stress distribution of Scenario_1. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 15 MPa, and at the bottom surface of salt formation, they are up to 30 MPa for Scenario_1.
Figure 5.49: Stress Contour of Scenario_1 for Teardrop Cavern

Figure 5.50 exhibits the stress distribution of Scenario_2. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 21 MPa, and at the bottom surface of salt formation, they are up to 36 MPa for Scenario_2.

Figure 5.50: Stress Contour of Scenario_2 for Teardrop Cavern

Figure 5.51 exhibits the stress distribution of Scenario_3. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 27 MPa, and at the bottom surface of salt formation, they are up to 42 MPa for Scenario_3.
Figure 5.51: Stress Contour of Scenario_3 for Teardrop Cavern

Figure 5.52 illustrates the stress distribution of Scenario_4. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 33 MPa, and at the bottom surface of salt formation, they are up to 48 MPa for Scenario_4.

Figure 5.52: Stress Contour of Scenario_4 for Teardrop Cavern
Figure 5.53 illustrates the stress distribution of Scenario _5. As we expected, the stress values increase with increasing depth. For example, at the top surface of salt formation, the values are around 39 MPa, and at the bottom surface of salt formation, they are up to 54 MPa for Scenario _5.

![Stress Contour of Scenario_5 for Teardrop Cavern](image)

**5.2.1.3.2 Total Displacement Analysis**

Figure 5.54 illustrates the total displacement contour of Scenario _1. Deformation characteristics of the cavern can be observed as shown in Figure 5.55. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern wall is the most disturbed region for Scenario _1. Figure 5.56 exhibits the total displacement values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.
Figure 5.54: Total Displacement Contour of Scenario_1 for Teardrop Cavern

Figure 5.55: Deformation Characteristics of Scenario_1 for Teardrop Cavern
Figure 5.56: Total Displacement Values of Scenario_1 for Teardrop Cavern at Specified Points

Figure 5.75 illustrates the total displacement contour of Scenario_2. Deformation characteristics of the cavern can be observed as shown in Figure 5.58. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern wall is the most disturbed region for Scenario_2. Figure 5.59 exhibits the total displacement values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.

Figure 5.57: Total Displacement Contour of Scenario_2 for Teardrop Cavern
Figure 5.58: Deformation Characteristics of Scenario_2 for Teardrop Cavern

Figure 5.59: Total Displacement Values of Scenario_2 for Teardrop Cavern at Specified Points

Figure 5.60 illustrates the total displacement contour of Scenario_3. Deformation characteristics of the cavern can be observed as shown in Figure 5.61. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_3. Figure 5.62 exhibits the total displacement
values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.

Figure 5.60: Total Displacement Contour of Scenario_3 for Teardrop Cavern

Figure 5.61: Deformation Characteristics of Scenario_3 for Teardrop Cavern
Figure 5.62: Total Displacement Values of Scenario_3 for Teardrop Cavern at Specified Points

Figure 5.63 illustrates the total displacement contour of Scenario_4. Deformation characteristics of the cavern can be observed as shown in Figure 5.64. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_4. Figure 5.65 exhibits the total displacement values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.

Figure 5.63: Total Displacement Contour of Scenario_4 for Teardrop Cavern
Figure 5.64: Deformation Characteristics of Scenario_4 for Teardrop Cavern

Figure 5.65: Total Displacement Values of Scenario_4 for Teardrop Cavern at Specified Points

Figure 5.66 illustrates the total displacement contour of Scenario_5. Deformation characteristics of the cavern can be observed as shown in Figure 5.67. This helps to understand the possible changes on the cavern in the future. Also, it indicates the location where more deformation may occur. For example, cavern bottom is the most disturbed region for Scenario_5. Figure 5.68 exhibits the total displacement
values at specified points. Also, the point of maximum total displacement is determined and it is shown in a red box.

Figure 5.66: Total Displacement Contour of Scenario_5 for Teardrop Cavern

Figure 5.67: Deformation Characteristics of Scenario_5 for Teardrop Cavern
As a result, total displacement increases dramatically with higher depth for all three specified cavern shapes. The effect of cavern shape on stability as a function of depth is investigated. The objective of this study is to investigate the most stable cavern shape under same conditions. Figure 5.69 illustrates the effect of cavern shape on stability analyses with various depth values.

Figure 5.69: The Relationship between Cavern Depth and Total Displacement of Specified Cavern Shapes

At relatively shallow depths, the cavern shape has not a significant effect on stability since the maximum displacement results are very close to each other for all specified cavern shapes. However,
the difference becomes larger with deeper caverns and the effect of shape can be realized clearly. Therefore, cylindrical shape is the most stable for underground natural gas storage. Furthermore, the caverns of Tuz Golu Storage Project are at more than 1,100 m depth, so cylindrical cavern is highly recommended for this project.

