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An investigation into design concepts, design methods and stability criteria of salt caverns

Rahim Habibi*

Msc in Tunneling and Underground Spaces, Urmia University, Urmia, Iran

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Abstract. Salt rock has been used as hast rock to storing hydrocarbons and disposing nuclear wastes because of its low permeability. On other hand it deforms under even low deviatoric stress which threatens the structural stability of salt caverns. Rock mechanical stability is one of important stages in salt cavern's design and construction, though mechanical factors (such as nonlinear behavior of rock salt), thermal factors (such as temperature changes during injection and production) and hydraulic factors (such as salt permeability and viscosity of stored material) affect on short term and long term behavior of salt cavern. Various criteria and methods have been investigated for salt cavern's design and stability analysis. In this paper, by taking into account the importance of structural stability of salt cavern, the general behavior of rock salt and salt cavern are given. It reviews the various design concepts and methods and, in the following, stability criteria including stress-based and damage-based are also discussed. It is assigned that the RD stability criterion is more comprehensive than others.

1 Introduction

Application of underground storage to storing oil and natural gas has been enhanced. One of the storing method is establishing the cavity in salt beds or domes. Salt rock because of its low permeability, self-healing of damage and good creep characteristics has been seen as a perfect medium for energy storage. It is widely accepted to store energy and resources in deep salt caverns. Table 1 gives some advantages and disadvantages of rock salt using for energy storage. Because of special features of rock salt such as low permeability and self-healing, not only these cavities have been used for oil or natural gas, but also it is best option to isolate nuclear wastes. In addition to natural gas, hydrogen and compressed air used to generate electricity also are stored which needs a new operation scenario. These new salt cavern operating modes raise new mechanical issues, particularly illustrated by spalling observed at the walls of some existing caverns.

Design, construction and operation (short term and/or long term) of these cavities as well as abandoning of them relate to short and long term structural stability from which the integrity of rock salt must be satisfied. So, due to stability satisfaction and damage suppression of walls and roof of cavern, the condition of microcrack generation must not be met based on stability criteria. It comes very important when a large flexibility of the operation of a salt cavern is required, as the stored material should be available for withdrawal at any point in the year with a preferably high rate.

The mechanical damage changes the hydrogeological properties of the zone surrounding an underground storage in rock by creating an Excavation Disturbed Zone (EDZ). Within the zone around underground facilities, rock salt dilates. As a matter of fact, its pore pressure decreases, the rock mass becomes partially unsaturated and its permeability increases. So, the stored material can migrate through EDZ zone which causes environmental problems. Some of the problems and accidents that have been occurred in salt caverns are given in Table 2.

Creep low is applied as first step during cavern design process which must take all aspects of salt behavior. Through the years, many creep laws have been developed for rock salt. Their complexity has increased, including new aspects of salt behavior. Development of the creep lows comprises in three steps. First attempts in developing the creep lows focused on general behavior of strain-time curve by which only transient and/ or stationary creep strain would be determined, such as Norton–Hoff (Bérest *et al.*, 2008), Lemaitre (Tijani *et al.*, 1983), Lubby2 (Heusermann *et al.*, 2003) and Munson–Dawson (Munson and Dawson, 1981). These lows have been applied to correlate the strain – time curve in different temperature and stress by taking into account creep mechanism map. Over the years, in 1990's decade, more phenomena such as dilatancy and healing were included by developing new lows, for instance

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* Corresponding author: `R.Habibi12@yahoo.com`

Table 1. Advantages and disadvantages of rock salt as a host rock.

Aspect	Advantages	Disadvantages
Geomechanical	Without considerable crack generation at low and average compression stresses Low Porosity and permeability Self-healing	Low tensile strength Dissolution specially for low-depth caverns
Economical	Economical justifiable of solution mining Low working gas High deliverability Low investment Low maintenance and operational costs Low energy required during injection and production cycles Accessibility of salt throughout of world	High creep closure rate at deep caverns
Environmental	No chemical reaction with stored material Low required surface facility Not affected or low affected by catastrophes	Extruding of salt produced by solution mining is challengeable abandoning
Strategic	Passive defense Controlling energy programs	Not enough Accessibility of salt caverns to market

Table 2. Some of instability-induced factors (Yang *et al.*, 2013).

Factor	Results	Example
Creep closure	Volume loss, introducing lateral pressure on casing	Eminence (USA), Tersanne (France) 40% and 30% of total volume was closed respectively
Dissolution	Irregular shape of cavern, not enough spaces for storing, solution of pillar located between caverns	Subsidence and crater induced at surface in Bayou Choctaw
Anomaly zones (high and low solubility zones and gaseous zones)	Introducing crack in roof and wall, volume loss resulting from compaction of insoluble sediments	Some space of Kiel was occupied resulting from insoluble zones
Week cementation at cavern's neck	Pipes corrosion, crack generation resulting in production leakage	Gas leakage and accumulation in layers in 22 years cause explosion and fire at Mount Belvieu
Cavern located at shallow depth	Nearness to the groundwater cause the roof of cavern to be leached	NGL-Kansas-USA
Injection and withdrawn rate	Tensile stress resulting in thermal changes during injection and withdrawn	
Thin cap rock	Development the crack in cap rock resulting in leaking	Failure in cap rock of Napoleonville, Louisiana, USA
Thin pillar	Failure in pillars located between caverns	Failure in pillar between two cavern at Mineola's facility in 1995, Texas, USA
Human errors	Low feasibility study, overfilling	Cavern damage resulting from overfilling, Petal and Brenham, USA
	Uncertainty in exploration, over-pressuring	

in SUVIC (Aubertin *et al.*, 1991), Cristescu (Cristescu, 1993), or Günther–Salzer (Günther *et al.*, 2010). In last years, in third step, early models were improved to take into account more phenomena as well: A version of Munson–Dawson (Munson, 1993) included inverse creep, and both the MDCF model (De Vries *et al.*, 2002) evolving from Munson–Dawson and Lux–Wolters (Wolters *et al.*, 2012) evolving from Lubby2 now include dilatancy, healing and the influence of the Lode angle. On other hand, in last decades, in order to determine the stability (and therefore feasibility) of an excavation stability criteria have been developed in parallel with creep laws (Labaune *et al.*, 2018).

In last decades, authors who research on stability and safety of caverns have focused on 3D numerical simulation using high-performance computers to understand the behavior of salt cavern in different condition. However, because of complexities of damage processes such as rock bursting and splitting, only using numerical methods (either continuum or discontinuum) does not always provide an accurate representation of the physical settings of underground engineering specially salt cavern (Labaune *et al.*, 2018). Some of authors applied discontinuum – based numerical methods such as 3DEC, DDA PFC3D (Cundall, 1988; Wu *et al.*, 2004; Cai *et al.*, 2007) to simulate the failure processes, however, their primary limitation lies in their computational constraints and poor understanding of the true physical response under complex conditions. In addition, geomechanical calculations based on suitable material law (creep low) are required to quantitatively assess the system stability and integrity at the specific geological conditions (Minkley *et al.*, 2001). For example, Staudtmeister and Rokahr (1997) used Finite Element Method (FEM) for salt cavern dimensional analysis and stability evaluation in complex loading histories. They concluded that systematic rock mechanics experiments were necessary before numerical simulation. The material laws must be able to properly capture the spectrum of mechanical properties of salt rocks and discontinuities, ranging from viscoplastic with time-dependent softening to extremely brittle fracture.

