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An agent-based resilience model of oil tank farms exposed to earthquakes

Xinxin Tan [a], Shenbin Xiao [b], Yu Yang [b], Nima Khakzad [c], Genserik Reniers [d], Chao Chen [a,*]

[a] School of Petroleum Engineering, Southwest Petroleum University, Chengdu, China
[b] School of Mechanical Engineering, Southwest Petroleum University, Chengdu 610500, China
[c] School of Occupational and Public Health, Toronto Metropolitan University, Toronto, Ontario, Canada
[d] Safety and Security Science Group, Faculty of Technology, Policy and Management, TU Delft, Delft, the Netherlands

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ABSTRACT

Frequent unpredictable earthquake disasters such as the Turkey Earthquake in 2023 pose an increasing threat to oil tank farms since they may trigger major accidents and domino effects, resulting in casualties, economic losses, and environmental pollution. Unpredictable earthquakes are definitely difficult to prevent and thus resilience strategies such as emergency response should be applied to reduce losses. However, little attention has been paid to the quantitative resilience modeling of oil tank farms, resulting in difficulties in decision-making on resilience assessment and management. Therefore, this study proposes a quantitative seismic resilience model of oil storage tanks by using a dynamic agent-based modeling approach. This approach models the storage tank, active fault, and the environment as three independent agents with their attributes and behaviors. The interaction between agents can also be modeled through disaster evolution rules, and the consequences of interactions can be adjusted through adaptation and recovery strategies. The dynamic propagation of earthquake accidents and the evolution of potential domino effects can be quantified from a bottom-up perspective, thereby quantifying the seismic resilience of oil tank farms. A case study is carried out to illustrate the application of the developed model in oil tank farms and to analyze the sensitivity of different model parameters. The results show that the developed model can dynamically characterize the evolution of earthquake-induced domino effects as well as the emergency and restoration processes, supporting the decision-making on the allocation of resilience measures.

1. Introduction

Petroleum and petrochemical industries play a dominant role in industry development, supporting the development of various sectors such as transportation, the chemical industry, and the pharmaceutical industry [1]. An oil tank farm is a hub connecting oil production, oil processing, oil transportation, and oil sales, playing an important role in the petroleum industry. However, oil tank farms store various oil products using different tanks relatively close to each other, posing serious safety risks due to fires, explosions, and domino effects [2–4]. Once an extreme natural disaster occurs, it may cause a major accident in an industrial park(also known as a NeTech event), and possibly trigger a domino effect, leading to even more serious consequences [5, 6]. Earthquakes are the result of active fault movements, characterized by strong suddenness and great destructive power. Among NaTechs, earthquake-induced accidents have received much attention as they are likely to damage safety barriers and delay the arrival of emergency response, cause fires or explosions, disrupt normal operations and threaten the safety of public life and property [7]. Typical events, such as the M7.4 earthquake in Kokhairi, Türkiye, in 1999, not only caused many casualties but also damaged many factories and facilities. The most severely damaged facility was a storage tank in the Tiprash Refinery. In 2011, a major earthquake and ensuing tsunami in northeastern Japan hit Fukushima, causing devastating damage to a local storage tank farm [8]. On February 6, 2023, a strong earthquake occurred on the border between Türkiye and Syria. The earthquake caused 59,259 deaths and economic losses ranging about $91 billion [9]. Campedel et al. [10] conducted a statistical analysis on 78 events caused by earthquakes, and the results showed that atmospheric storage tanks account for a higher proportion of damaged equipment.

To reduce the consequences caused by these NaTech accidents, many scholars have researched the risk assessment of NaTech events induced by earthquakes. For instance, Salzano et al. [11] developed a Probit model to estimate the failure probability of atmospheric tanks, simplifying the quantitative risk analysis of earthquake-related accidents. Antonioni et al. [12] developed a QRA framework to analyze the risk of

* Corresponding author.
E-mail address: chenchaoswpu@gmail.com (C. Chen).

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earthquake triggered accidents. Campedel et al. [13] developed a quantitative risk analysis method to assess the risk of earthquake events to the overall industry. Earthquake are highly likely to trigger domino effects; therefore, many scholars proposed risk analysis methods to tackle the earthquake-induced domino effects. Alessandri et al. [14] developed a probabilistic seismic risk assessment method for storage tank farms, considering the propagation of major accidents by automatically generating samples of damage propagation chains. Huang et al. [15] established a method based on Monte Carlo simulation for assessing Natech event risks triggered by earthquakes in storage tank farms, considering possible domino effects.

Although a lot of attention has been paid to the prevention of NaTechs, the actual results are usually not so satisfactory due to the high unpredictability and uncertainty of natural disasters (e.g., the Türkiye-Syria double earthquake in 2023) [16]. As a result, the issue of emergency response and resilience of industrial facilities hit by natural disasters has started to draw increasing attention [17,18]. Resilience engineering is to enhance the system's ability to absorb, adapt, and recover from damage in order to reduce the impact of failures or attacks on system performance [19]. Therefore, resilience engineering in industrial processes has become a trending research topic in the field of safety engineering [20–24]. Although the definition of resilience varies in different fields [25], resilience engineering in industrial processes often manifests as the ability to maintain or enhance certain functions [26]. Yang et al. [27] analysed the resilience composition of complex equipment system and provided the framework of resilience engineering and the optimization. Geng et al. [28] defined resilience as the ability to maintain required functionality and quickly recover in the event of an interruption, and developed a framework to evaluate resilience.

Besides the above qualitative and semi-quantitative research, scholars also developed quantitative resilience models to evaluate resilience in industrial process resilience engineering. Yodo et al. [29] used probabilistic resilience metrics to develop a DBN approach for modeling resilience performance which depends on restoration, reliability and disruptions. Bayesian networks are often used to quantify the resilience of industrial processes [30–35]. Chen et al. [36] developed a method for quantifying the resilience of hazardous storage systems, taking into account the dynamic random evolution of damage caused by escalation effects and dynamic recovery processes. Zeng et al. [18] applied a DBN model to assess the resilience of chemical industrial areas, mainly considering the vulnerability of storage tanks exposed to natural disasters and domino effects.

In general, many quantitative methods have been developed for assessing equipment vulnerability and risk assessment of earthquake-induced NaTech events. However, there is still a lack of quantitative research on resilience assessment of storage tank farms exposed to earthquakes. Besides, most relevant research on earthquake-induced NaTech event were conducted for specific earthquake magnitude scenarios, neglecting the uncertainty and complexity of earthquakes. Moreover, previous research has mainly focused on the vulnerability, neglecting the role of emergency response and restoration. Therefore, this study develops an agent-based resilience assessment methodology for oil storage farms, considering resistance, mitigation, adaptation, and recovery abilities of oil storage farms. Besides, the interaction between earthquakes and storage tanks, and the propagation of possible major accidents are modeled, considering the uncertainty in earthquakes and propagation of domino effects. This study is organized as follows: the relationship used for resilience assessment of an oil tank farm is presented in Section 2, an agent-based resilience approach is developed in Section 3; the approach is applied to an oil storage case in Section 4; the conclusions of this study are summarized in Section 5.

