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Probabilistic simulation model of resilience assessment of natural gas pipeline systems

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Probabilistic simulation model of resilience assessment of natural gas pipeline systems

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Abstract. The study for the natural gas pipeline system (NGPS), particularly about the resilience evaluation, is still in its early stages. Resilience is a hot point in the most important aspects of system security assessment. An integrated simulation model is presented for assessing the gas supply of NGPS, incorporating the topological and operational circumstances. This model takes different forms of disruptions into consideration. Analysis is done on the properties of probabilistic disturbances. The novel ideas include the global resilience and temporal resilience as the indicators for evaluating resilience. By integrating the maximum flow algorithm and the shortest path algorithm with operational and structural parameters, the gas supply volume and routes were determined before and after system disturbances. Based on the theories of complex network and graph theory, researchers have moved the traditional viewpoint from the entire system to the affected regions. The use of simulation models in research can facilitate the development of pre-warning for natural gas supply systems (NGPS), including optimization of gas supply amount and supply routes arrangement, as well as formulation of pipeline maintenance strategies. In addition, simulation models can also support the rapid analysis of disturbance results, thus improving the accuracy of resilience evaluation for NGPS.

1. Introduction

Resilience is a term with several concepts that refers to a system's or unit's capacity to foresee, resist, absorb, react to, and emerge from a disruption. There are several methods to categorize the many definitions of resilience, including certain and uncertain approaches, as well as those that include or exclude preparedness. Based on the previous classification methods, the certain approaches relies on deterministic disturbance event, whereas the uncertain approaches take into consideration the probabilities in both the occurrence and impact of disturbance events, utilizing probability as a means of quantification. The latter classification [1] shows that resilience process includes absorb, response and recovery phases [2–6]. The difference between that is including preparedness phase or not [7–10].

Research on the resilience of NGPS is still in early stages and mainly focuses on reliability and integrity. The present studies mostly concentrate on the approach for general resilience evaluation for energy systems. Bayesian Networks (BN) and Dynamic Bayesian Networks (DBN) have been used to assess the resilience of energy system [11,12]. This works well for systems with a straightforward topology and set of operations. The in-cascading effects and disturbances for NGPS are both fairly complicated. The network flow system modeling makes extensive use of the maximum flow and other related algorithms [9]. In intricate networks, it can be utilized for transmission scheduling and route selection. The maximum flow approach, specifically for NGPS, can make the complicated hydraulic calculations simple. For uncertainty analysis, Monte Carlo simulation has been widely used method for handling uncertainty [13–15].

However, the disruptions that the NGPS encounters are filled with uncertainty, particularly about the time and location of their occurrence. In order to assess NGPS resilience based on unpredictable disruptions, this study constructs a probabilistic simulation model.

2. Resilience to probabilistic disturbance

NGPS components degrade for a variety of reasons, including corrosion and different environmental variables. Therefore, the time and location of disturbance occurrences are unknown in these network systems with many pipes. A state matrix and state transition probability matrix are applied to determine and quantify this.

The Markov process is used to characterize the stochastic state change of the NGPS. It is assumed that each pipeline of the NGPS is initially in a state of normal operation. The whole flow of methodology is illustrated in Figure 1. Based on the limit state equations presented in the red frame, together with pipeline data statistics, operating data parameters and structural characteristics, it is possible to calculate the probability of a pipeline transitioning between a normal and a fault state [15–18]. The three stages of the corroding process are considered: small leak, large leak, and rupture. The three states are determined by comparing the values of the average internal, burst and rupture pressures, as indicated in L_1, L_2, and L_3, respectively. There are two ways to compute or simulate the internal pipe pressure in NGPS, each of which are based on previous data collected from measurements or commercial software like TGNET. The probability of a pipeline existing defects is the probability that the pipeline will fail due to corrosion. The probability of incorrect operation and third-party interference can be calculated from historical data of actual NGPSs. Based on a summary of failure probabilities for interference, corrosion, and other factors, the total failure probabilities are determined. The state matrix represents the current pipeline states, and the components of the transition probability matrix are composed of these probabilities. The pipe's state in period T with time step Δt is determined using Monte Carlo algorithm with N times simulations. After determining the pipeline states for each cycle, the gas supply quantity for the NGPS is calculated using the maximum flow algorithm and the shortest path algorithm, and the resilience and temporal resilience are assessed.