Generation and growth of cracks would be limited, when the integrity and structural stability of cavern are satisfied. It should be noted that large deviatoric stress, the difference between internal pressure of cavern and geostatic stress, not be induced in cavern's wall and roof. It aids dilation and developing increased – permeability zone (EDZ) around cavern (De Vries *et al.*, 2002, 2005). In caverns including natural gas, the large amount of deviatoric stress is neutralized by brine (Halmostatic pressure) in construction stage and by gas in operation stage, nevertheless the pressure resulting from natural gas would not be large enough to prevent dilation or fracturing around cavern. So, maximum pressure (optimized pressure), which relates to working gas capacity, of natural gas must be determined and considered in every injection-withdrawn cycles. Based on modeling the distribution of stress state around cavern, the dilation stress, and subsequently fracture stress, is as a function of pressure changes rate of operation cycles and time dependent characteristics of rock salt (Wallner, 1988). Operational pressure range must be as exactly as possible determined at which the stability of cavern either at minimum or maximum pressure is satisfied.

Structural stability of these cavities depend on Hydrogeology of site, site's and host rock's characteristics, operation method, depth, geometry and location of cavern in bed or dome, etc. (De Vries *et al.*, 2005) (Fig. 1). Therefore, understanding the time dependent and time independent behavior of rock salt at such complicated stress state around the cavern are very important, it would be more difficult because of complexity in behavior of rock salt. On other hand, design concepts and construction of salt caverns are very complicated as well. By now, various methods of design and criteria of stability, based on either Lab or *in-situ* investigations, have been investigated and applied.

Various stability criteria has been proposed to limit the crack generation and growth around cavern. Some of them include a comprehensive set of parameters which have been applied in engineering works. So far, several research studies have been conducted to assess the safety of the salt caverns as underground storage systems. Table 3 gives some of researches that have been performed by authors in cavern stability field. The research results show that the stability and availability evaluation of salt caverns are complicated and deeply concerned problems so that Staudtmeister and Rokahr (1997) concluded that systematic experiments on the rock mechanics of surrounding rock are the prerequisite for the analytical analysis and numerical simulation.

In this paper, first, the parameters, which have influence on short term and long term behavior of salt cavern, are introduced. In second section, some of researches performed to understanding salt cavern behavior and stability are given. In third and fourth section, concepts and methods of salt cavern design, also their development process are discussed respectively. Development of stability criteria, their advantages and disadvantages are discussed in fifth section. It is assigned that, based on investigation and discussion, the so called RD stability criterion is more comprehensive than others.

2 General remarks on salt cavern behavior

Rock salt in almost homogeneous salt formation creeps in geological time scale from which principal stress becomes Hydrostatic. At such the salt mass stress redistribution and resulting in the induced deformation around cavern tends to be uniform by which long term and stability of the cavern is satisfied. In contrast, in some areas (particularly in bedded salt formation) rock salt and non-salt rock's deformation would be non-uniform (Fig. 2). In addition, the integrity of caverns constructed in inhomogeneous salt structures no longer solely relies on the quality of the surrounding salt: they also have to rely on the interaction between different geological formations (Axel, 2007). As tightness is a decisive factor for storing in salt caverns, researchers focus on the tightness properties of the caverns to check their feasibility for storing different media. Then, creep closure of salt cavern is one of most considerable issue in cavern stability and tightness which depends on geo-mechanical characteristics of rock salt and stress state around cavern. In some areas where the rock salt is thick, the deformable behavior of salt resulting from $k = 1$ (a ratio between horizontal and vertical geostatic pressure), as the stress state is more or low monotonic, by increasing time rock salt behaves similar as a Newtonian material. However, in condition where the stress state is not monotonic (*i.e.* $k \neq 1$), for example in bedded rock salt with low thickness, the stress state must be investigated as exactly as possible

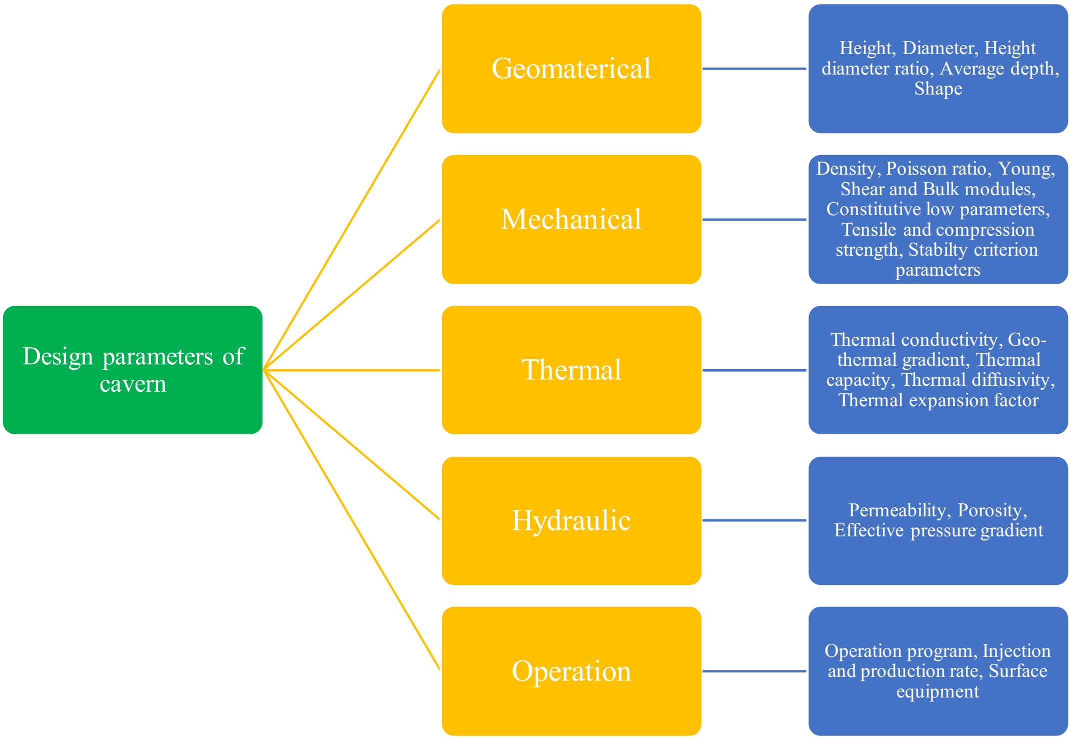

Fig. 1. Design parameters of a single cavern located in salt bed or dome.

(Heusermann *et al.*, 2003). Also, based on investigation of uniaxial compression tests, Liu *et al.* (2016) concluded that deformation and damage would be occurred different in rock salt including inclusions. Also, it was deduced that the reason of longitudinal cracks is because of deformation inconsistency between almost hard mud stone and rock salt at such the condition the lateral deformation of rock salt becomes larger than Cohesion. Otherwise, in triaxial stress states, the difference deformations are limited such that the longitudinal cracks would not be visible.

So, the mechanical properties of rock salt vary (either bedded or dome) greatly due to differences in the environments where they were formed, sediment components, crystal geometries, content and distribution of impurities, tectonic histories experienced, etc. (Hou, 2003; De Vries *et al.*, 2005; Liang *et al.*, 2007). Based on various Lab investigations have been performed to understand the behavior of rock salt, it is concluded that the behavior is very complicated which depends on stress amount and history, temperature, moisture, etc. But, authors have the same viewpoint in following features:

1. Salt behaves like a fluid in the sense that it flows even under small deviatoric stress. Salt is a non-Newtonian fluid and its strain rate is proportional to a rather high power of applied deviatoric stress (which means that the creep rate of a cavern is a highly non-linear function of its internal pressure or, more precisely, of the gap between the lithostatic pressure at cavern depth and its internal pressure) (Berest *et al.*, 1998).
2. The strain rate is also strongly influenced by temperature; enlarging by one or two orders of magnitude when the temperature increases by 100 °C, (*i.e.* 180 °F) (Berest *et al.*, 1998).
3. As increasing the deformation, rock salt dilates.