2. Seismic resilience of oil tank farms

The seismic resilience of an oil tank farm is defined as the farm's ability to (1) resist earthquake damage, (2) mitigate domino effects caused by earthquakes, (3) adapt to the earthquake-damaged environment, and (4) quickly recover after earthquake damages, as demonstrated by maintaining the storage performance of the farm. Resistibility refers to the ability of oil tank farms to directly withstand earthquake damage. Mitigation capability refers to the ability of oil tank farms to reduce further damage caused by earthquake-induced domino effects. Adaptability refers to the ability of oil tank farms to keep a minimum storage performance before restoration. Recovery capability refers to the ability of oil tank farms to quickly restore their pre-disaster storage performance by repairing or replacing damaged storage tanks.

As shown in Fig. 1, when an earthquake occurs, the storage performance of the oil tank farm may change, which can be divided into six stages. In the initial stage ($t_0 \sim t_1$), there is no earthquake, and the storage performance (S_0) of the oil tank farm remains unchanged. A sudden earthquake occurs at t_1, the oil tank farm exerts resistance ability, and its storage performance decreases (S_1) due to the earthquake damage. During the domino phase ($t_1 \sim t_2$), the storage performance of the oil tank farm continues to decline (S_2) due to earthquake-induced domino effects. During the adaptation stage ($t_2 \sim t_3$), the oil tank farm employs appropriate adaptation strategies to partially improve its storage performance (S_3). During the recovery phase ($t_3 \sim t_4$), the oil tank farm selects appropriate recovery measures to continuously restore its storage performance (S_0). When the complete recovery point (t_4) is reached, it indicates the end of the oil tank farm recovery phase.

Based on the dynamic evolution of the storage capacity of an oil tank farm, a seismic resilience index would be needed that characterizes the resilience of each disaster evolution scenario and evaluates the system behavior. Due to the uncertainty of the dynamic evolution process, assuming there are H evolution scenarios, the following seismic resilience index (R) [37] is calculated as:

$$R = \frac{1}{H} \sum_{i=1}^{H} \frac{\int_{t_1}^{t_{\max}} S_i(t) \mathrm{d}(t)}{S(t_0)(t_{\max} - t_1)} \tag{1}$$

where, $t_{\max}$ represents the longest evolution time, and $S(t)$ represents the storage performance at time t. For most tank farms, the resilience value lies within (0, 1). When $R = 0$, all storage tanks are in a damaged state, the oil tank farm is destroyed and cannot be restored or replaced with new ones. When $R = 1$, the earthquake does not cause any damage to the oil tank farm. According to Eq. (1), the seismic resilience of the storage tanks is related to their storage performance S, which can be represented by the sum of all storage tank volumes. As a result, the evolution of storage performance can be used to quantify the seismic resilience of storage tanks.

3. Modeling

To model the storage performance during an earthquake scenario and thus to quantify the seismic resilience, an agent-based seismic resilience model is developed. Agent-based modeling and simulation (ABMS) is a computational method that simulates the response results of complex systems caused by simple rules and interactive behavior of agents [38], targeting the basic unit agents of the system, rather than the system behavior, structure, and attributes [39]. In recent years, agent-based modeling methods have received widespread attention from scholars and have been applied in various fields, including social sciences, healthcare, economic management, and risk assessment [40–43]. However, its application in the field of resilience assessment is novel and will be introduced in this section.

The modeling and simulation model based on the main agent has three typical elements through continuous application and development.

(1) A set of agents and their attributes and behaviors should be defined. The attributes of an agent include those required for actual modeling, and its behavior refers to the agent's perception

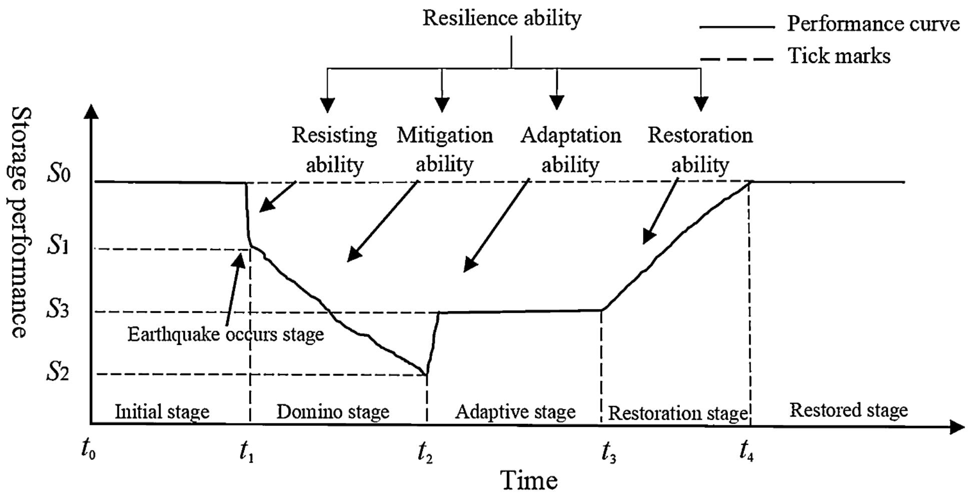

Fig. 1. The storage performance of oil tank farms over time.

of the surrounding environment and the process of taking actions and responses, defined through simple rules.

(2) Agent relationships and interaction methods should be defined. Such relationships and interaction rules determine the interaction behavior between agents and other agents or environments, defined through simple rules.

(3) The agents' environment should be defined: Agents interact with their environment in addition to other agents [38].

The agent-based seismic resilience model of an oil tank farm considers the dynamic evolution process of performance as a behavior of the system, which is composed of the interaction (seismic motion caused by active faults, thermal radiation caused by fires) of the basic units of the system (including active fault agent, storage tank agent, and environment. The process has accident evolution complexity, possible fire domino effects, and uncertainty in the emergency response time. The agent-based model simplifies the modeling of complex systems from a bottom-up perspective, starting from the basic units. Therefore, using an agent-based seismic resilience model can simulate the complex process of dynamic evolution of performance and thus quantify seismic resilience of oil tank farms.

3.1. Agents and environment modeling

3.1.1. Attributes of agents and the environment

The agent-based resilience model consists of two agents: active fault agents and storage tank agents. Different agents have different attributes and states, resulting in different behaviors at different times. Each agent has many attributes, but only the attributes related to the resilience model are listed in the agent model. Active faults are the origin of earthquakes and a tank farm may be affected by many nearby active faults. In this study, different active faults are considered to be independent agents, that is, whether they generate earthquakes is not affected by the surrounding active faults [44]. Active faults have many attributes related to earthquake frequency and magnitude calculation such as location, failure form, fracture area, and maximum magnitude, as shown in Table 1.

Besides active faults, an oil storage tank, as the main component of an oil tank farm, is the other agent in the agent based seismic resilience model. An oil storage tank is affected by the seismic motion and thermal radiation caused by adjacent fires. The storage performance of the oil tank farm directly depends on the attributes and states of storage tank agents. Table 2 shows the attributes of oil storage tanks. The position of a storage tank represents the distance between the tank and the seismic source and the distance between different tanks. Shape characterizes the type of oil storage tanks. Material indicates the oil types stored in the tank. Volume describes the storage capability of tanks.