In order to take into account many views on resilience, the complete assessment approach for the supply resilience of NGPS is designed in reference to two indicators: global resilience and temporal resilience. In the resilience modeling process of NGPS, complex network theory, maximum flow algorithm, shortest path algorithm, Markov chains and Monte Carlo (MCMC) are the main foundational methods.

Among them, the maximum flow algorithm is used to solve combinatorial optimization problems with the objective of maximizing the transmission flow of the network system. The calculation is shown by Equation (1), where f^* represents the gas flow, $l(f)$ represents the objective function, s represents the source node, t represents the terminal node, and i represents the joint node in the network.

$$s.t\begin{cases}\max l = f^* \\ \sum f_{ij} - f_{ji} = 0 \qquad (i \neq s,t) \\ \sum f_{sj} - f_{js} = l(f) \quad (i{=}s) \\ \sum f_{ij} - f_{ji} = -l(f) \quad (i{=}t)\end{cases} \tag{1}$$

Optimization problem on a weighted directed graph $G=(V, E, W)$ are efficiently solved by the shortest path method. In this algorithm, the weight of each edge (each pipeline) $e_{ij}=\{v_i, v_j\}$ is a positive number $W_{ij}(e_{ij})$, which are the distance and the cost of supply gas from node v_i to node v_j. The aim is to minimize the sum of pipeline weights from all the alternative routes. To calculate the flow of NGPSand direction in the NGPS before and after disturbance, the maximum flow algorithm and the shortest path algorithm are combined in this study. Based on statistical estimates and random sampling, the Monte Carlo simulation with Markov process (MCMC) approach enables the estimation of random variable of pipeline.