On the other hand, few well-documented field data are available. Some deep natural gas storages have experienced large volume losses; well known cases include the Eminence salt dome gas storage in Louisiana (Baar, 1977) and the Kiel gas cavern in Germany (Kuhne *et al.*, 1973). Several shut-in tests or brine flow measurements have been performed in different sites. The results are, in general, heavily influenced by brine thermal expansion (Berest *et al.*, 1998), where the real effect of creep is hidden by the leading part played by brine temperature variations.

3 Design concepts

To answer the question on "What basis must be designed the salt cavern?", the design concepts would be appeared. Based on Lab and *in-situ* investigations, various authors have proposed variant concepts. Some of them such as Limited Plastic Zone (LPZ) and Permissible Convergence Rate (PCR) are based on Lab investigation proposed in early 1970 and in the late 1970 respectively (Rokahr and Durup, 2009). In 1960s, based on investigation of pillar models, Dreyer proposed a concept by which it could be possible to determine the minimum internal pressure to stabilize cavern geomechanically. Dreyer introduced a relationship

Table 3. Summary of researches performed in salt cavern stability in last decades.

Author(s)	Year	Subject or/and results
Albrecht *et al.*	1980	Stability of cavern including stored material was investigated.
Dreyer	1982	Stability of cavern was investigated and some possible mechanisms incorporated in hydraulic fracturing were discussed.
Hoffman and Ehgartner	1993	A 3D finite element model to investigate the effects of a number of caverns on storage losses, surface subsidence, and cavern integrity have been developed.
Barron	1994	Two of USA's strategic caverns based on their location, depth, shape, spacing, internal and operation pressure were investigated.
Chan *et al.*	1996	An investigation into generation and growth crack in rock salt was done.
Staudtmeister and Rokahr	1997	Cavern design's processes were divided in four steps and a design concepts were approached.
Adams	1997	A guidelines for the gas pressure inside the cavern using a 2D finite element model has been developed. The minimum and maximum gas pressure and the proper distance between the adjacent caverns were investigated.
De Vries *et al.*	2002	A continuum damage criteria to determine minimum operational pressure for caverns located in salt beds was developed.
Heusermann *et al.*	2003	Methodology of cavern design by using numerical methods was discussed.
Bruno *et al.*	2005	Geo-mechanical analyses to determine operational pressure range for cavern located in salt beds in USA was investigated.
De Vries *et al.*	2005	A finite element model to evaluate the effects of the cavern design parameters (roof thickness, depth, and aspect ratio) on the minimum allowable gas pressure of the cavern has been developed.
Sobolik and Ehgartner	2006	Safety factor, volume loss and subsidence resulting from the cylindrical salt caverns, also caverns with wide part at above, middle and bottom were investigated.
Han *et al.*	2007	A finite difference model in FLAC3D for a single-bedded salt cavern has been developed.
Ardeshiri & Yazani	2008	The influence of faults on the seismic behavior of the underground caverns using the FLAC2D have been studied. A dynamic non-linear analysis was performed under an earthquake ground motion at the bottom of the model.
Hilbert & Exponent	2008	The casing failures associated with the caverns in bedded salt domes using a finite element model have been investigated.
Wang *et al.*	2009	Stability of cavern's roof was investigated.
Wang *et al.*	2011	Maximum displacement, plastic deformation and optimized width of the pillars in cylindrical and pear-shaped caverns were investigated.
Ma *et al.*	2012	The convergence of salt caverns in an ultra-deep formation at high temperatures using the creep tests have been investigated.
Nazary Moghadam *et al.*	2013	A Lagrangian finite element formulation of the salt cavern with an elasto-viscoplastic constitutive model for the salt to evaluate the dilatancy and creep of the cavern in short terms and long terms have been developed.
Wang *et al.*	2013	Used 3D geomechanical simulation to validate the analytical model of underground salt cavern shape optimizing, showing that the newly proposed salt cavern could achieve greater effective volume and ensure better stability during a long-term creep.
Djizanne *et al.*	2014	The stability of the overhanging blocks under the debrining and speedy gas production was studied in gas storage salt cavern including irregular shape using a 2D numerical model.

(Continued on next page)

Table 3. (Continued)

Author(s)	Year	Subject or/and results
Wang *et al.*	2015	The stresses, deformation and safety factors of pillar located between two adjacent caverns using a 3D geomechanical model were studied.
Liang *et al.*	2016	Applying a systematic and comprehensive investigations on the factors influencing stability and on the evaluation criteria, the design parameters are optimized to ensure the safe and stable long-term operation of salt cavern gas storages.
Wang *et al.*	2016	The distance, in which the safety of caverns is met, is determined using Lab measurement and 3D numerical modeling.
Zhang *et al.*	2017	A 3D-geomechanical simulation model considering operating conditions is built to evaluate the stability and availability of the SPR salt caverns in China.
He *et al.*	2018	A novel model for fatigue life prediction is proposed on the basis of energy dissipation and the result of model is validated by tests results.
Labaune *et al.*	2018	A new approach for salt cavern design based on the use of the onset of dilatancy as a design threshold is applied.

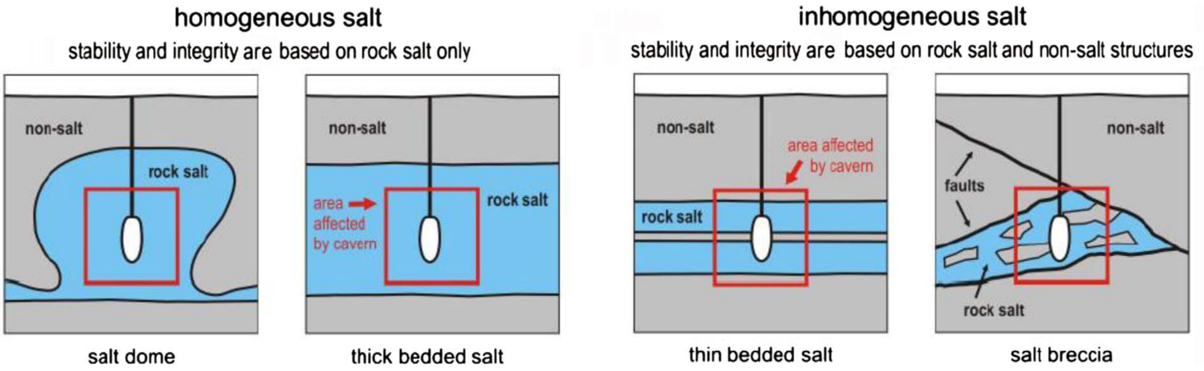

Fig. 2. Influence of salt and non-salt on the integrity of caverns in homogenous and inhomogeneous salt formations (after Axel, 2007).

between Maximum Permissible Pressure (MPP) and failure of cavern by which the structural stability of salt cavern was met. Based on the MPP, the minimum internal pressure of cavern was determined so that minimum plastic deformation would be induced around the cavern, whereas, the minimum thickness of pillar between two caverns was investigated by LPZ. Based on the low amount of cohesion and tensile strength of rock salt, it was concluded that (in the late 1970) the plastic zones would be appeared around the cavern even in low deviatoric stresses which was in contrast to PCR, so, it was concluded that as an unsuitable concept. For example, in 1970s, Tersanne Te02 which was designed based on LPZ showed considerable convergence so that significant volume loss was taken place in 8 MPa as its internal pressure (Boucly and Legeneur, 1980). Changing the design concept into the PCR encountered the high rate of creep closure of the cavern. So, a new concept so called Permissible Convergence Rate (PCR) (or Maximum Allowable Pressure) was introduced. One of important advantages of PCR was minimization of subsidence (Rokahr and Durup, 2009).

Up to 1990s, more than 100 natural gas and oil filled cavern was successfully constructed using Maximum Permissible Pressure (Dreyer concept) in Germany. In this concept, maximum pressure is determined as a function of the pressure gradient in cavern. In 1962, the first salt cavern included natural gas using Maximum Permissible Pressure Gradient (MPPG) 0.15 bar/m was constructed in Marysville (Michigan). Over 40 years later, the MPPG in USA and Canada was considered 0.8 psi/foot and 0.9 psi/foot respectively (Rokahr and Durup, 2009).