Table 3 lists the main attributes of the environment, including place and time parameters (i.e., location, time, and ground roughness) and weather parameters (e.g., direction of wind, speed of wind, and air humidity). The environment attributes of the oil tank farm have an

Table 1
Attributes of active faults.

Attributes	Description
Index	Unique marking of active faults
Location	Geographical location of active faults
Fault types	There are three main types of faults in terms of kinematics: normal faults, reverse faults, and strike slip faults.
Fracture area	The total area of active faults where faults occur
Maximum magnitude	The maximum possible magnitude of the active fault
Distance	The closest spatial distance between the active fault and the storage tank farm
Slip rate	The sliding displacement on both sides of the fault divided by the time it occurred.

Table 2
Attributes of oil storage tanks.

Attributes	Description
Index	Unique marking of storage tanks
Position	The distance between different tanks and the distance between the tank and the seismic source
Pressure	All oil storage tanks are atmospheric pressure tanks.
Shape	All oil tanks are vertical cylindrical tanks
Material	Information on substances stored in storage tanks (e.g., gasoline and diesel oil)
Volume	Volume of storage tanks

Table 3
Attributes of the environment.

Attributes	Description
Place and time	Location and time of the accident
Ground roughness	Ground roughness is open country, urban or forest and open water
Direction of wind	Wind direction on the day of the accident
Speed of wind	Wind speed on the day of the accident
Cloud coverage	Cloud coverage on the day of the accident
Air temperature	Air temperature on the day of the accident
Air humidity	Air humidity on the day of the accident

impact on the domino effects. For instance, the wind speed influences the heat radiation intensity of earthquake-induced fire, and thus affects the propagation of fire-induced domino effects.

3.1.2. States of agents

The state of an active fault agent can be divided into two types: creeping (slow sliding) and sudden sliding, as shown in Table 4. When the active fault agent is in a creeping state, there is minor seismic activities or no earthquake in the area usually with no physical damage to the oil tanks. When the active fault agent suddenly slides, it may cause strong seismic waves.

Strong seismic waves caused by changes in the state of an active fault agent may lead to the state of the tank agent transitioning into a failure state. To simplify the evolution process of earthquake disasters, it is conservatively assumed that the state of the tank agent immediately transfers from a failure state to a fire state after being damaged by earthquakes. The detailed state categories of the storage tank agent are shown in Table 5. Among the five states of oil storage tanks, a tank in an operational and restored state has storage capability for normal operation of the tank, otherwise, the storage capability equals zero.

3.2. Agent interaction modeling

Modeling agent interaction behavior based on agent attributes and states is the foundation for establishing a seismic resilience model for oil tank farms. The dynamic evolution of seismic resilience in oil tank farms is mainly caused by the interaction behavior between active fault agents and storage tank agents (seismic damage), as well as the interaction behavior between storage tank agents and the environment.

3.2.1. Agent interaction between seismic faults and storage tanks

The strong seismic motion caused by active faults in a sudden sliding state is the main cause of damage to oil storage tanks [43]. Due to the uncertainties of earthquakes, the Probability Seismic Hazard Analysis (PSHA) method is often used to identify the peak seismic acceleration (PGA) which is a predictive factor to evaluate the risk of earthquakes [45,46], as:

$$P(PGA > PGA*|m,r) = 1 - \Phi\left(\frac{\ln(PGA) - \ln(\overline{PGA})}{\sigma_{\ln(PGA)}}\right) \tag{2}$$

where, $P(\text{PGA}>PGA^*|\ m,\ r)$ represents the conditional probability of PGA exceeds PGA^* at a distance of r from the source in earthquakes of magnitude m, and its value depends on the selected ground motion attenuation model.

To evaluate the vulnerability of storage tanks exposed to earthquakes, the Probit model is used to calculate the probability of the tank failure (Y) caused by earthquakes [13,47], as:

$$Y = k_1 + k_2\ln(100PGA) \tag{3}$$

Where k_1 and k_2 are probit coefficients [11]. The failure probability P_f of tanks can be calculated based on the density function of the cumulative standard normal distribution Φ [11], as:

$$P_f = \Phi(Y-5) \tag{4}$$

The active fault agent causes strong seismic phenomena, leading to the failure of tank agents in the oil tank farm, resulting in a sudden drop

Table 4
State of the active fault agent.

Status	Description
Creeping	Faults generally have no seismic activity or are only accompanied by small earthquakes
Suddenly sliding	Sudden release of energy from faults will result in a strong earthquake

Table 5
The state of the tank agent.

State	Description
Operational	The storage tank is working normally and has not been physically damaged
Failure	The storage tank is damaged due to earthquakes or fire
Fire	The storage tank has caught fire
Extinguished	The burning storage tank is extinguished
Restored	The storage tank is restored after being damaged by disaster evolution

in the storage performance of the oil tank farm and a dynamic evolution of its storage performance. The storage performance of the oil tank farm after an earthquake (S_1) is calculated using the following equation, as:

$$S_1 = S_0 - V_{\text{ti}} \tag{5}$$

where, V_{ti} represents the volume of the failed storage tank during the earthquake, m^3. Due to the uncertainty of the earthquake dynamic evolution process, the damaged storage tanks of an earthquake are determined by randomly sampling the value of P_f using a Monte Carlo simulation.

3.2.2. Agent interaction between different storage tanks

Due to possible fire-induced domino effects caused by earthquakes, the agent interaction between different storage tanks is considered in the domino stage. The interaction between different storage tanks is obtained by studying heat radiation. Heat radiation transfers from the storage tank with a fire state to tanks with an operational state. The arrangement of storage tanks in an oil tank farm is relatively close. When one or more storage tanks catch fire, it may trigger a synergistic effect [7], causing a storage tank to simultaneously receive heat radiations from multiple burning tanks. Therefore, the total received heat radiation by a tank is equal to the sum of the heat radiations received from nearby tanks with a fire state, as:

$$Q_{k,t} = \sum_{j=1}^{m} Q_{jk,t} \tag{6}$$

where, $Q_{jk,t}$ represents the heat radiation from tank j to tank k. The time to failure (ttf) of a storage tank, as a quantitative indicator for determining tank failure, can be calculated by the total thermal radiation ($Q_{k,t}$) [47], as:

$$ttf_{k,t} = \frac{\exp\left(c_1 \times V_k^{c_2} + c_3\ln\left(Q_{k,t}\right) + c_4\right)}{60} \tag{7}$$

where, c_1, c_2, c_3, and c_4 are constants determined based on the type of storage tank, and V_k represents the volume of the storage tank k. The heat radiation received by the storage tank varies over time since the state of the storage tanks changes with time. Therefore, when calculating ttf, it is necessary to stack the heat radiation received at different times, which is known as the "superimposing effect" [6]. When the received heat radiation changes at $t+\Delta t$, the ttf at this moment can be expressed as:

$$ttf_{k,t+\Delta t} = \left(\frac{Q_{k,t+\Delta t}}{Q_{k,t}}\right)^{c_3} \times \left(ttf_{k,t} - \Delta t\right) \tag{8}$$