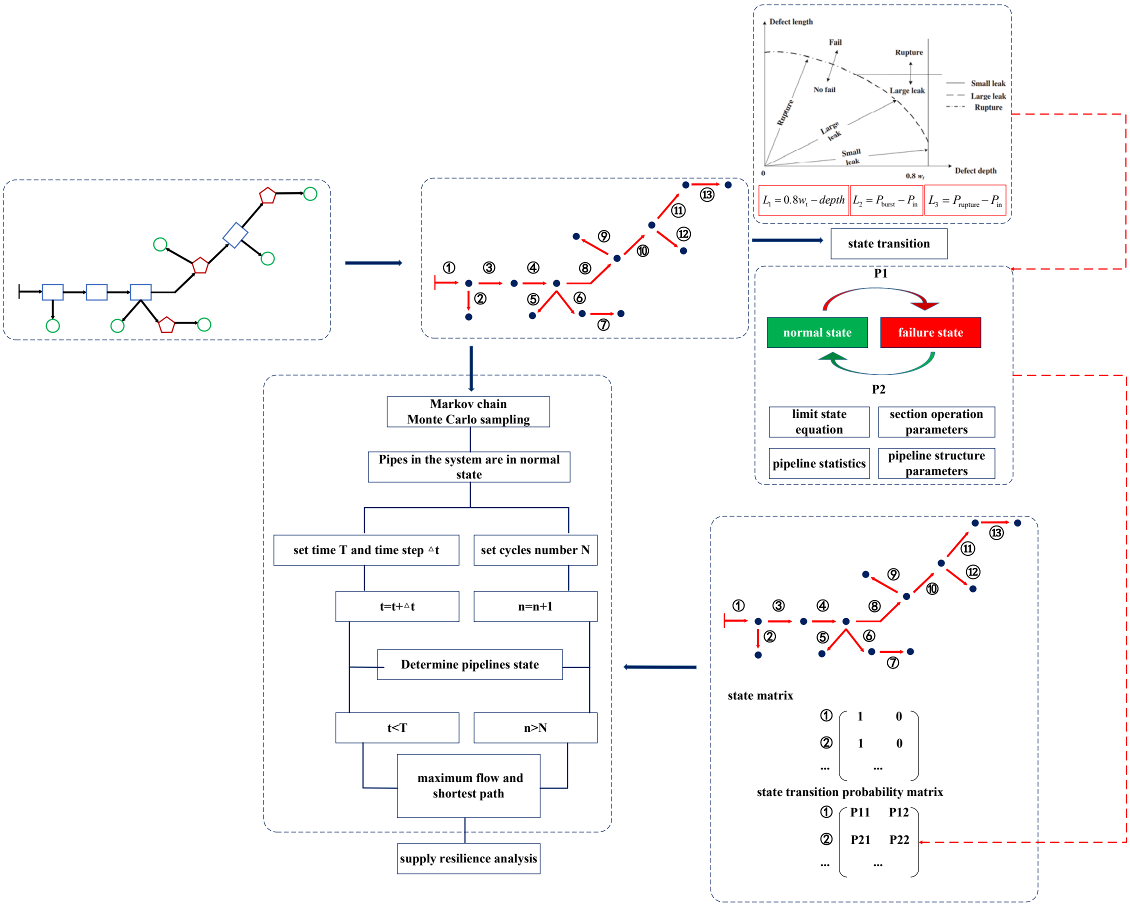

Figure 1. Resilience analysis for probabilistic disturbance.

The global resilience is defined as:

$$R_{\mathrm{w}}(t)=\frac{\int_{T_0}^{T} Q(t)dt}{\int_{T_0}^{T} Q_{\mathrm{cri}}(t)dt} \tag{2}$$

where $R_{\mathrm{w}}(t)$ denotes the evaluation index of global resilience; $Q(t)$ denotes the gas supply amount; $Q_{\mathrm{cri}}(t)$ is critical gas supply amount, which can be explained as the minimum amount to meet all the users; T_0 and T indicate the time of the objective process at the beginning and the end.

In addition, the temporal resilience is proposed, it can be defined as follows:

$$R_{\alpha}(t)=\frac{\int_{T_0}^{T} Q_p(t)^{\alpha}[Q_p(t)-\overline{Q}(t)\geq 0]dt}{\int_{T_0}^{T} Q_p^D(t)^{\alpha}\,dt}(\alpha=0;1) \tag{3}$$

where α denotes the value of 0 or 1, which means the types of Eq. 3. If α=0, Eq. 3 means the NGPS temporal resilience; If α=1, Eq. 3 means the NGPS threshold resilience, which is the ratio of practical gas supply amount to the critical area, unlike to the traditional methods. The [P] in the formula is the Iverson Bracket. [P] is equal to 1 when P is true; if P is false, [P] = 0. D represents the gas demand. $\overline{Q}(t)$ is the threshold amount that NGPS needs to satisfy. $Q_p(t)$ is the practical gas supply amount after the disturbances happening.

3. Numerical example analysis

In reality, the NGPS may be already in an intermediary state when an unintentional interruption occurs. A NGPS from China (Figure 2.) is used as an example to study the resilience and prove the rationality of the methodology.

