Tunnelling and Underground Space Technology 79 (2018) 12–26

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Reliability analysis of hydrologic containment of underground storage of liquefied petroleum gas

Xu Gao[a], E-Chuan Yan[a], Tian-Chyi Jim Yeh[b,c,*], Yuli Wang[c], Yue Liang[d], Yonghong Hao[b]

[a] Faculty of Engineering, China University of Geosciences, Wuhan 430074, China
[b] Key Laboratoryfor Water Environment and Resources, Tianjin Normal University, Tianjin, China
[c] Department of Hydrology and Atmospheric Sciences, University of Arizona, Tucson, AZ 85721, USA
[d] National Engineering Research Center for Inland Waterway Regulation, Chongqing Jiaotong University, Chongqing 400074, China

ARTICLE INFO

Keywords:
Unlined rock cavern
Hydrologic containment
Reliability
Water-certain borehole
Saturated hydraulic conductivity
Petroleum gas

ABSTRACT

The objectives of this paper are (1) to introduce a numerical first order method to calculate the gas containment reliability within a heterogeneous, two-dimensional, unlined rock caverns (URCs), and (2) to suggest a strategy for improving the gas containment reliability. In order to achieve these goals, we first analyzed the spatial variability of saturated hydraulic conductivity (K_s) at a field site. We then conducted deterministic simulations to demonstrate the importance of heterogeneity of K_s in the analysis of gas tightness performance of URCs. Considering the uncertainty of the heterogeneity in the real world situations, we subsequently developed a numerical first order method (NFOM) to determine the gas tightness reliability at crucial locations of URCs. Using the NFOM, the effect of spatial variability of K_s on gas tightness reliability was investigated. Results show that as variance or spatial structure anisotropy of K_s increases, most of the gas tightness reliability at crucial locations reduces. Meanwhile, we compare the results of NFOM with those of Monte Carlo simulation, and we find the accuracy of NFOM is mainly affected by the magnitude of the variance of $K_{s.}$ At last, for improving gas containment reliability at crucial locations at this study site, we suggest that vertical water-curtain holes should be installed in the pillar rather than increasing density of horizontal water-curtain boreholes.

1. Introduction

Underground storage of liquefied petroleum gas (LPG) in unlined rock caverns (URCs) has many advantages over above ground storage in terms of economy, environment and safety (Kjørholt & Broch, 1992; Sun & Zhao, 2010; Wang et al., 2016). The basic principle of LPG preventing leakage from URCs is that hydraulic head (potential) in the surrounding rock must be larger than the storage caverns potential (Aberg, 1977; Goodall et al., 1988; Gustafson et al., 1991). Large hydraulic head in the surrounding rock can be achieved by constructing URCs at a sufficient depth or by installing water-curtain system surrounding the caverns, which traditionally are horizontal wells installed over the cavern roofs. The performance of water curtains during construction and operation becomes the major concern for performance assessment of the storage caverns. Generally, this assessment is evaluated by numerical simulations. During the simulation, isotropic and homogeneity of hydraulic properties of rock mass are widely assumed (Lu, 1998; Cha et al., 2008; Yu et al., 2013; Dai & Zhou, 2015; Wang et al., 2015; Li et al., 2017). However, in addition to the variability of properties of the matrix, the fractures' density, orientation, connectivity, and hydraulic aperture in the rock mass lead to significant spatial variability of hydraulic properties of rock mass (Odling et al., 1999; Koike & Ichikawa, 2006; Frankel et al., 2007; Lin et al., 2016). The variability of hydraulic properties (in particular, hydraulic conductivity) has significant impacts on hydraulic head distributions, but it is practically impossible to characterize the spatial distribution of these properties in detail at the site of URCs. This dilemma forces us to cope with uncertainty in our evaluations of gas containment. As a consequence, the uncertainty-based analysis is deemed more appropriate than the traditional deterministic analysis.