When the $ttf_{k,t}$ is equal to zero, tank k is considered a failure and catches fire at time t, resulting in propagation of fire-induced domino effects. To prevent the propagation of domino effects, emergency response is always used in oil tank farms. If the emergency response starts before tank failure, the propagation can be prevented, otherwise, the propagation occurs. The ability to respond to emergencies depends on the time to emergency response (tte) [30], This model uses the cumulative lognormal distribution function to model emergency response [19], as:

$$\log tte \sim N(u, \sigma^2) \tag{9}$$

When emergency response measures are taken in a timely manner, the domino effect can be alleviated. Therefore, emergency response is crucial for domino effect prevention and mitigation since it disrupts the interaction between different storage tanks. When the domino effect propagation ends, we subtract the storage capacity lost by the domino effect (V_d) from the existing storage capacity of the oil tank farm to obtain the remaining storage capacity (S_2), as:

$$S_2 = S_1 - V_d \tag{10}$$

3.3. Adaptation modeling

At the end of the domino stage, multiple storage tanks may be damaged, and their storage performance reaches the lowest level (S_2). The adaptability of oil tank farms can be enhanced by adopting adaptation strategies (e.g., using spare storage tanks and adjusting storage plans). The performance of an adaptation strategy is modeled by the increased storage performance (V_a) induced by the implementation of the adaptation strategy. The storage performance (S_3) of an oil tank farm after using the adaptation strategy can be calculated using Eq. (11).

$$S_3 = S_2 + V_a \tag{11}$$

3.4. Recovery modeling

Although an oil tank farm can restore some of its lost storage performance using adaptability, this strategy may only recover part of the lost performance and cannot be useful in the long-term. To quickly resume the normal operation and economic benefits of the oil tank farm, recovery of the damaged storage performance may be inevitable. This model defines a quantitative indicator of time to recovery (*ttr*) as a performance parameter for recovery ability. The recovery strategy often involves rebuilding or repairing damaged tanks, assuming that all damaged tanks should be restored. The duration of tank reconstruction is directly proportional to the volume of the tank, and the reconstruction sequence may affect *ttr*. According to the performance curve of the oil tank farm in Fig. 1, when its storage performance returns to its initial state (S_0), the complete recovery time (t_4) and the start recovery time (t_3) of the oil tank farm is used to calculate the *ttr*, as:

$$ttr = t_4 - t_3 \tag{12}$$

3.5. State transition modeling

According to the agent models and agent interaction models, the state transition model can be obtained, as shown in Fig. 2. Active faults have two states (creeping and suddenly sliding) which can transform to each other with the occurrence and ending of the earthquake. An active fault with a creeping state transforms to a suddenly sliding state, resulting in an earthquake. After the earthquake, the state of the active fault changes back to a creeping state. If an active fault's state changes multiple times in a short time, or if the states of multiple active faults transfer suddenly from a creeping state into a sliding state, it can cause a synergistic damage to the storage tanks due to multiple earthquakes, such as the Turkey Earthquake in 2023.

Oil storage tanks have five states: operational, failure, fire, extinguished, and restored. Initially, all storage tanks are supposedly in an operational state, but they may change to the failure state due to the impact of seismic waves. Besides, the damaged tanks may catch fire, and their state changes from failure to fire. The storage tanks with a fire state can transfer heat radiation to tanks with an operational state, resulting in the tanks exposed to heat radiation changes to a failure state, resulting in a fire-induced domino effect. When fire propagation ends and all tanks with a fire state extinguish, the state of all damaged tanks transfers to an extinguish state. By the application of repair or rebuild strategies,

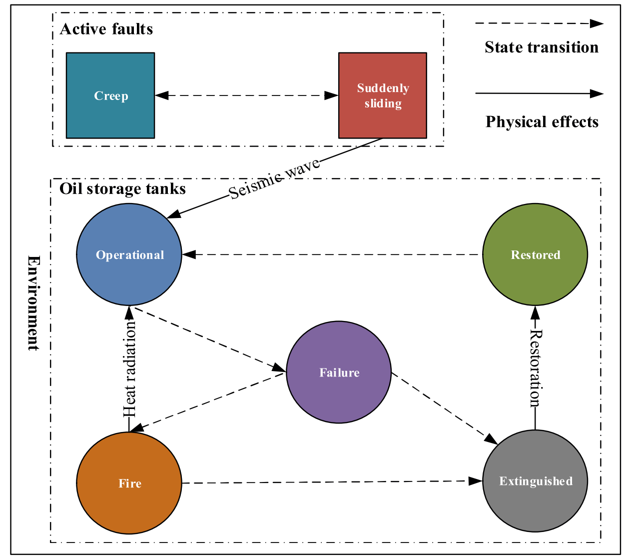

Fig. 2. State transition of agents.

these tanks with an extinguish state may transition to a restored state. Finally, when the oil tank farm returns to the normal operation, all the tanks are in an operational state.

3.6. Simulation algorithm

Due to the uncertainty and randomness in the occurrence and evolution of earthquake disasters, the solution of the agent-based model and calculation of the seismic resilience of oil tank farms are very complex. Thus, a dynamic Monte Carlo method is used to develop a simulation algorithm to simulate the evolution scenario of earthquake disasters in oil tank farms, characterize the uncertainty of an earthquake disaster evolution, consider possible domino effects and calculate the seismic resilience value of oil tank farms, as shown in Fig. 3. Firstly, needed data such as active fault agent attributes, storage tank agent attributes and environmental attributes are inputted. At the beginning, $t = 0$, the number of iterations N (the number of earthquake disaster evolution scenarios) needs to be inputted, and current iteration (current scenario) starts with $n = 1$. Firstly, the initial storage performance of the oil tank farm is calculated. By generating a transcendental function and using the MATLAB function to fit the optimal coefficients, a PGA matrix for earthquake occurrence is generated. Then, the vulnerability of storage tanks during earthquakes is evaluated. Random numbers are generated to determine the damaged storage tanks during earthquakes, and the storage performance S_1 of the oil tank farm after earthquakes is calculated. Assuming that the failed storage tanks in the earthquake immediately catch fire, the tanks in the fire state is also determined at this moment. Then the interaction model between different oil tanks is solved by dynamically calculating the *ttf* of different oil tanks in an operational state. By generating random data according to the cumulative lognormal distribution function to determine *tte*, the tanks that fail due to domino effect can be obtained. As a result, the evolution end time t_2 and the remaining storage performance S_2 of the oil tank farm can be determined. Based on the adopted adaptation strategy, the storage performance S_3 of the oil tank farm is obtained through the adaptation model, determining t_3. According to the restoration strategy, t_4 is obtained. Finally, $n = n + 1$, and the above steps are continuously iterated. When $n > N$, iteration ends, we can determine t_{max} in the evolution scenario, and obtain the final seismic resilience value.