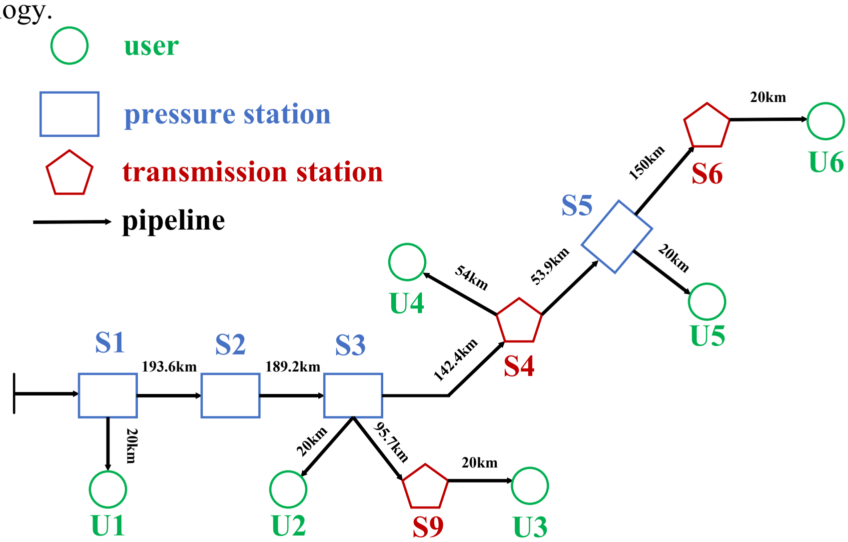

Figure 2. Topology of NGPS.

The user demand and the system's gas supply amount in one, two and three years are shown in the results. To achieve this, the gas demand profiles of three Chinese cities were utilized for demand calibration. Additionally, gas supply amounts were determined using different probabilities of degradation states and repair times, as delineated in Figures 3., 4. and 5. To represent different levels of customer demand satisfaction, some data were assumed for the lack of actual customer demands.

The study reveals that a degradation probability threshold exists, beyond which the long-term stabilization of gas supply amount at a constant level after reduction. The periodical checks and repairs frequencies are based on operation and structure data, and in this study, the repair probability was considered as the set value, which is equal to 1.388×10^{-6}. The results show that when the failure probability is lower than 1.549×10^{-9}, a balance between failure and service is achieved, resulting in a stable gas supply capacity for the NGPS. Figure 6. illustrates the global resilience between gas supply and demand. However, temporal resilience (Figure 7.), provides insight into how timely gas supply meets customer demand. For NGPS, the global resilience definition has been set as the area ratio. Since the available data does not include gas demand, three different gas demand levels are chosen to represent fully, partially, and unmet demands. The gas demand levels are based on the cities in different scales. It needs to be explained here that if the supply amount is beyond the demand amount, the demand is totally met, resulting in system function integration greater than demand integration. Thus, global resilience may exceed 1.0 in such cases. The results of the study indicate that the natural gas supply in NGPS is affected by material failure and pipeline corrosion. In considering these factors, a new perspective is presented by the resilience analysis framework, which provides useful information for decisions on pipeline maintenance periodicity and frequency.

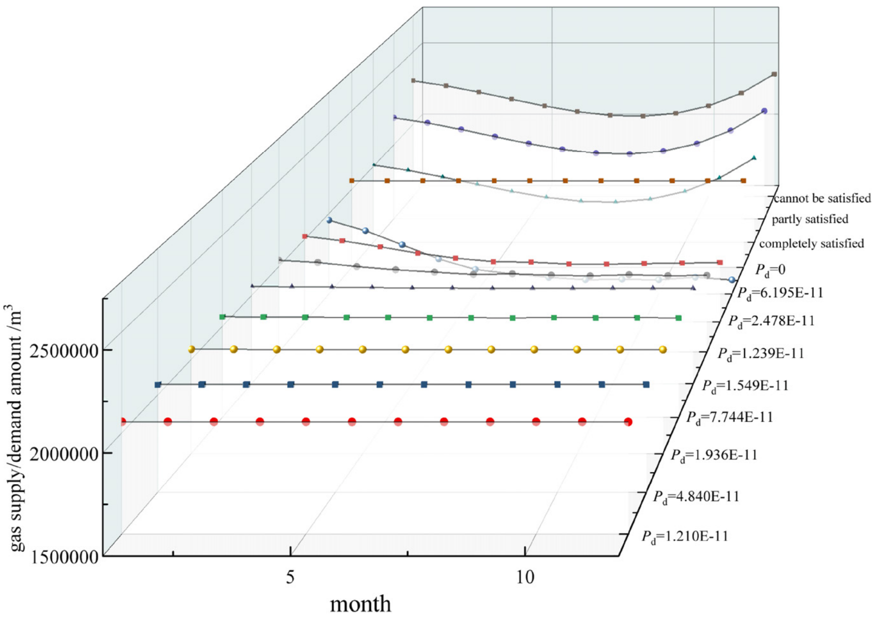

Figure 3. The comparison between supply and demand of NGPS over 12 months.