The uncertainty analysis generally uses probabilistic approaches. These approaches have been applied to many underground geotechnical engineering problems, such as cavern stability (Li & Low, 2010; Goh & Zhang, 2012; Zhang & Goh, 2012) and tunnel water discharge (Ando et al., 2003; Jiang et al., 2010; Javadi et al., 2016b). While stochastic methods have been applied to these problems, their applications to gas containment problem for underground LPG storage caverns are limited. For instance, Chung et al. (2000) employed a

---

[*] Corresponding author at: Department of Hydrology and Atmospheric Sciences, The University of Arizona, 1133 E. James E. Rogers Way, 122 Harshbarger Bldg 11, Tucson, Arizona 85721, USA.

E-mail address: yeh@hwr.arizona.edu (T.-C.J. Yeh).

https://doi.org/10.1016/j.tust.2018.04.037
Received 6 April 2017; Received in revised form 10 April 2018; Accepted 29 April 2018

Monte Carlo Simulation (MCS) technique to assess the safety factor that considers the spatial variability of hydraulic conductivity. Later, based on MCS, Chung et al. (2003) suggested a method for determining the hydraulic safety factor for gas containment in underground storage caverns, considering the heterogeneity of hydraulic conductivity. Using MCS, Kim et al. (2007) investigated two different covariance functions of the hydraulic conductivity and their effect on critical hydraulic head and gradient. These studies, however, did not consider the gas containment reliability, nor did they explore advantages of the stochastic approach to design the gas containment facilities to reduce the uncertainty or the risk.

Besides, most previous studies have relied on MCS to determine the mean and variance of hydraulic head or gradient. While MCS is straightforward, it requires a large number of simulations, which demand a significant amount of CPU time, computer memory, and storage (Li & Yeh, 1998). An alternative to MCS is the first order analysis through Taylor series expansion of numerical models. This approach has been used in the past to derive approximate mean and variance of flow processes (Mao et al., 2013). The advantage of numerical first order method over MCS is that the covariance function of the hydraulic head can be explicitly related to the covariance functions of aquifer parameters. As a result, the mean and variance of the hydraulic head can be obtained without conducting a large number of simulations, and then the computational issues associated with MCS can be avoided. To our best knowledge, applications of the first order analysis to the investigation of gas tightness reliability have not yet been reported.

For water-curtain system design in URCs, Rehbinder et al. (1988) conducted experiments to obtain the relationship between the number of water-curtain boreholes and the pressures in the cavity. Li et al. (2009) likewise developed an experimental physical system to evaluate the performance of water curtain systems with different geometrical parameters. Through a curtain system injection test in laboratory experiments, Wang et al. (2015) addressed the influence of the orientations of rock joints on the arrangement of water-curtain boreholes and concluded that the boreholes should be arranged perpendicularly to the dominant joints. These studies relied on laboratory or field experiments, which are tailored to some specific conditions, and the results are likely not general. Therefore, numerical experiments, which could consider various heterogeneity in the water-curtain system design, are more flexible and thus are desirable. They may lead to general and realistic conclusions.

In order to address aforementioned issues, this article first introduces stochastic conceptualization of heterogeneity, then develops a numerical first order method (NFOM) to calculate gas containment reliability. Afterward, the geology of an underground LPG storage cavern is described, and its geostatistical characteristics are analyzed based on borehole water-pressure tests. Subsequently, stochastic simulation computes the gas containment reliability for crucial locations by NFOM. MCS is also used to compare with the results computed by NFOM. Meanwhile, the effects of the spatial structures of hydraulic conductivity on gas containment reliability are discussed. Lastly, numerical experiments are presented to demonstrate the effectiveness of several water curtain designs for improving gas containment reliability.