4. Application of the approach

In this section, the developed agent-based resilience assessment

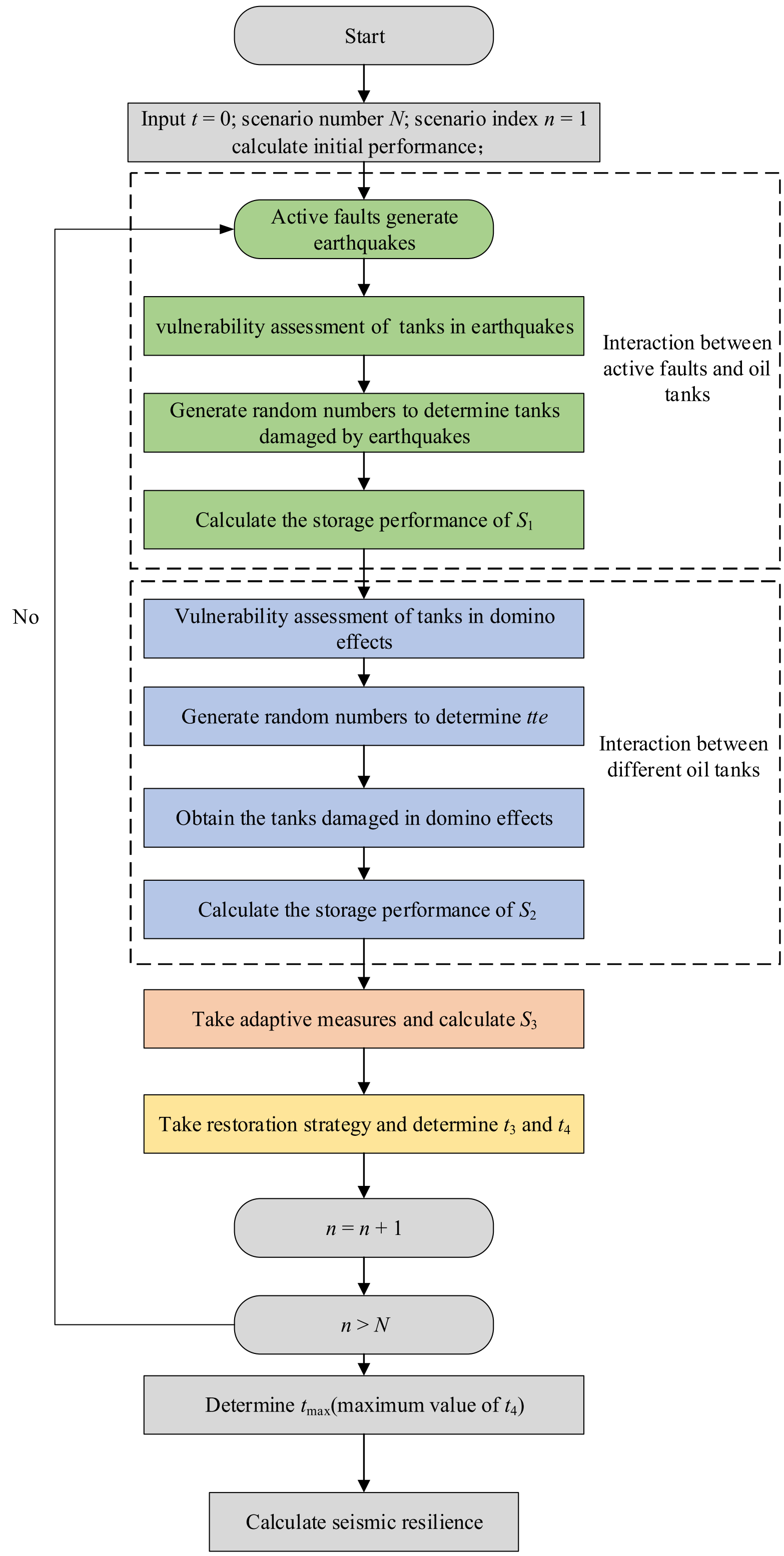

Fig. 3. Solving algorithm for the agent-based seismic resilience model.

approach is applied to a practical oil tank farm located near multiple seismic faults for illustrating and verifying the developed methodology.

4.1. Case study

The case is an oil tank farm with 8 storage tanks surrounded by 30 active faults (AF1-AF30), as shown in Fig. 4. In normal conditions, the mean value (μ) and the variance (σ) for the emergency response parameter *tte* are 15 min and 5 min, respectively. If the oil tank farm is damaged by an earthquake, a recovery strategy is used by rebuilding damaged tanks, restoring their storage performance in descending order (the restoration order has no influence on resilience) of tank volumes, and ultimately achieving normal operation. Table 6 summarizes all the attribute information required by the storage tank agent in the resilience

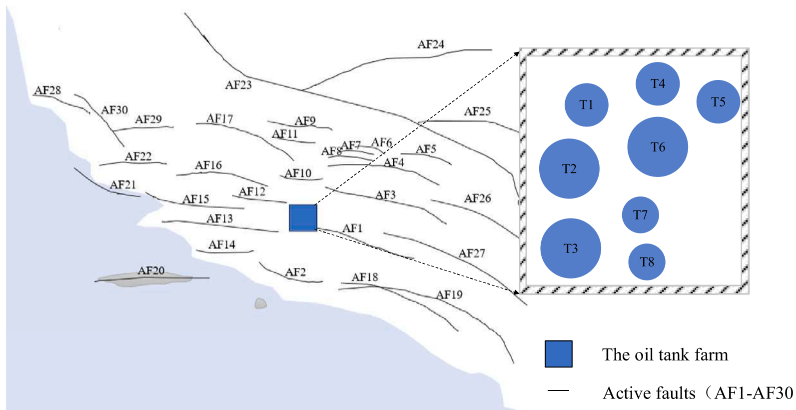

Fig. 4. Layout of tank and active fault agents.

Table 6
Attributes of storage tanks.

Tank number	Fuels	Diameter (m)	Height (m)	Volume (m^3)	Rebuilding time (day)
T1, T4, T5	gasoline	15.7	12	2000	60
T2, T3, T6	gasoline	24	12	5000	150
T7, T8	gasoline	11.5	10	1000	30

assessment.

Besides the direct damage caused by earthquakes, fire and fire-induced domino effects may be triggered by the earthquake. To quantify the consequences of fire-induced domino effects, the possible heat radiation generated by each tank should be calculated. Therefore, the consequence analysis software ALOHA [48] is employed to estimate the heat radiation caused by fires based on detailed attribute information in Table 6. Table 7 shows the ALOHA results in terms of the heat radiation generated by tank i and received by tank j.

4.2. Results

According to the parameters listed in Section 4.1, the solving algorithm for the agent-based resilience assessment model is used to calculate the seismic resilience of the oil tank farm. The algorithm has a total number of iterations $N = 10^5$. That is, a total of 10^5 evolution scenarios are considered, and each evolution scenario has a storage performance curve and scenario resilience value. According to the simulation algorithm, we can obtain seismic hazard curves with different time intervals and the failure probability of storage tanks caused by earthquakes, as shown in Fig. 5a. In 50 years, the probability of PGA > 0.2 exceeds 0.2, and the 50-year seismic hazard curve is used for the calculation of the failure probability of storage tanks.