Nevertheless, one of most important disadvantage of these concepts was that the second (or induced) stress state were not considered. In 1990s, the team headed by K.H. Lux in Clausthal-Zellerfeld, and the IUB team in Hannover (Lux, 1997) modified the MPP in which the second stress state was included as well. In this concept, the stress components running perpendicular to the internal pressure are used as the design parameter. These have to be a certain amount higher than the internal pressure. The zone that surrounds the whole cavern, and which satisfies this criterion, must also have a specific thickness to guarantee the

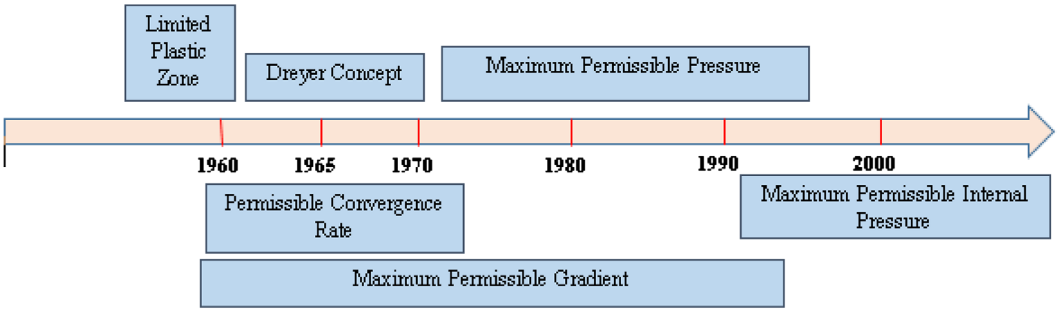

Fig. 3. Design Concepts

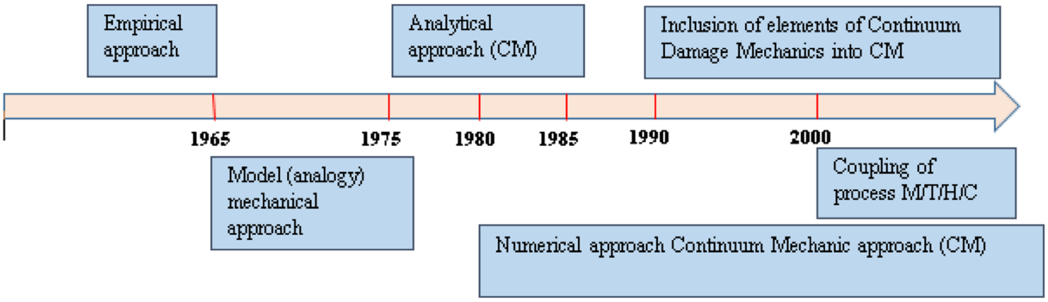

Fig. 4. Design Methods (Asgari and Brouard, 2014)

integrity of the cavern. Figure 3 shows the development of Design Concepts in historical view.

4 Design methods

To answer the question "How would appear the concept parameter in deformation process of salt cavern based on the initial and boundary condition?", the stability criterion is utilized (Sect. 5), but, in order to make a relationship between concept parameter and stability criterion, it must be applied the Design Methods. Various methods have been proposed by authors (Fig. 4). Earlier, experimental methods were applied but they were unable to consider all parameters and characteristics included in integrity and stability of cavern. On other hand, Analytical Methods, because of their complexity, only have been applied in caverns including simple geometry. In last decades, some of salt's characteristics such as damage onset and dilation strength have been defined based on Continuum Damage Mechanics (CDM), nonetheless, the behavior of salt had been considered in Continuum Mechanics (CM). It is assumed in CM, salt has no micro-crack and behaves ductile in which volume changes during creep deformation and failure resulting from macroscopic creep rupture. Based on Lab and *in-situ* investigations, attitude on behavior of rock salt has been changed, authors concluded that as loading rate and stress intensity reaching a certain level, mainly intercrystalline micro-fractures open; with increasing stress or deformation the micro-fractures grow and connect as well. Nevertheless, the CM is not suitable to describe such the behavior of rock salt. Based on the Lab investigation, dilation increases the permeability, it means that the mechanical damage affects on hydraulic behavior of rock salt. On other hand, temperature and pressure of stored material change (as a part of thermo-dynamical behavior of stored material) during injection and production. The knowledge of the Thermo-Hydro-Mechanical (THM) material behavior of the *in-situ* rock salt is a main assumption to proof the static stability and tightness of salt which not considered in earlier methods. Nowadays very complex numerical codes, such as LOCAS (Brouard Consulting, 2014) and enhanced material models, such as Lux/Wolters (Wolters *et al.*, 2012), are used to simulate the behavior of salt caverns by which the thermal, hydraulic, thermo-dynamical, and geomechanical history of the cavern are modeled simultaneously.

5 Development of stability criteria

Salt caverns progressively close because salt deforms continuously (creeps) when subjected to shear stress resulting from the difference between the cavern pressure acting on the walls of the cavern and the *in situ* stress in the surrounding salt. The shear stresses increase as the cavern pressure decreases. In turn, the rate of creep closure increases nonlinearly as a power function of the shear stress. Creep deformation alone is a constant volume process in salt. However, if the pressure in a cavern is decreased too far, the shear stresses in the surrounding salt can exceed the strength of the salt. The salt then will microfracture or dilate, creating additional porosity in the salt, and its volume will increase during creep deformation. Microfracturing, which is referred to as damage, causes the creep rate of salt to increase because the salt is weakened and its resistance to shear stress is reduced. In some cases, salt caverns are designed for seasonal operation scenario, nonetheless, in other cases, politics and demands cause the cavern to be designed for weekly, daily and even hourly operation scenario. So, a systematic and comprehensive stability and evaluation criteria including influencing factors that are relevant during the short and long-term operation of underground salt cavern gas storages is required.

High deliverability of salt cavern are controlled by following geotechnical and operational constraint:

1. Operational constraint: wellbore performance (gas pressure loss), production tubing erosion and noising, cavern performance (cavern pressure/temperature drop), Hydrate formation at wellhead (low withdrawal temperature) (Karimi-Jafari *et al.*, 2011). If the temperature of gas is enough low, hydrate formation would be appeared in pipes. Temperature level for Hydrate formation depends on gas pressure and water content. Sometimes, before gas withdrawal, gas hydrate inhibitors are injected into the well.
2. Geotechnical constraint: injection and withdrawn cause temperature changes resulting in thermal stresses on wall, in turn, it causes microfracturing and damage. On other hand, in fast cycles, the rate of pressure changes are high, with considering the fatigue behavior of salt and time-dependent behavior of stress redistribution, mechanical problems would be appeared (Karimi-Jafari *et al.*, 2011).

Similar to the creep, damage is also a progressive process to overcome the shear strength by resulting from shear stress. So, at such the condition, induced stress in long term or cyclic operation (resulting from injection and withdrawn) causes microfracturing at which salt facing to flake and collapse at wall and roof of cavern respectively. So, it must be applied a comprehensive stability criterion to describe the behavior of salt in different conditions.

5.1 Stability analysis criteria

These criteria are applied to investigate the integrity and stability of caverns based on stability parameter which, in turn, corresponding to design concept. It is comprised in 6 groups:

1. No or low dilatant zone: as dilation occurs in rock salt resulting in strength loss at such the condition suspect that introduced shear stress cause failure (Brouard *et al.*, 2007).
2. No or low tensile zone: generally, cavern is subjected in compression, but when the cavern pressure is low and cavern profile including no non-convex portions, tensile zones are introduced in which lead to roof and wall spalling (Karimi-Jafari *et al.*, 2011).
3. No or low tensile effective stress (Brouard *et al.*, 2007).
4. Low volume loss or low volume loss rate (Brouard *et al.*, 2007).
5. Subsidence (Brouard *et al.*, 2007).
6. Strain – Creep, accumulated strain must not be larger than a certain amount. In pillar of salt mines, 5%–10% of creep strain is common (Karimi-Jafari *et al.*, 2011).