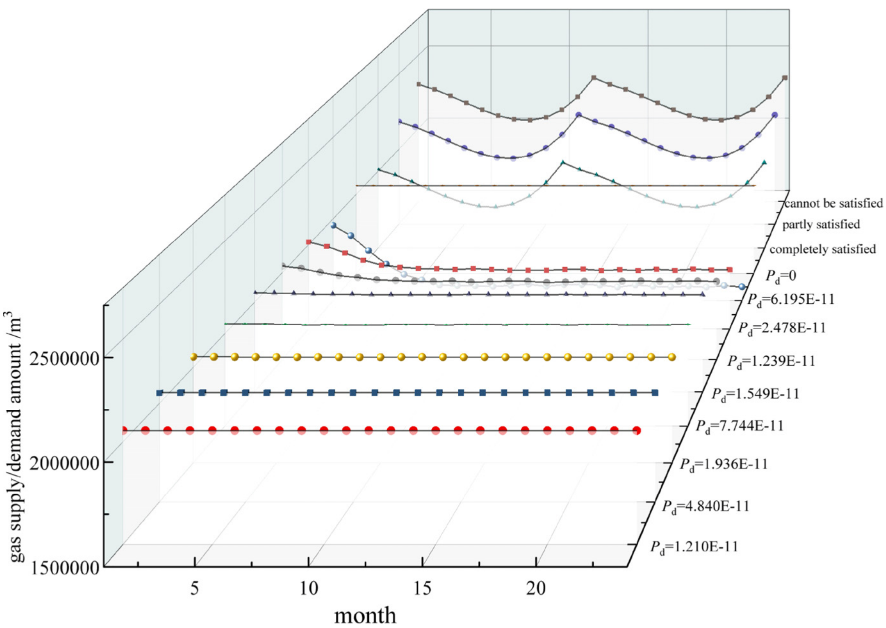

Figure 4. The comparison between supply and demand of NGPS over 24 months.

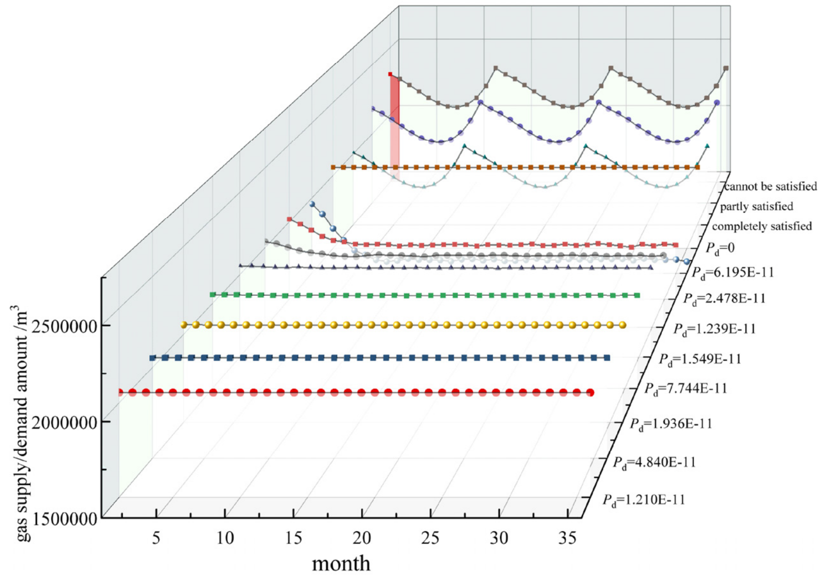

Figure 5. The comparison between supply and demand of NGPS over 36 months.