Fig. 5b shows the failure probability of storage tanks caused by direct earthquake damage and potential domino effects in 50 years. The direct damage probability caused by an earthquake is 0.62 for all the storage tanks because the PGA is identical for all the storage tanks in the oil tank farm. The failure probability caused by domino effects is different since each tank has different capability to initiate and propagate domino effects.

Table 7
Possible heat radiation Tj receives from the fire at Ti.

Tank (i, j)	T1	T2	T3	T4	T5	T6	T7	T8
T1	–	9	0	30	0	3	0	0
T2	12	–	7	1	0	16	5	1
T3	0	7	–	0	0	0	3	5
T4	12	1	0	–	40	12	0	0
T5	1	0	0	12	–	5	1	0
T6	10	28	4	20	22	–	12	5
T7	0	4	3	0	0	3	–	12
T8	0	1	2	0	0	1	12	–

By considering the restoration strategy in the solving algorithm, the resilience value of the oil tank farm can be calculated as 0.53, which is in a medium level. In that case, multiple tanks are likely to be directly damaged by earthquakes, and domino effects are triggered during the disaster evolution process. Fig. 6 shows a typical storage performance evolution scenario, and Fig. 7 shows the details of the evolution.

According to Fig. 6, at time $t = 0$, an earthquake occurs, causing direct damage to three gasoline tanks (T1, T3, T5) in the oil tank farm, resulting in a sudden decline in storage performance (decreased by 9000 m^3) from the initial performance (23,000 m^3). Then, the damaged tanks trigger fire and domino effects, leading to failure of more storage tanks and further reduction of storage performance (further decreased by 7000 m^3 due to the damage to T2 and T4). After 30 days of restoration preparation, the damaged storage tanks are rebuilt in a descending order of tank volumes until the storage performance is completely recovered on the 510th day (t_4).

Fig. 7 shows the earthquake disaster evolution process. At time $t = 0$, an earthquake occurs (Fig. 7a), immediately causing direct damage to the three gasoline tanks (T1, T3, T5) and triggering fire in the oil tank farm (Fig. 7b). At $t = 5$ min, T4 catches fire due to the damage of domino effects caused by fire at T1, T3 and T5, as shown in Fig. 7c. At $t = 12$ min, T2 is also damaged and catches fire due to the propagation of fire (Fig. 7d). All the fires are extinguished at 30 min due to the start of emergency response (Fig. 7e). Then the damaged tanks are sequentially restored. Fig. 7f shows the time when T3 is restored, and Fig. 7g show the time when T2 is restored. At $t = 390$ day, T1 is restored (Fig. 7h), and finally all the tanks are restored (Fig. 7i).

5. Discussion

To deal with extreme earthquakes such as the Turkey Earthquake in 2023, this section discusses the influence of multiple earthquakes on the resilience of oil tank farms under different model parameters. In that case, we simultaneously generate multiple earthquakes in each iteration to obtain the resilience value of exposed oil tank farms. The results are discussed in the following sections.

5.1. The influence of slip rate on seismic resilience under multiple earthquakes

Slip rate is an important parameter in the quantitative study of active faults, representing the average rate of active faults over a certain period of time and reflecting the rate of strain energy accumulation on fault zones [42]. Therefore, this article analyzes the impact of slip rates on the seismic resilience of oil tank farms by setting the slip rates to 0.2, 0.5, 2,

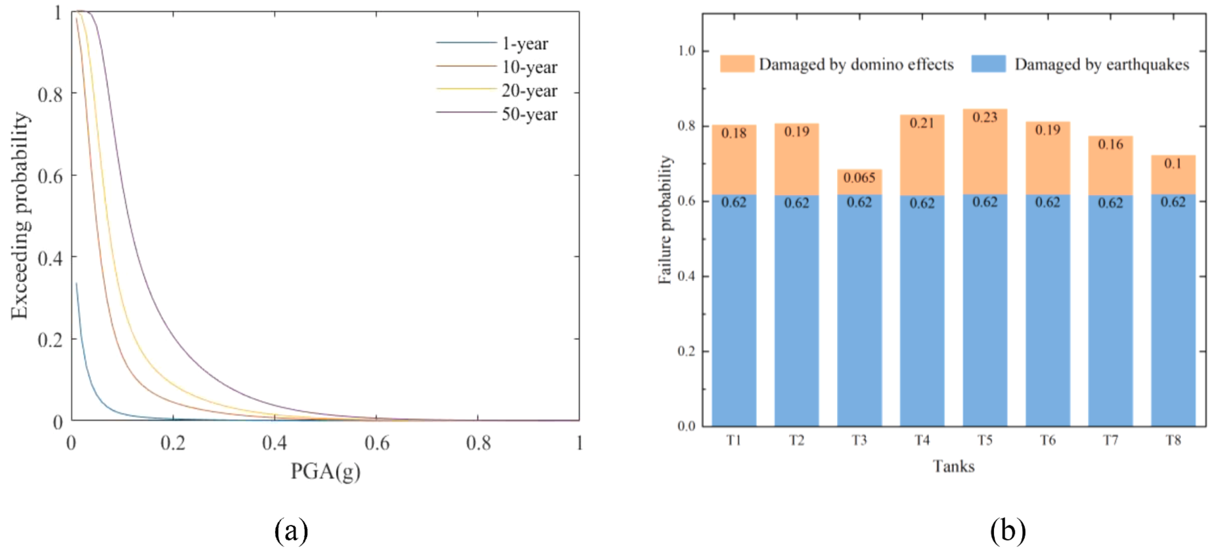

Fig. 5. Resistant results of (a) seismic hazard curve of the oil tank farm and (b) failure probability of storage tanks.

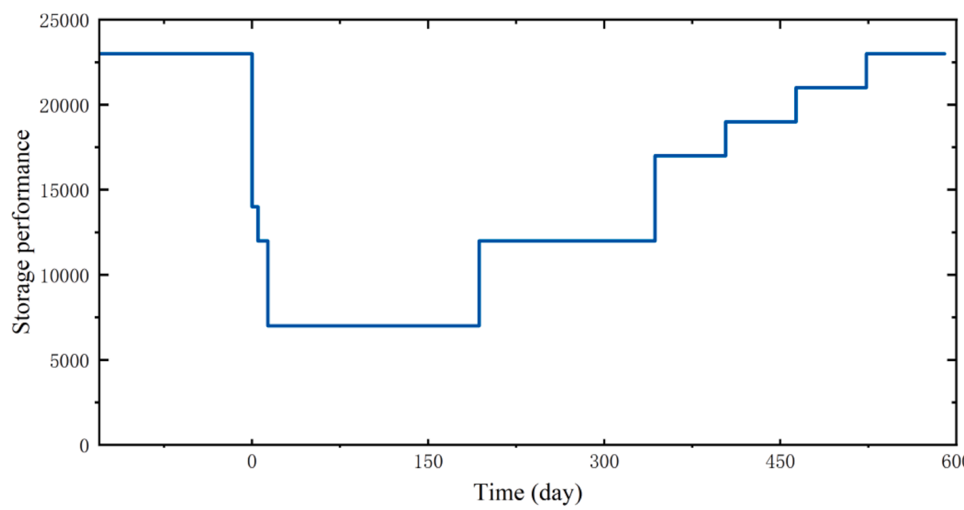

Fig. 6. Storage performance of a typical earthquake disaster.