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Low volume loss or low volume loss rate (Brouard *et al.*, 2007).

Subsidence (Brouard *et al.*, 2007).

Strain – Creep, accumulated strain must not be larger than a certain amount. In pillar of salt mines, 5%–10% of creep strain is common (Karimi-Jafari *et al.*, 2011).

On one hand, the Low volume loss and Subsidence are almost same which have low applicability. On other hand, the 4th, 5th and 6th have not been applied in engineering works. So in following, we only focus on the others.

5.1.1 No or low tensile zone

Generally, the tensile strength of rock salt (1.5–2 MPa) is low and behaves brittle in tension states. So, it must be neglected in designing. Karimi-Jafari *et al.* (2011) concluded that roof collapses are common at tension state. Various factors such as over-pressuring, thermal shocks resulting from fast cold during withdrawn and existence of an extended roof, cause tensile stress around caverns. Large tensile stresses cause the cracks to be generated in which resulting in fracturing and spalling on wall and roof. In general, stresses around cavern are compressive, but in following cases, the tensile stress would be appeared around cavern:

When cavern pressure is low and cavern's profile including no non-convex portions (An example of this is described in Nieland and Ratigan, 2006).

When cavern pressure suddenly decreased (pressure loss cause the temperature of gas to be decreased), temperature loss depends on production rate, size and shape of cavern. Tensile stresses resulting from temperature loss. As tensile stress is larger than the difference between geostatic and cavern pressure, the microcracks are generated (more detail are discussed in: Bauer and Sobolik, 2009; Staudtmeister and Zapf, 2010; Karimi-Jafari *et al.*, 2011; Rokahr *et al.*, 2011; Bérest *et al.*, 2012; Leuger *et al.*, 2012; Lux and Dresen, 2012).

In most cases, depth of these microcracks are low and perpendicular to cavern wall. As the depth of the cracks becomes larger, distance between two cracks becomes larger as well, in which resulting in slabs of rock salt cut off from cavern wall. Nevertheless, these slabs are clung on rock salt, as the depths are low (Bérest *et al.*, 2012; Pellizzaro *et al.*, 2011).

In mine's wells, thermal fracturing are common in unlined wells (Wallner and Eickemeier, 2001; Zapf *et al.*, 2012). Since, wells are cold in winters, at least experience this condition for months, and normal stress on wall is low compressive than geostatic stress, in most cases, fracturing is occurred horizontally.

5.1.2 No or low effective tensile stress

Effective tensile stress relates with porosity of the rock, it is applies progressively at reservoir engineering. It equals actual stress (the compressive is negative) plus fluid pressure in pores. Since porosity and permeability of rock salt are low, defining the effective stress in rock salt is still complex and challengeable, nevertheless, it is defined easily at cavern wall as sum of actual stress and cavern (fluid) pressure (Brouard *et al.*, 2007). Actual stress at cavern wall including normal stress, tangential stress and circumferential stress. Based on the definition, since the normal stress equals cavern pressure, then, the effective stress is zero. Nevertheless, on such condition that cavern experiences, effective stresses could be negative (tensile) or positive (compressive). Some of authors believe that the effective stress at cavern wall must be smaller than a certain amount so called Tensile Strength. So, the no or low Effective Stress Zone is defined:

$$\sigma_{\min} + P < T \tag{1}$$

where T, tensile strength, P, cavern pressure and $\sigma_{\min}$ is smallest tangential compressive stress. According to equation (1), when cavern experience large and fast cycles, developing the effective tensile stress are possible. So, salt caverns including natural gas which experience large cycles, developing these zones are easily occurred. Microcracking is initiated when the equation (1) is met, resulting in the permeability increase and salt softens (Bérest *et al.*, 2001; Malinsky, 2001; Stormont, 2001). Selecting $T = 0$ (because of safety), definition of criterion would be simple in which the tensile effective stress must not be appeared.

Brouard *et al.* (2007) studied the effect of fast pressure increase at caverns which experience actual operational cycles on stability of caverns. They took three constitutive models for a cavern located at 1500 m depth. The results showed that such pressure changes introduce effective tensile stress at cavern wall, in which, the dependence of effective tensile stress on the number of cycles is more sensitive than on pressure change rate at which, as the number of cycles is increasing, the effective tensile zone is increasing as well. Also, they investigated developing of effective tensile stress possibility in caverns which subjected to high pressure changes such as natural gas's caverns, it was concluded that the possibility is high at cavern wall because of high pressure changes. It causes redistribution stress around cavern when cavern pressure is low enough in which the deviatoric stress slowly increase resulting in the difference between tangential and radial stress decrease. At end of the period, when gas is injected into cavern, large elastic stresses are introduced at cavern wall, in turn, resulting in the tangential stress to be larger than normal stress. Such that condition, the effective tensile stress at cavern wall would be generated. Nevertheless, Brouard *et al.* (2007) studied conservatively, tensile strength assumed zero and fluid pressure in rack mass considered equal cavern pressure.

Djizanne *et al.* (2012) discussed the criterion of Effective Tensile Stress. They investigated the effective tensile zones in Etzel K-102 at Germany which has been operated for 20 years. Based on their results, effective tensile stress is generated when rapid increase or decrease pressure is occurred. Also, during fast pressure loss in cavern including gas or fast pressure increase in brine-filled cavern, effective tensile zones are appeared, in which microcracking is initiated and, in turn, causes permeability increase. The zones would be larger, when cavern subjected to very fast pressure changes in which it was idle before this pressure changes. In some cases, it is not thickness. Nevertheless, the integrity of cavern is treated considerably when the distance between top of the salt formation and roof is low. Accordance to these results, the effective tensile stress is considered at interpretation of hydraulic fracturing.

5.1.3 Dilation boundary criteria

A dilatancy boundary models could be able to determine the dilatant behavior of salt around the salt cavities, to achieve which it must be determined the stress state using Closed Form Methods (CFM), Finite Element Methods (FEM), Difference Element Methods (DEM), etc. Dilatancy surfaces (which have damaged resulting from onset of volumetric dilation under loading) have been extensively studied. Some of Dilatancy boundary models have been proposed in recent years (*e.g.* Spiers *et al.*, 1988; Ratigan *et al.*, 1991; Stormont *et al.*, 1992; Hunsche, 1993; Thorel *et al.*, 1996; Hatzor and Heyman, 1997).

Dilatancy boundary models have been proposed in two format: 1) including stress invariant with experimental fitting parameters (invariant or damage-based), 2) including minimum principal stress and effective stress (stress-based). Dilatancy models have been applied extensively to distinguish such a condition in which accumulated damage at cavern could be appeared (Van Sambeek *et al.*, 1993; Chabannes *et al.*, 1999; Thoms *et al.*, 1999; Ehgartner and Sobolik, 2002; Nieland *et al.*, 2001).

5.1.3.1 Stress-based dilatant boundary criteria

These criteria make a linear or non-linear dilatancy boundary dividing two parts so that above the boundary, dilatant would be occurred. Models developed in stress concept are listed in Table 4. Also, Figure 5 shows the relationship resulting from these criteria as a comparison. Based on De Vries *et al.* (2002), it could be concluded that the dilatancy-based criteria enable to estimate the dilatancy boundary of rock salt more exactly with respect to stress -based criteria. The lower minimum gas pressure determined using the damage-based criterion is possible as well.