2. Methodology

2.1. Governing equation

In this study, we focused on steady-state flow in URCs, which is appropriate for long-term safety analyses. Since unsaturated zone and the water table are likely to exist at many URCs sites, the governing flow equation in variably saturated heterogeneous geologic media was adopted. For the flow in a 2-D vertical URCs cross-section, we used the following equations:

$$\frac{\partial}{\partial x}\left(K(P)\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial z}\left(K(P)\frac{\partial (P+z)}{\partial z}\right)=0 \tag{1}$$

subjected to the following boundary conditions:

$$P(x,z)|_{\Gamma_D}=P_D \tag{2}$$

$$K(P)\frac{\partial P}{\partial x}n_x+K(P)\left(\frac{\partial P}{\partial z}+1\right)n_z\bigg|_{\Gamma_N}=q_N \tag{2}$$

where P is the pressure head [L]; it is a positive value if the medium is fully saturated and is negative if the medium is unsaturated; $z$is the elevation head [L]; $K(P)$is the hydraulic conductivity [L/T], which varies with pressure head under unsaturated conditions; $P_D$is the prescribed pressure head at the Dirichlet boundary Γ_D; q_N is the specific flux at the Neumann boundary Γ_N. $n_x$and $n_z$are the components of the unit vector $\boldsymbol{n}$, which is normal to the boundaryΓ_N.

The hydraulic conductivity and pressure head relationship $K(P)$in Eqs. (1) and (2) are given as the MVG model (Mualem (1976) and van Genuchten (1980)) to simulate flow in URCs using the governing equation and its boundary. The model is listed below:

$$K(P)=\left(\begin{array}{ll} K_s(1-(\alpha\,|P|)^{n-1}[1+(\alpha\,|P|)^n]^{-m})^2[1+(\alpha\,|P|)^n]^{(-m/2)} & P<0\\ \qquad\qquad\qquad K_s & P\geqslant 0\end{array}\right. \tag{3}$$

$$\theta(P)=\left(\begin{array}{ll} (\theta_s-\theta_r)[1+(\alpha\,|P|)^n]^{-m}+\theta_r & P<0\\ \qquad\quad \theta_s & P\geqslant 0\end{array}\right. \tag{4}$$

where $[1/L]$,[1/L], $n[\sim]$ (dimensionless) and $m[\sim]$ are soil parameters and m= 1 - $1/n$; $\theta$is the volumetric water content $[\sim]$; $\theta_s$and $\theta_r$denote the saturated and residual moisture content $[\sim]$, respectively; $K_s$is the saturated hydraulic conductivity [L/T].

Notice that most of the underground LPG storage caverns are constructed in hard rocks, where fractures' density, orientation, connectivity, and hydraulic aperture likely control the LPG leakage. Because of the presence of fractures, it appears that Eqs. (1) through (4), developed for porous media, are inappropriate for analysis of leakage from LPG storage caverns. In order to clarify this misunderstanding, we present the following facts. First, characterizing fractures in detail at a field scale problem is intractable, at least at present. Furthermore, apertures of most fractures are known to be small, and flow in the fractures is generally laminar. Because of the laminar flow, Hagen-Poiseuille's law has been used to analyze flow through the aperture between two parallel plates, which is analogous to a fracture. Likewise, the Hagen-Poiseuille's law has been extended as Darcy's law for flow through porous media (Yeh et al., 2015b). For this reason, most theories for flow through discrete fractures adopt Darcy's law for flow through a single fracture. The difference between the theories for flow through fractures (Discrete Fracture Network Model, DFN) and Equivalent Porous Medium Model (EPM) for field scale problems thus stems from the definition of permeability. In the case of flow through fractures, the cubic law defines the permeability with aperture, width, and length of the fracture, and perhaps the roughness of fracture surfaces. On the other hand, the porosity, average radius of pores, and tortuosity define the permeability. That is, the governing equations in DFN and EPM are identical, except that permeability contrast between fractures and their surrounding matrix is dramatic. For this reason, one can envision that fracture rocks are merely highly heterogeneous porous media with sparsely distributed distinct, elongated highly permeable inclusions.

In order to make an EPM comparable to a DFN, one has to employ very small control volumes (CV) and has to map the spatial distribution of fractures in detail. Notice that interaction between fractures and the matrix is inherent in EPM while DFN has to use interaction term for this purpose. Besides, DFNs treat fractures as tiny planar pores, which is practically impossible to map. They have to generate randomly distributed planar pores as such. That is to say, DFNs cannot predict flow