5, 10, and 12 mm/yr.

Fig. 8 shows the influence of slip rates on the seismic resilience of the oil tank farm and the failure probability of storage tanks under a different number of earthquakes. The seismic resilience decreases since the failure probability of storage tanks increases with increasing the number of earthquakes and slip rates. But the decrease of the seismic resilience rate decreases with increasing slip rates, which is identical to the change trend of the failure probability. As a result, multiple simultaneous or highly-intensity earthquakes can lead to more severe consequences and reduce the seismic resilience of oil tank farms.

5.2. The influence of source distance on the seismic resilience under multiple earthquakes

Source distance is a key parameter for determining the PGA for the storage tanks. The PGA decreases with increasing the source distance, that is, a longer source distance means a safer oil tank farm. Fig. 9a shows the influence of source distance on seismic resilience of the oil tank farm under different number of earthquakes. The seismic resilience of the oil tank farm increases with increasing source distance regardless the number of concurrent earthquakes. When the source distance is larger than 180 km, the influence can be neglected since the oil tank farm is almost not affected by an earthquake of source distance. These results can also be verified by the failure probability of storage tanks. As shown in Fig. 9b, the failure probability decreases with increasing the source distance and approaches zero when the source distance is larger than 180 km. Multiple earthquakes only affect the values of seismic resilience and failure probabilities but do not influence the trend.

5.3. The influence of the number of faults on the seismic resilience under multiple earthquakes

Multiple seismic faults may exist near an oil tank farm. In that case, it should be determined which faults should be considered in resilience assessment. For instance, a total of 30 active faults are considered in the case study. To determine if it is possible to reduce the number of active faults to simplify the calculation, the seismic resilience values considering different number of active faults are calculated, and the results are shown in Fig. 10a. The seismic resilience of the oil tank farm decreases with increasing the number of active faults since the failure probability also increases with increasing the number of active faults, as shown in Fig. 10b. However, the decline rate of the farm's resilience decreases with increasing the number of active faults. Consequently, considering more active faults can produce more accurate results yet in the expense

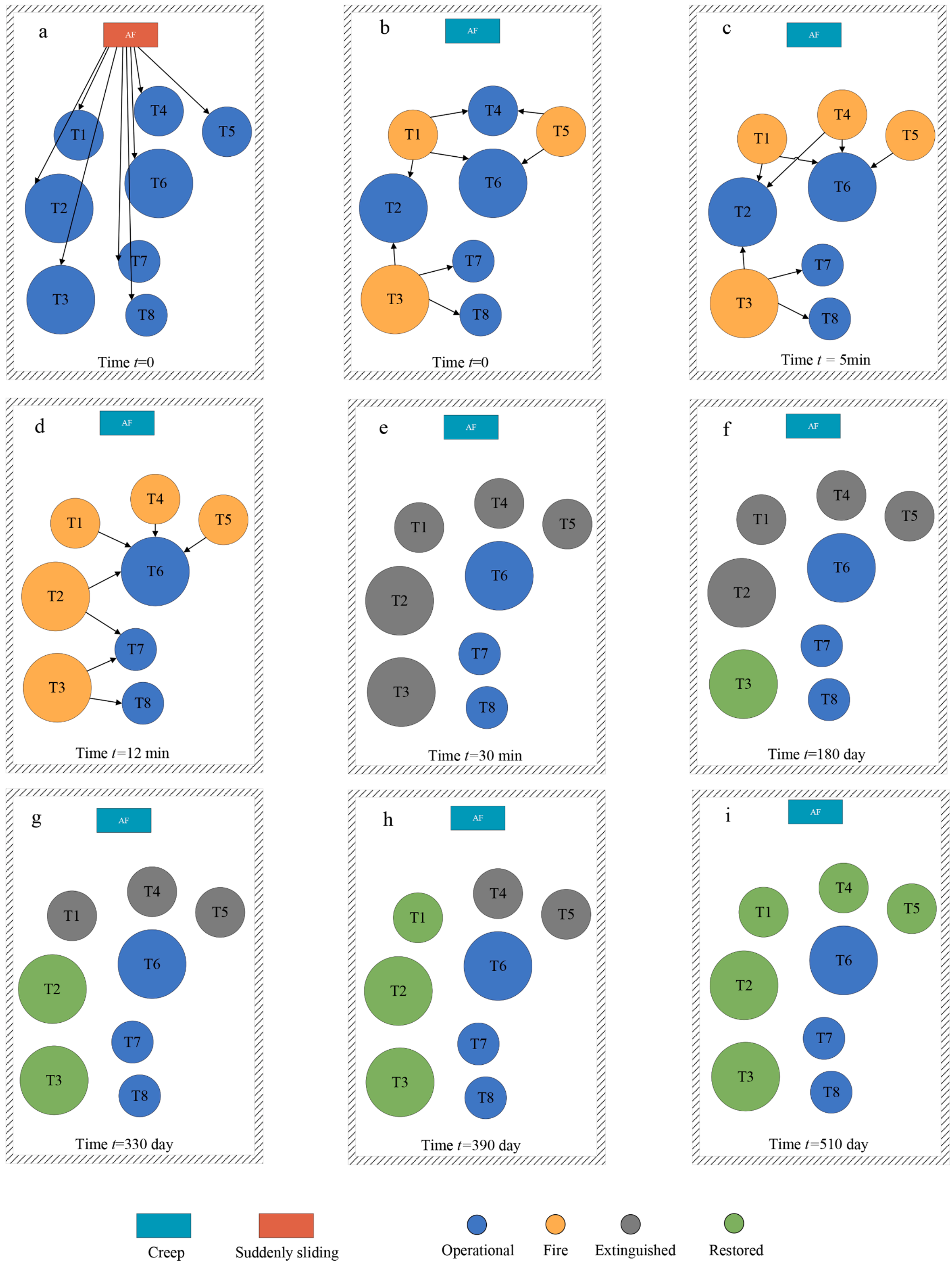

Fig. 7. Schematic diagram of earthquake disaster evolution.

of more computational resources. Neglecting one or more active faults may result in unacceptable errors. Therefore, combining with the results obtained in Section 5.2, it is recommended to consider all the active faults in 180 km.