The working gas capacities of the caverns are directly proportional to the volume of the caverns. Cavern volume

Table 4. Stress-based Dilatancy boundary models.

Model	Author(s)	Description
CDM	Hampel (2012)	In high stress differences of boundary, damage and dilatant changes are modeled as a function of creep strain. This model enables to consider effects of common and reverse transient creep (Hampel, 2012).
Gunther and Salzer	Gunther and Salzer, 2007	This is a strain hardening model in which total deformation rate is a function of effective strain hardening (Gunther and Salzer, 2007).
Minkley and Muhlbauer	Minkley and Mühlbauer, 2007	In this model, stress-strain relationship is modeled by a developed Burgers model in which deformation history is considered through a state variable. Also, this model includes a damage module to consider the damage changes, fracture and post failure (Minkley and Mühlbauer, 2007).
KIT	Pudewills, 2007	This model applies elasto-visco-Plastic context to describe the total deformation rate (Pudewills, 2007).
Lubby2-MDCF	Institut fur Unterirdisches Bauen, IUB	In this model, total inelastic deformation rate in non-dilatant creep and dilatant creep are described by shear deformation and tensile deformation respectively (IUB).
Hou and Lux	Hou and Lux, 1999	In this model, inelastic strain rate is considered through adaption of visco-plastic deformation in creep without volume changes, damage and healing resulting from dilatancy and compression respectively (Hou and Lux, 1999).

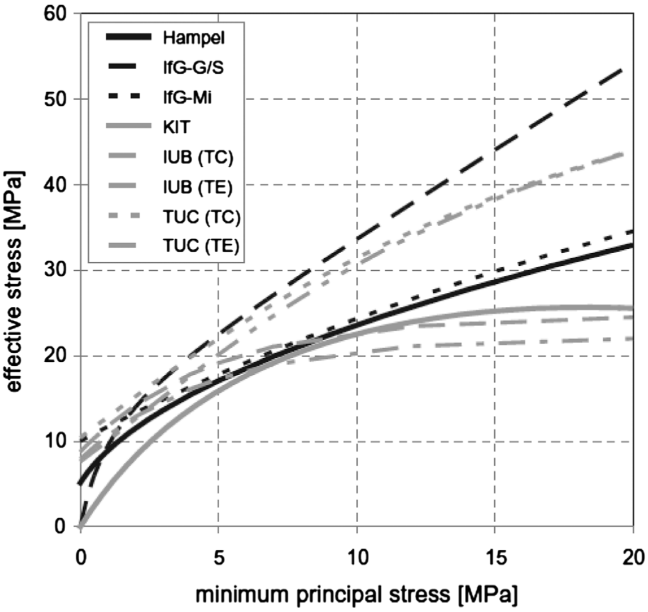

Fig. 5. Different dilatant boundary criterion developed through minimum principal stress and effective stress TC: triaxial compression, TE: triaxial extension (after Hampel *et al.*, 2012).

is reduced by creep closure. The creep closure rate of the cavern is inversely proportional to the minimum gas pressure and is highly nonlinear. The damage-based approach predicts lower allowable minimum gas pressures than those predicted by the conventional stress-based criterion. The lower minimum gas pressures predicted using the damage-based criterion could increase the initial working gas capacity of the existing cavern (Fig. 6). For example, De Vries *et al.* (2003) in Bay Gas Well No. 1 and 2 showed that the lower minimum gas pressures predicted using the damage-based criterion could increase the initial working gas capacity of the existing cavern by about 18 percent and the cavern under development by about 8%.

5.1.3.2 Damage-based dilatant boundary criteria

Dilatancy- based criteria have been developed on Continuum Damage Approach and damage potential parameter. Damage potential is defined as a ratio between stress invariants ($\sqrt{J_2}/I_1$, where $J2$, second invariant of deviatoric stress and, I_1, first invariant of stress), so, these criteria are also defined as a function of stress invariant either intercept or not. Nevertheless, effects of loading history are not considered in this model, De Vries *et al.* (2002) showed that the minimum allowable gas pressure (which controls the amount of working gas) for gas-filled caverns is lower when damage-based criteria are applied, however, the stress-based criteria overestimate the minimum allowable gas pressure. Figure 6 shows stress invariant-based criteria with respect to damage-based criteria. In the following, these criteria are briefly discussed. Also, Figures 7 and 8 give a comparison of damage-based criteria in respect of each other.

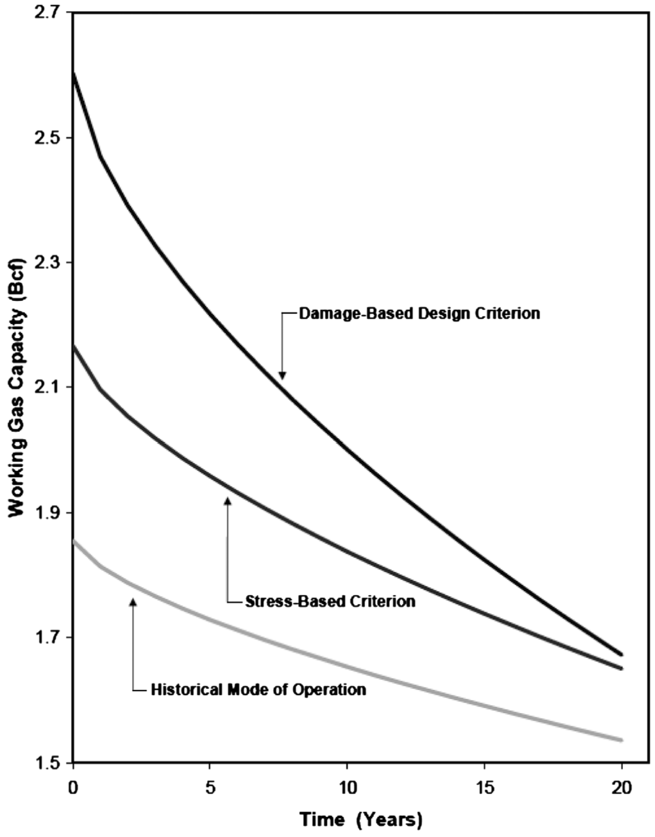

Fig. 6. Comparison stress-based against damage-based criteria (after De Vries *et al.*, 2003).

5.1.3.2.1 Spiers et al.

Spiers *et al.* (1988) used the results of constant strain rate tests that had been performed on samples which obtained from Asse salt mine in Germany, a dilatancy criterion proposed:

$$\varDelta\sigma = 2.74P + 6.4 \tag{2}$$

In stress invariant, are given:

$$\sqrt{J_2} = 0.27I_1 + 1.9 \tag{3}$$

where P, confining pressure, $\varDelta\sigma$, difference between axial stress and confining pressure in MPa. Equation (2) is a linear function aspect toI_1 and J_2, it means, the damage is linear as well. However, based on lab and in-site investigation, damage is non-linear function in stress space. One important shortcoming is, the tests only based on cylindrical samples which conducted in triaxial compression state, despite, cavern experiences tensile state especially at roof. Also, stress path and history not considered.