5.2.2 Multiple Caverns Design

For multiple caverns design, the cavern interaction is the basic consideration to investigate the effects on damage propagation and deformation of neighboring caverns. The highest stresses normally occur at points on or close to the cavern boundary in a single cavern. The optimum distance is determined to eliminate mutual interactions between caverns. Increasing the number of horizontal caverns provides financial benefits. In such cases, the stability of the cavern array must be high priority. The displacement is selected as a kinematics quantity to observe cavern interactions.

Cylindrical cavern is the most suitable for multiple cavern designs due to the regular geometry in this study. Total displacement contour plots are very good indicators for observing the interaction between proposed neighboring caverns. It is seen that single cavern may influence up to 300 m. Also, the diameter of cavern is 150 m. Therefore, the typical rule of thumb of a minimum of 2-diameter of distance between structures also applies to the design.

Furthermore, the optimum distance between neighboring caverns is investigated by plane strain model. Three different distance specifications from 150 m to 300 m are examined. The cavern location is constant where the top cavern is at 1,000 m and the bottom cavern is at 1,300 m. Also, the diameter of cavern is 150 m.

Figure 5.70 illustrates the total displacement contour of the model when the distance between caverns is 150 m that is equal to the diameter of cavern. It is observed that there is a mutual interaction between caverns, so this distance is not enough.
Figure 5.70: Distance between Neighboring Caverns is 150 m for Total Displacement

Figure 5.71 exhibits the total displacement contour of the model when the distance between caverns is 225 m that is equal to 1.5-diameter of cavern. It is observed that even though the interaction decreases, it is still a problem.

Figure 5.71: Distance between Neighboring Caverns is 225 m for Total Displacement
Figure 5.72 shows the total displacement contour of the model when the distance between caverns is 300 m that is equal to 2-diameter of cavern. It is observed that the mutual interaction between caverns is almost zero. Therefore, the optimum distance between caverns to remove the mutual interaction should be equal to 2-diameter of cavern.

Figure 5.72: Distance between Neighboring Caverns is 300 m for Total Displacement

5.3 Salt Thickness Analysis

Salt thickness between cavern top and salt formation is a critical consideration for cavern design. Sufficient salt should be left above the cavern to provide the safe redistribution of stresses from cavern development. This helps to relieve the formation and reduces the effect of stresses during storage operations. Also, it prevents to influence the top boundary of salt formation. When the thickness is not sufficient, the boundary may be disturbed. This situation is not favorable for cavern designs. The objective of this study is to determine the optimum distance between cavern top and salt formation to eliminate mutual interaction for more stable cavern designs.

In this study, there are six different salt thickness specifications from 50 m to 300 m. The cavern location is constant where the top cavern is at 1,000 m and the bottom cavern is at 1,300 m. As it is expected, the total displacement of top salt boundary decreases with higher salt thickness. The following figures, from Figure 5.73 to Figure 5.78, exhibit total displacement contours of the specified salt thickness between cavern top and salt formation.
Figure 5.73: Salt Thickness between Cavern Top and Salt Formation is 50 m for Total Displacement

Figure 5.74: Salt Thickness between Cavern Top and Salt Formation is 100 m for Total Displacement
Figure 5.75: Salt Thickness between Cavern Top and Salt Formation is 150 m for Total Displacement

Figure 5.76: Salt Thickness between Cavern Top and Salt Formation is 200 m for Total Displacement
When the thickness is not sufficient to remove the interaction between top cavern and salt formation, up to 150 m in this study, as shown in Figure 5.73 and Figure 5.74, the boundary is disturbed. For example, it is observed that the total displacement on the top salt formation is around 10 cm at 50 m salt thickness; however, this value becomes almost zero with 150 m of thickness. Therefore, the optimum distance is determined by these results. Accordingly, the minimum distance between top cavern and salt formation should be equal to diameter of cavern in this study.
Chapter 6

CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

The study of design parameters of salt caverns for storage of natural gas was performed using the numerical analysis based on the finite element modeling (FEM), using a commercial software Phases© 7.0 by RocScience. The analysis included a parametric study of different input variable to see the sensitivity of the model to these parameters. This included geometrical parameters of the cavern i.e. shape and size, depth, specific gravity of overburden rocks and thus the in-situ stresses, ratio of lateral stress, elastic properties of rock, strength of rock salt, and finally the creep properties of the salt. The results of the study can be summarized in following concluding points.