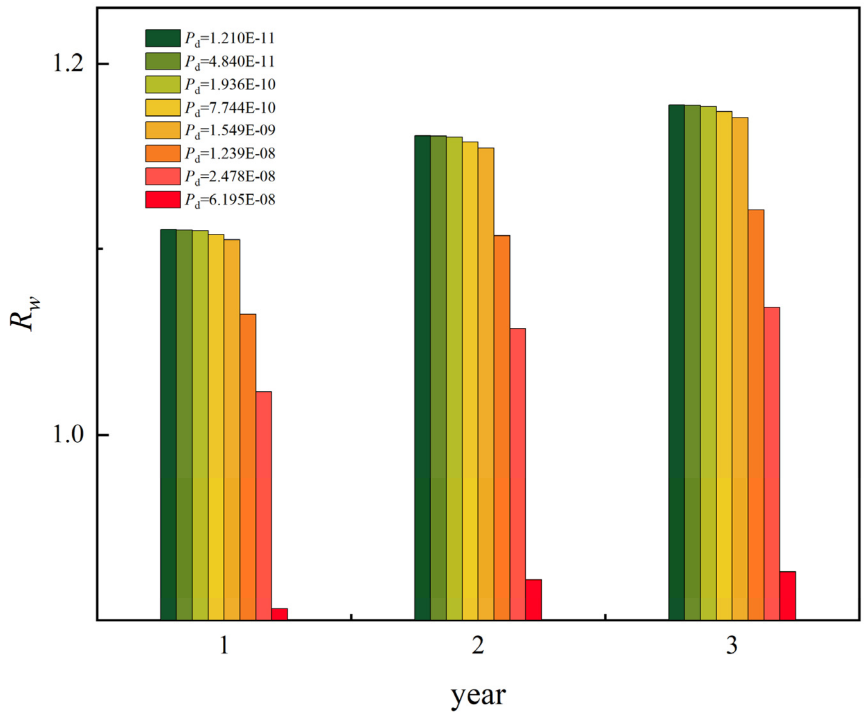

Figure 6. The global resilience under probabilistic disturbance.

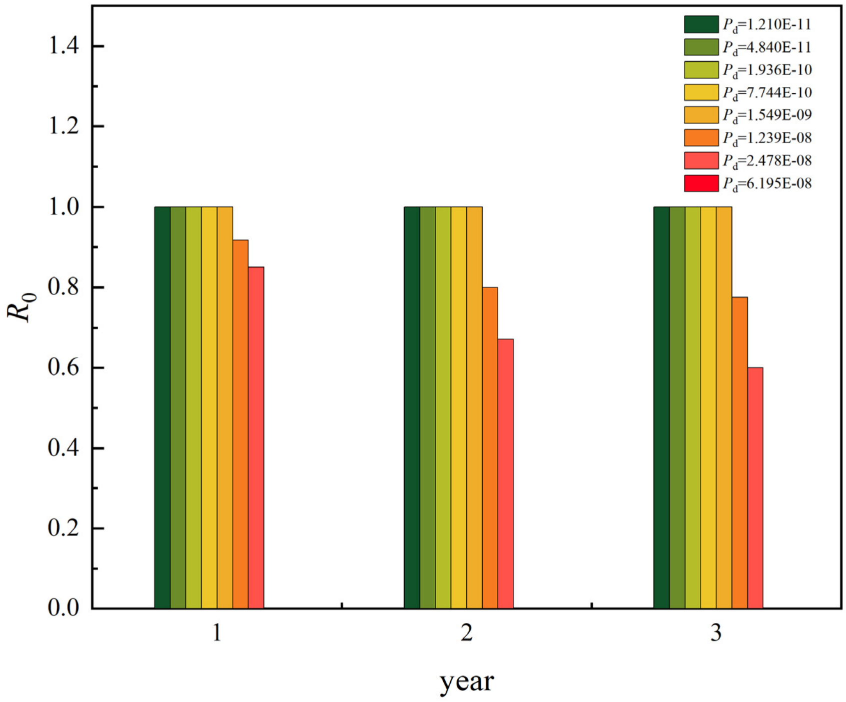

Figure 7. The temporal resilience under probabilistic disturbance.