5.1.3.2.2 Ratigan et al.

Based on the damage potential of WIPP rock salt, Ratigan *et al.* (1991) developed a dilatancy criterion. This criterion is based on the results of volumetric strain rate changes of WIPP and Avery Island in Louisiana, and also, on creep tests had been performed in room temperature. The negative volumetric strain rate was defined as "non-dilatanting" and *vice versa*. Based on this definition, following criterion was proposed to distinguish the dilatancy boundary:

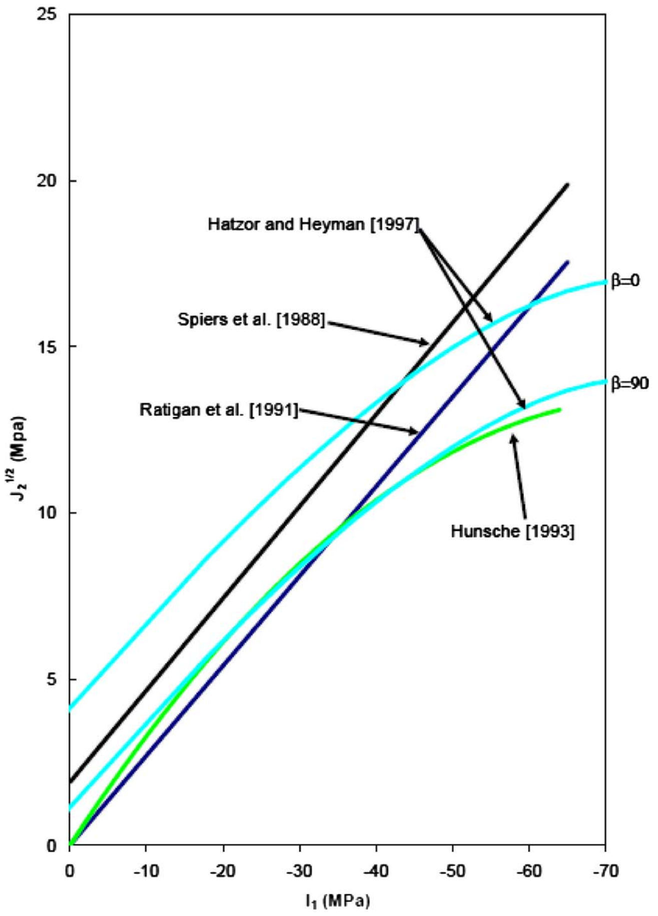

Fig. 7. Comparison salt dilation boundaries of different research organizations (after De Vries *et al.*, 2005).

$$\sqrt{J_2} = 0.27I_1 \tag{4}$$

In fact, this is highly similar to that of Spiers *et al.* (1988). In this criterion, not only stress path and history not considered, also the intercept was neglected.

5.1.3.2.3 Hunsche

Based on 14 triaxial tests performed on cubic sample that had been obtained Asse salt mine, Hunsche (1993) proposed a compressibility/dilatancy boundary criterion (Hunsche notified that sample shows either volume increase or volume decrease, then, a compressibility/dilatancy term was applied). The boundary is determined by volumetric strains and acoustic emission rates:

$$\tau_{\text{oct}} = f_1\sigma_m^2 + f_2\sigma_m \tag{5}$$

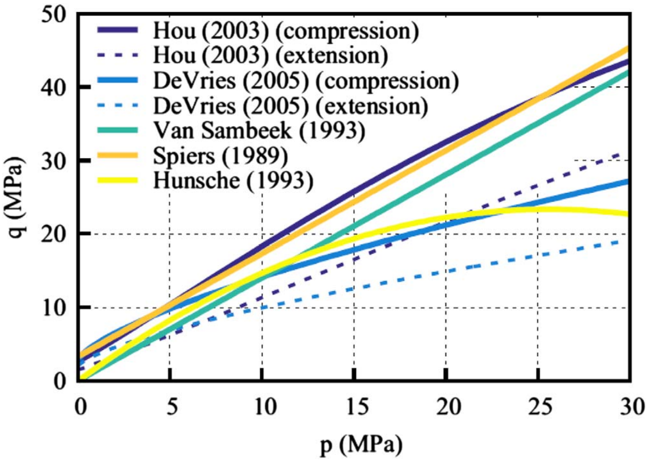

Fig. 8. Comparison of damage – based salt dilation boundaries of different authors (after Labaune *et al.*, 2018).

In stress invariant, are given:

$$\sqrt{J_2} = \sqrt{\frac{3}{2}}\left(f_1\frac{I_1^2}{9} + f_2\frac{I_1}{3}\right) \tag{6}$$

where τ_{oct}, octahedral shear stress and σ_m, octahedral normal stress or mean stress. f_1, f_2 are constant, $-0.0168\ \text{MPa}^{-1}$ and 0.86 respectively. This criterion is also based on triaxial compression tests and no consideration for stress path and history.

5.1.3.2.4 Hatzor and Heyman

Using by results of constant strain rate that had been performed on cylindrical samples obtained Mount Sedom Diaper in Israel, Hatzor and Heyman (1997) proposed a dilatancy criterion. Salt formation in this area is layer which is almost perpendicular near to ground level and as depth increase, the slope is decrease. So, they consider the layer orientation in the criterion. Based on the results, it is demonstrated when maximum compressive principal stress is applied perpendicular to bedding plane orientation, strength of rock salt decrease. Then, the criterion was developed based on principal stresses and bedding orientation (β). The empirical model to consider compressibility/dilatancy of anisotropic rock salts are given:

$$\sigma_1 = k_1 e^{k_2\beta} \tag{7}$$

$$k_1 - 0.0743\sigma_2^3 + 3.2223\sigma_3 + 12.9 \tag{8}$$

where k_1 is a function of minimum principal stress, k_2, is a constant, -0.0057 which is determined from regression analysis with the constant k_1 by second equation. Since this formulation is for an anisotropic material, isotropy in stress space is lost and their equation cannot be cast in terms of the stress invariants and compared with the other dilation criteria presented here.

5.1.3.2.5 De Vries et al.

During a project on samples obtained *Cayuta of USA* which sponsored by *RESPEC*, De Vries *et al.* (2005) developed a comprehensive dilation criterion. It is based on Mohr-Coulomb dilatant which applied to evaluate potential pf microcracking in cavern using Damage Potential (DP). Shortcomings identified for the DP criterion are that this criterion does not include: 1) no nonzero intercept, 2) no nonlinear relationship for dilatancy boundary in $I_1 - \sqrt{J_2}$ space, 3) no cover effects of Lode angle. The old damage-based dilation boundary criteria such as Mohr–Coulomb were not considered the effects of Lode angle changes, resulting in no consideration for mean stress changes (Fig. 9). However, De Vries *et al.* (2005) covered these shortcoming and proposed a comprehensive dilation criterion:

$$\sqrt{J_2} = \frac{D_1\left(\frac{I_1}{\text{sgn}(I_1)\sigma_0}\right)^n + T_0}{\left(\sqrt{3}\cos\psi - D_2\sin\psi\right)} \tag{9}$$

where n is a power less than or equal to one and σ_0 is a dimensional constant with the same units as I_1. D_1, D_2 are material constant. T_0, ψ are tensile strength and Lode angle respectively.

6 Distance from adjacent cavern and dome edge

The cavern concept and design are single cavern-related subjects, however, the stability must be met in appearance of cavern group located either salt layer or salt dome. So, two subject including distance between two adjacent caverns (pillar) and distance from roof and/or dome edge would be appeared.

6.1 Pillar stability

How to design the width of pillar is a difficult engineering problem, since the pillar width is greatly influenced by many factors such as strength of rock salt and non-salt formations, rock salt creep characteristics, cavern dimensions, etc. The overburden pressures and far field *in-situ* stresses are two major reasons of pillars failure located between salt caverns. For storage caverns in salt rock, with increasing deformation, the creep damage zones would be appeared in different places of pillar which trend to link up with each other. Considering narrow pillar, the creep damage zones easily merge and cracks develop in the pillar which threat the tightness or stability.