A parametric study was performed to look into the impacts of various parameters including depth, salt properties, in situ stresses, and cavern shape. The outcome showed that the cavern stability is very sensitive to cavern depth since increasing depth leads to less stable caverns due to higher displacement and strain results. The ground stress ratio (k) has a significant effect on cavern stability, so the range between 0.5 and 1.0 is reasonable and results in conditions suitable for more stable caverns. The result of sensitivity analysis showed that the cavern stability is very sensitive to unit weight of overburden since cavern displacement and strains increase significantly with higher values. The outcome showed that the cavern stability is less sensitive to elastic moduli of salt (Young’s modulus and Poisson’s ratio) since the results of cavern displacement and strains are close to each other. The result of sensitivity analysis showed that the cavern stability is not sensitive to tensile strength of salt since the results of displacement and strains are almost the same. The outcome showed that the cavern stability is very sensitive to friction angle and cohesion of salt since higher values lead to more stable caverns due to lower displacement and strain results. Dilation angle of salt has a significant effect on cavern stability since cavern displacement and strains increase with higher values.

Total displacement of cavern increases dramatically with higher depth for all three specified cavern shapes. The effect of cavern shape on stability as a function of depth was investigated. The objective of this study was to investigate the most stable cavern shape under same conditions. At relatively shallow depths, the cavern shape has no significant effect on stability since the maximum displacement results are very close to each other for all specified cavern shapes. However, the difference becomes larger
with deeper caverns and the effect of shape can be realized clearly. Therefore, cylindrical shape is the most stable for underground natural gas storage.

Maximum displacement often occurs in the floor of flat shape caverns, otherwise on the sidewalls, where the long unsupported span is located.

Maximum displacements of less than 2% diameter is often considered as acceptable for stability of underground structures, and can be used as a general measure of acceptability of wall displacement for given cavern sizes, shapes, and depth. In this study, the diameter of cylindrical cavern was 150 m, and the limit for maximum displacement should be less than 3 m to meet the specification. The models in this study provided suitable results for this issue and in most cases, this requirement was met.

In general the cylindrical cavern showed the least displacements and better stability indicators.

In multiple cavern designs, the optimum distance was determined to eliminate mutual interactions between caverns and possibility of excessive ground movements and displacements. Total displacement contour plots were deemed to be very good indicators to observe the interaction between neighboring caverns. It is clearly seen that single cavern may influence up to 300 m. Thus with the diameter of cavern being 150 m, the typical rule of thumb of a minimum of 2-diameter of distance between structures also applies to the design of salt caverns.

Salt thickness or distance between cavern top and salt formation is a very critical consideration for cavern design. Sufficient salt should be left above the cavern to provide the safe redistribution of stresses from cavern development. Implementing sufficient distance from the cap rock helps to relieve the formation and reduces the effect of stresses during storage operations. When the thickness is not sufficient, the boundary between the salt and overburden rocks may be disturbed. The optimum distance between cavern top and salt formation was studied to minimize the possibility of adverse effects. The results show that the thickness less than 150 m will cause some disturbance in the boundary. Given the diameter of cavern of 150 m, it seems like the minimum depth of cavern in the salt formation should be equal to diameter of cavern.
6.2 Suggestions to Future Work

Following recommendations are made for continuation of this study:

- A more detailed analysis of properties of salt in the target area for refining the models and improving the design and related analysis for the final cavern design.
- Comparison of the result of modeling using Phases with other comparable programs such as FLAC with better capabilities to analyze and handle large ground deformations.
- Including more detailed information about the impacts of anisotropy in the rock and its impact on stress concentrations and displacements in the cavern wall.
- Study of the case histories in construction of salt caverns relative to possible failures in the cavern and causes to revisit the criteria used in this study for evaluation of the ground stability, which was the deformations of less than 2% of cavern dimension.
- Study of the cavern construction method using the solution mining to observe the actual shape of the caverns relative to the idealized cavern shapes in this study and revising of the models based on the actual shape. Also evaluation of the drilling methods in deep salt deposits and feasibility of drilling the right size holes and implementation of the solution mining for the desired geometry from within the well.
- Study of loading and unloading of the cavern by injection/storage, and withdrawal of the gas during the life cycle of the caverns during the operation and its impact on the displacements and cavern stability.