4. Model limitation and simplification

The simulation model for assessing NGPS resilience are in some simplification, which bring the limitations such as:

(1) the simulation model is founded on network theory and does not consider hydraulic and thermal features;

(2) pressures of the gas which is transported in pipelines are not considered, which are gate station pressure requirements and compressor inlet pressure requirements;

5. Conclusions and future work

This paper proposes and describes the notion of gas supply resilience in NGPS and proposes indicators and evaluation methods for its assessment under uncertain failures. The results of this analysis provide valuable guidance for the design and operation of NGPS.

The stochastic processes of pipe's wall failure and corrosion in NGPS are mainly based on probabilistic evaluation. The state matrix describes the states of the pipeline and the state transfer process is calculated by MCMC. The state transfer probabilities can be efficiently determined based on the historical data, state equations, operation and structure parameters. Monte Carlo simulation is employed to sample the states of pipelines in NGPS, while user demands are obtained by fitting to three different cities. The NGPS resilience under probabilistic disturbances is based on global and temporal resilience. The results can effectively guide the maintenance strategy of pipelines by taking into account the uncertain failure process.

Enhancements will be made to the model utilized for the assessment of gas supply resilience, especially for (i) taking into account the gas supply priorities among distinct gas users; (ii) the maintenance time should be taken into consideration; (iii) incorporating the time lag associated with line-pack with the model.

Reference

[1] Fisher R et al 2010 Constructing a Resilience Index for the Enhanced Critical Infrastructure Protection Program.

[2] Longstaff P H and Armstrong N 2010 Building Resilient Communities: A Preliminary Framework for Assessment. (Homel. Secur. Aff.) 4, 1–23.

[3] Fiksel J 2006 *Sustainability and resilience: toward a systems approach*. Sustain. (Sci. Pract. Policy) 2, 14–21.

[4] Allenby B and Fink J 2005 *Toward inherently secure and resilient societies*. (Science) 309, 1034–1036.

[5] Holling C S 2013 *Resilience and stability of ecological systems*. (Futur. Nat. Doc. Glob. Chang.) 4, 245–256.

[6] Norris F H and Stevens S P 2008 Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. (Am. J. Community Psychol.) 41, 127–150 .

[7] Tierney K J 2003 Conceptualizing and Measuring Organizational and Community Resilience: Lessons from the Emergency Response Following the September 11 , 2001 Attack on the World Trade Center. (Preliminary) pp 1–8.

[8] Kahan J and Allen 2009 *A Concept Development: An Operational Framework for Resilience.* (concept Dev. an Oper. Framew. Resil.).

[9] Marino A and Zio E 2021 A framework for the resilience analysis of complex natural gas pipeline networks from a cyber-physical system perspective. (Comput. Ind. Eng.) p 162.

[10] DHS 2010 Quadrennial Homeland Security Review Report: A Strategic Framework for a Secure Homeland. pp 1–108

[11] Cai B et al 2021 Resilience evaluation methodology of engineering systems with dynamic-Bayesian-network-based degradation and maintenance. (Reliab. Eng. Syst. Saf.) 209, 107464 .

[12] Kammouh O and Gardoni P 2020 Probabilistic framework to evaluate the resilience of engineering systems using Bayesian and dynamic Bayesian networks. (Reliab. Eng. Syst. Saf.) 198, 106813.

[13] Rausand M and Hoyland A 2003 System reliability theory: models, statistical methods, and applications. (John Wiley & Sons) vol. 396.

[14] Zio E 2013 Monte Carlo simulation: The method. Springer Series in Reliability Engineering (Springer) vol. 68.

[15] Su H et al 2018 An integrated systemic method for supply reliability assessment of natural gas pipeline networks. (Appl. Energy) 209, 489–501.

[16] Alamilla, J. L., Oliveros, J. & García-Vargas, J. Probabilistic modelling of a corroded pressurized pipeline at inspection time. *Struct. Infrastruct. Eng.* 5, 91–104 (2009).

[17] Zhang S and Zhou W 2013 System reliability of corroding pipelines considering stochastic process-based models for defect growth and internal pressure. (Int. J. Press. Vessel.) pp. 111–112, 120–130.

[18] Oil C S A 2019 Gas pipeline systems, CSA Standard Z662-19. Mississauga, Canada.