In last decades, various pillar design methods and stability criteria have been proposed which comprise three main groups including: analytical (such as cusp catastrophe theory), experimental (such as Van Sambeek, 1997) and numerical. Earlier, the pillar (between two adjacent caverns) was considered as engineering problem at salt caverns similar to which has been considered in salt mining (rectangular in shape). In 1972, Thom (1972), firstly, proposed the cusp catastrophe theory, which was mainly used to depict numerous sudden discontinuous change phenomena in nature and predict the critical conditions of structure mutations. Even though, researchers could not

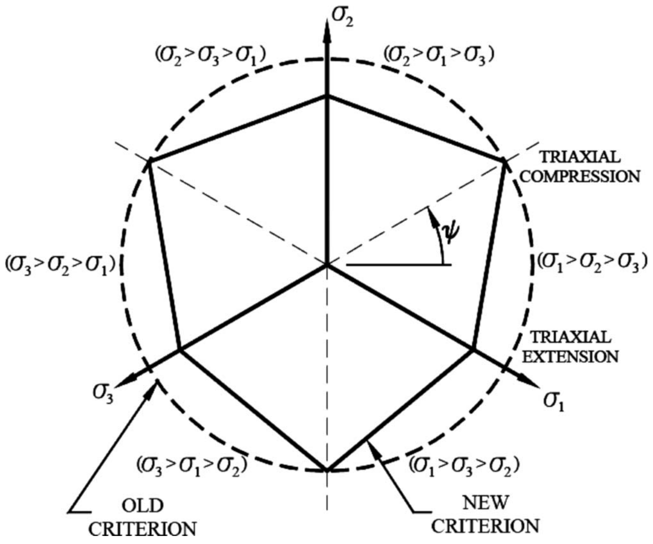

Fig. 9. Illustration of the original stress-based dilation criterion and the new Mohr-Coulomb criterion plotted in principal stress space (after De Vries *et al.*, 2005).

be able to get the differential equations of the system or how to solve these equations, the qualitative or quantitative state of the system can be predicted by it (as an advantage of cusp catastrophe theory). This theory, successfully, has been applied by many authors (Fu and Chen, 2008; Kenneth *et al.*, 2008; Li *et al.*, 2008; Pan *et al.*, 2009; Leynaud and Sultan, 2010; Yang *et al.*, 2010) to analyse the stability of nonlinear material structures so that the corresponding failure mechanisms are revealed. In 90's decade, some experimental methods for pillar designing and stabilizing proposed. In 1996, Van Sambeek proposed a new method at which the stress states within the salt pillar could be approximate using average vertical stress in the pillar. It was validated by comparing with numerical simulation in highly correlation (Frayne and Van Sambeek, 2002). Except experimental figures, it was only considered the pillar dimensions (height, width and length). Staudtmeister and Rokahr (1997) proposed a guideline for designing cavern shape and pillar width. In 1993, considering the pillar as support of cavern roof, Waltham and Chorlton (1993) developed a roof and pillar model to evaluate the deformation within the pillar. Contemporary, in 1993 firstly, Hoffman (1993) investigated the effect of pillar width on the stability of gas storage caverns in salt domes using in a 3-D finite element software so called JAC3D. These days, numerical simulations are widely-used by authors to investigate the stability of pillars. Zhao *et al.* (2002) applied SR FEM to overcome the local failure of structures (which takes place in numerical simulation), by which the overall stability factors of structures as well as the detailed information of each node (*e.g.* stress, strain, and deformation) were given. However, taking into account the irregular shapes of actual salt caverns and material properties difference, may cause stresses and deformations, at some Gaussian points, to reach the yielding strength quickly during pillar stability evaluation by SR FEM (Wang *et al.*, 2015) resulting in the divergence of numerical simulations and imprecise results. In order to overcome the shortages, De Vries *et al.* (2005), based on their engineering experience, suggested that the salt cavern gas storages could be considered in critical failure state during numerical simulations, when the plastic zone area achieved 40 m^2.

6.2 Edge stability

Analysing the distance from edge, firstly, was considered in salt mining to determine the boundary of safe deformation in the roof protection shelf. Sałustowicz *et al.* (1963) considered the dependence of the bending of an elastic beam loaded with mass forces, however, they considered not the rheological viscous properties of rock salt. Kortas (1979) claimed that the tensile strain of the roof is the major reason which makes instability near non-salt materials, based on this theory, he studied the catastrophic inrush of water into the underground Wapno salt mine (Poland) in 1977.

In current practice of cavern dimensioning, so far, no concept was published how a gas storage cavern should be dimensioned in the salt dome edge region and what distance should a cavern have from the salt dome boundary (Zapf, 2014). In rock mechanics point of view for gas storage caverns it is, for example, recommended to follow a safety distance between the caverns. Based on a role of thumb which developed using a concept, so called central pillar region, it must be considered an area in which the stress state of the rock salt during the entire operating history is below the dilatancy limit, which should be remained at least with a horizontal dimension of 1.8–2.2 times of the average diameter of two neighbour caverns (Zapf, 2014). On other hand, some general rock mechanical investigations concerning caverns in the salt dome edge region had been carried out, for example, by Gehle and Thoms (1983) and Michael *et al.* (2002) who proposed some guidance on the influences of layering on roof deformation and stability within the interfaces considering maximum tensile and shear stress components of a simple composite beam theory. Nevertheless, because of complexity of analytical solutions in roof beams of greater complexity than a couple layers, as well as, other influences, the equations can only be used to compare the relative stresses and fracture risks developed for alternative composite roof configurations.

Additionally, in last decades some regulations (in point of view of general mining) such as ABVO, in Germany (1966), have been developed which considers an empirical value for the distance between salt mines and salt borders. Based on it, if the geological profile can clearly be determined, it must be considered at least 150 m from the salt edges. However, because these values probably originated from the intention to avoid possible water ingress in salt mines, cannot be helpful these days. (Zapf, 2014). While the ABVO is valid for the building of salt mines, the mining regulation for deep drillings, underground storage buildings and the extraction of mineral resources, BVOT (2006), contains regulations for the construction of caverns in rock salt in which only some advices are given, for instance, caverns have to be built stable and enough salt should be remained between the cavity and the salt edges. The values given in the ABVO are not given in the BVOT (Zapf, 2014).

On other hand, several organizations have developed guidance documents for designing and operating storage salt caverns such as CSA (1993), API (1994), IOGCC (1995). Some parts of these efforts, however, have focused on some of the critical technical aspects related to cavern development in thin, heterogeneous, bedded salt formations. Zapf and Staudtmeister (2009) proposed some rock mechanical aspects for the design of gas caverns in the border region of salt domes. Vining and Buchholz (2013) addressed the limitations of the numerical software and the impact that *in situ* stress, material properties, and constitutive models have on the predicted solution. However, Zapf (2014), created a numerical model that takes into account the essential and non-negligible influences in the salt dome edge area and time-dependent, thermo-mechanical coupled calculations, introduced a recommendation for the selection of a suitable calculation model of a cavern in the border region of a salt dome using numerical modeling.

So, based on the above-mentioned techniques, it could be summarized the methods in four major groups including: empirical, analytical, regulations and numerical modeling.

7 Conclusion

Mechanical, thermal and Hydraulic parameters of either rock salt or overburden control the short and/or long term behavior of the salt cavern. So, design and construction of salt caverns are so complex. Various design concepts have been proposed by authors among them Lux (1997), because of considering induced stresses, is more suitable. Also, various stability criteria have been proposed at which a certain parameter to considering salt behavior at different stress states are applied. Effective Tensile Stress, because of difficulty in effective definition in rock salt, unable to describe salt behavior in operation especially at very fast cycles. Since at only certain condition, cavern experience tension state, so, no or low tensile zone is not applicable in stability analysis as well. Nevertheless, in above mentioned two criteria, all parameters which must be interfered in stability of cavern are not considered. However, damage-based dilatant criteria, including stress states, propose suitable response in respect of others. For example, they estimate the minimum allowable gas pressure accurately which controls the working gas capacity. The criterion so called RD proposed by De Vries *et al.* (2005), not only considers the stress state, but also considers the effect of Lode angle as well. In general, for assurance, it must be accommodated the results of the criterion with *in-situ* results. Considering a group of caverns located in salt dome, by now, expect numerical modeling, no practical method has not been proposed to take into account pillar stability and safe distance from dome edge.

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