The recommended studies will complement the analysis performed in this study and will be essential for final design of the salt caverns for gas storage.
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APPENDIX A: Parametric Study on Cylindrical Cavern

Figure A.1: Total Displacement Plot for Specified Depth Values of Cylindrical Cavern

Figure A.2: Shear Strain Plot for Specified Depth Values of Cylindrical Cavern
Figure A.3: Volumetric Strain Plot for Specified Depth Values of Cylindrical Cavern

Figure A.4: Total Displacement Plot for Specified Total In-situ Stress Ratio Values of Cylindrical Cavern
Figure A.5: Shear Strain Plot for Specified Total In-situ Stress Ratio Values of Cylindrical Cavern

Figure A.6: Volumetric Strain Plot for Specified Total In-situ Stress Ratio Values of Cylindrical Cavern
Figure A.7: Total Displacement Plot for Specified Unit Weight of Overburden Values of Cylindrical Cavern

Figure A.8: Shear Strain Plot for Specified Unit Weight of Overburden Values of Cylindrical Cavern
Figure A.9: Volumetric Strain Plot for Specified Unit Weight of Overburden Values of Cylindrical Cavern

Figure A.10: Total Displacement Plot for Specified Young’s Modulus of Salt of Cylindrical Cavern
Figure A.11: Shear Strain Plot for Specified Young’s Modulus of Salt of Cylindrical Cavern

Figure A.12: Volumetric Strain Plot for Specified Young’s Modulus of Salt of Cylindrical Cavern
Figure A.13: Total Displacement for Specified Poisson’s Ratio of Salt of Cylindrical Cavern

Figure A.14: Shear Strain for Specified Poisson’s Ratio of Salt of Cylindrical Cavern
Figure A.15: Volumetric Strain for Specified Poisson’s Ratio of Salt of Cylindrical Cavern

Figure A.16: Total Displacement Plot for Specified Tensile Strength of Salt Values of Cylindrical Cavern
Figure A.17: Shear Strain Plot for Specified Tensile Strength of Salt Values of Cylindrical Cavern

Figure A.18: Volumetric Strain Plot for Specified Tensile Strength of Salt Values of Cylindrical Cavern
Figure A.19: Total Displacement Plot for Specified Friction Angle of Salt Values of Cylindrical Cavern

Figure A.20: Shear Strain Plot for Specified Friction Angle of Salt Values of Cylindrical Cavern
Figure A.21: Volumetric Strain Plot for Specified Friction Angle of Salt Values of Cylindrical Cavern

Figure A.22: Total Displacement Plot for Specified Cohesion of Salt Values of Cylindrical Cavern
Figure A.23: Shear Strain Plot for Specified Cohesion of Salt Values of Cylindrical Cavern

Figure A.24: Volumetric Strain Plot for Specified Cohesion of Salt Values of Cylindrical Cavern
Figure A.25: Total Displacement Plot for Specified Dilation Angle of Salt Values of Cylindrical Cavern

Figure A.26: Shear Strain Plot for Specified Dilation Angle of Salt Values of Cylindrical Cavern
Figure A.27: Volumetric Strain Plot for Specified Dilation Angle of Salt Values of Cylindrical Cavern
APPENDIX B: Parametric Study on Tapered Cylinder Cavern

Figure B.1: Total Displacement Plot for Specified Depth Values of Tapered Cylinder Cavern

Figure B.2: Shear Strain Plot for Specified Depth Values of Tapered Cylinder Cavern
Figure B.3: Volumetric Strain Plot for Specified Depth Values of Tapered Cylinder Cavern

Figure B.4: Total Displacement Plot for Specified Total In-situ Stress Ratio Values of Tapered Cylinder Cavern
Figure B.5: Shear Strain Plot for Specified Total In-situ Stress Ratio Values of Tapered Cylinder Cavern

Figure B.6: Volumetric Strain Plot for Specified Total In-situ Stress Ratio Values of Tapered Cylinder Cavern
Figure B.7: Total Displacement Plot for Specified Unit Weight of Overburden Values of Tapered Cylinder Cavern

Figure B.8: Shear Strain Plot for Specified Unit Weight of Overburden Values of Tapered Cylinder Cavern
Figure B.9: Volumetric Strain Plot for Specified Unit Weight of Overburden Values of Tapered Cylinder Cavern

Figure B.10: Total Displacement Plot for Specified Young’s Modulus of Salt of Tapered Cylinder Cavern
Figure B.11: Shear Strain Plot for Specified Young’s Modulus of Salt of Tapered Cylinder Cavern

Figure B.12: Volumetric Strain Plot for Specified Young’s Modulus of Salt of Tapered Cylinder Cavern
Figure B.13: Total Displacement for Specified Poisson’s Ratio of Salt of Tapered Cylinder Cavern

Figure B.14: Shear Strain for Specified Poisson’s Ratio of Salt of Tapered Cylinder Cavern
Figure B.15: Volumetric Strain for Specified Poisson’s Ratio of Salt of Tapered Cylinder Cavern

Figure B.16: Total Displacement Plot for Specified Tensile Strength of Salt Values of Tapered Cylinder Cavern
Figure B.17: Shear Strain Plot for Specified Tensile Strength of Salt Values of Tapered Cylinder Cavern

Figure B.18: Volumetric Strain Plot for Specified Tensile Strength of Salt Values of Tapered Cylinder Cavern
Figure B.19: Total Displacement Plot for Specified Friction Angle of Salt Values of Tapered Cylinder Cavern

Figure B.20: Shear Strain Plot for Specified Friction Angle of Salt Values of Tapered Cylinder Cavern
Figure B.21: Volumetric Strain Plot for Specified Friction Angle of Salt Values of Tapered Cylinder Cavern

Figure B.22: Total Displacement Plot for Specified Cohesion of Salt Values of Tapered Cylinder Cavern
Figure B.23: Shear Strain Plot for Specified Cohesion of Salt Values of Tapered Cylinder Cavern

Figure B.24: Volumetric Strain Plot for Specified Cohesion of Salt Values of Tapered Cylinder Cavern
Figure B.25: Total Displacement Plot for Specified Dilation Angle of Salt Values of Tapered Cylinder Cavern

Figure B.26: Shear Strain Plot for Specified Dilation Angle of Salt Values of Tapered Cylinder Cavern
Figure B.27: Volumetric Strain Plot for Specified Dilation Angle of Salt Values of Tapered Cylinder Cavern
APPENDIX C: Parametric Study on Teardrop Cavern

Figure C.1: Total Displacement Plot for Specified Depth Values of Teardrop Cavern

Figure C.2: Shear Strain Plot for Specified Depth Values of Teardrop Cavern
Figure C.3: Volumetric Strain Plot for Specified Depth Values of Teardrop Cavern

Figure C.4: Total Displacement Plot for Specified Total In-situ Stress Ratio Values of Teardrop Cavern
Figure C.5: Shear Strain Plot for Specified Total In-situ Stress Ratio Values of Teardrop Cavern

Figure C.6: Volumetric Strain Plot for Specified Total In-situ Stress Ratio Values of Teardrop Cavern
Figure C.7: Total Displacement Plot for Specified Unit Weight of Overburden Values of Teardrop Cavern

Figure C.8: Shear Strain Plot for Specified Unit Weight of Overburden Values of Teardrop Cavern
Figure C.9: Volumetric Strain Plot for Specified Unit Weight of Overburden Values of Teardrop Cavern

Figure C.10: Total Displacement Plot for Specified Young’s Modulus of Salt of Teardrop Cavern
Figure C.11: Shear Strain Plot for Specified Young’s Modulus of Salt of Teardrop Cavern

Figure C.12: Volumetric Strain Plot for Specified Young’s Modulus of Salt of Teardrop Cavern
Figure C.13: Total Displacement for Specified Poisson’s Ratio of Salt of Teardrop Cavern

Figure C.14: Shear Strain for Specified Poisson’s Ratio of Salt of Teardrop Cavern
Figure C.15: Volumetric Strain for Specified Poisson’s Ratio of Salt of Teardrop Cavern

Figure C.16: Total Displacement Plot for Specified Tensile Strength of Salt Values of Teardrop Cavern
Figure C.17: Shear Strain Plot for Specified Tensile Strength of Salt Values of Teardrop Cavern

Figure C.18: Volumetric Strain Plot for Specified Tensile Strength of Salt Values of Teardrop Cavern
Figure C.19: Total Displacement Plot for Specified Friction Angle of Salt Values of Teardrop Cavern

Figure C.20: Shear Strain Plot for Specified Friction Angle of Salt Values of Teardrop Cavern
Figure C.21: Volumetric Strain Plot for Specified Friction Angle of Salt Values of Teardrop Cavern

Figure C.22: Total Displacement Plot for Specified Cohesion of Salt Values of Teardrop Cavern
Figure C.23: Shear Strain Plot for Specified Cohesion of Salt Values of Teardrop Cavern

Figure C.24: Volumetric Strain Plot for Specified Cohesion of Salt Values of Teardrop Cavern
Figure C.25: Total Displacement Plot for Specified Dilation Angle of Salt Values of Teardrop Cavern

Figure C.26: Shear Strain Plot for Specified Dilation Angle of Salt Values of Teardrop Cavern
Figure C.27: Volumetric Strain Plot for Specified Dilation Angle of Salt Values of Teardrop Cavern