5.4. The influence of the tte delay on the seismic resilience under multiple earthquakes

Emergency response can effectively alleviate and prevent the evolution of domino effects and thus reduce the consequences of earthquake disasters. However, an earthquake can not only damage storage tanks but also destroy emergency response facilities, delaying the *tte*. To quantify the influence of *tte* delay, we calculate the resilience values with different *tte*, as shown in Fig. 11. The resilience value of the oil tank farm decreases with increasing *tte*, that is, the seismic resilience decreases with increasing *tte* delay since the failure probability caused by domino effects increases with increasing *tte* delay, as shown in Fig. 11. When *tte* increases from 0 to 60 min, the resilience value under

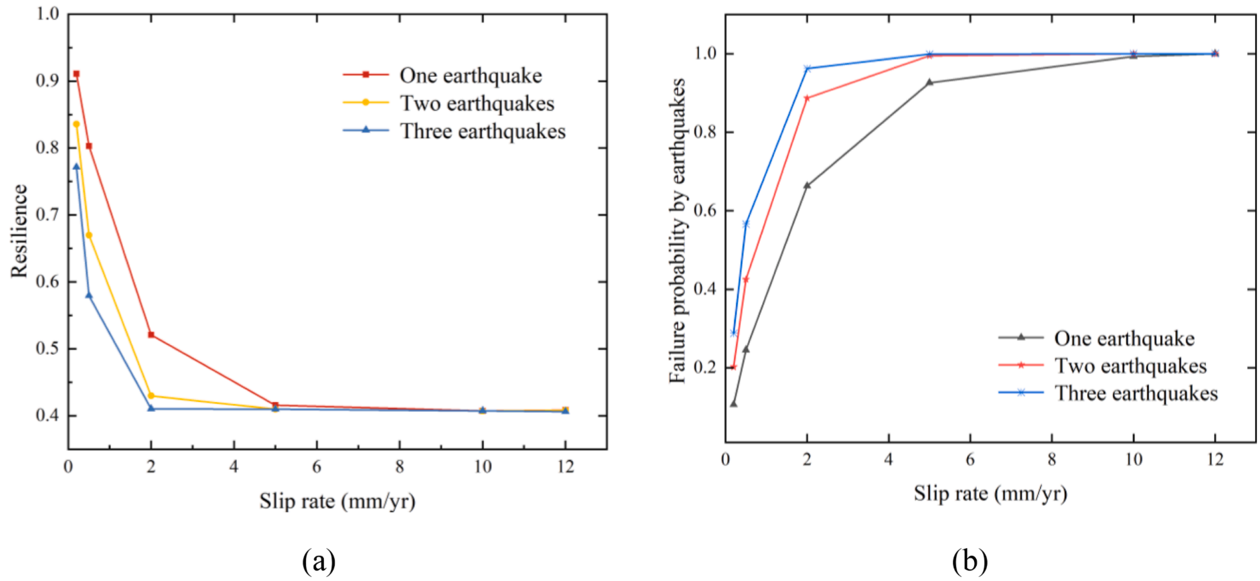

Fig. 8. The influence of slip rate on (a) the seismic resilience of the oil tank farm and (b) the failure probability of storage tanks under multiple earthquakes.

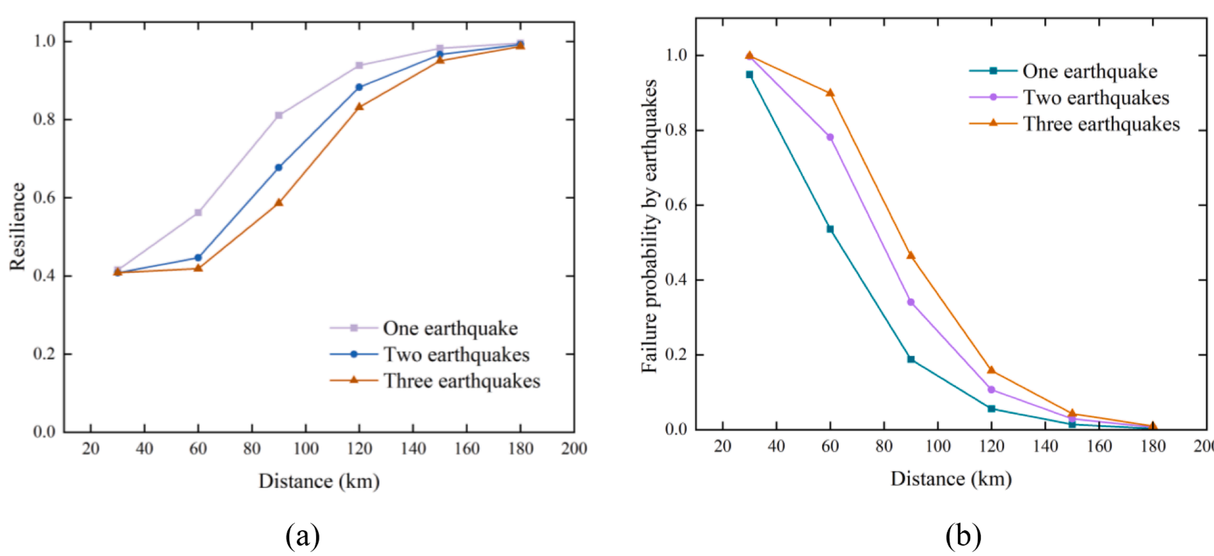

Fig. 9. The influence of source distance on (a) the seismic resilience of the oil tank farm and (b) the failure probability of storage tanks under multiple earthquakes.

two earthquakes decreases from 0.51 to 0.39, demonstrating that the damage to emergency response can significantly decrease the seismic resilience of oil tank farms. To enhance the seismic resilience of oil tank farms, the ability of emergency response facilities to withstand earthquakes should also be strengthened to effectively prevent the propagation of possible domino effects induced by earthquakes.

6. Conclusions

In this study, seismic resilience is defined as the ability to resist earthquake damage, mitigate domino effects caused by earthquakes, adapt to the earthquake damaged environments, and quickly recover after earthquake damages. We developed an agent-based seismic resilience model to quantify the seismic resilience of oil tank farms, considering possible domino effects induced by earthquakes. In our model, storage tanks and active faults are modeled as agents with attributes, behaviors, and states. Further, the dynamic complex evolution of storage performance of tank farms is simplified from a bottom-up perspective, thereby quantifying their seismic resilience. By the developed simulation algorithm, the seismic resilience of oil tank farms can be rapidly calculated, considering the uncertainties in the resistant stage and domino stage, and adaptation and restoration strategies at the end of disaster evolution.

The results obtained from this study can be summarized as follows: The agent-based seismic resilience model can reflect the influence of multiple active faults and earthquakes, avoiding the underestimation of earthquake risks and overestimating seismic resilience of oil tank farms. Multiple earthquakes increase the failure probability of storage tanks and thus reduce the seismic resilience value of oil tank farms, and the seismic resilience decreases with increasing the number of earthquakes. The seismic resilience increases with increasing source distance and with decreasing slip rates. As a result, the location of oil tank farms should be away from active faults with greater slip rates to improve the inherent safety and seismic resilience management of oil tank farms. Active faults with a distance larger than 180 km have little impact on the resilience of oil tank farms, so only the active faults in 180 km should be used as inputs of seismic resilience calculation. More attention should be paid on seismic resistance of emergency response facilities since the

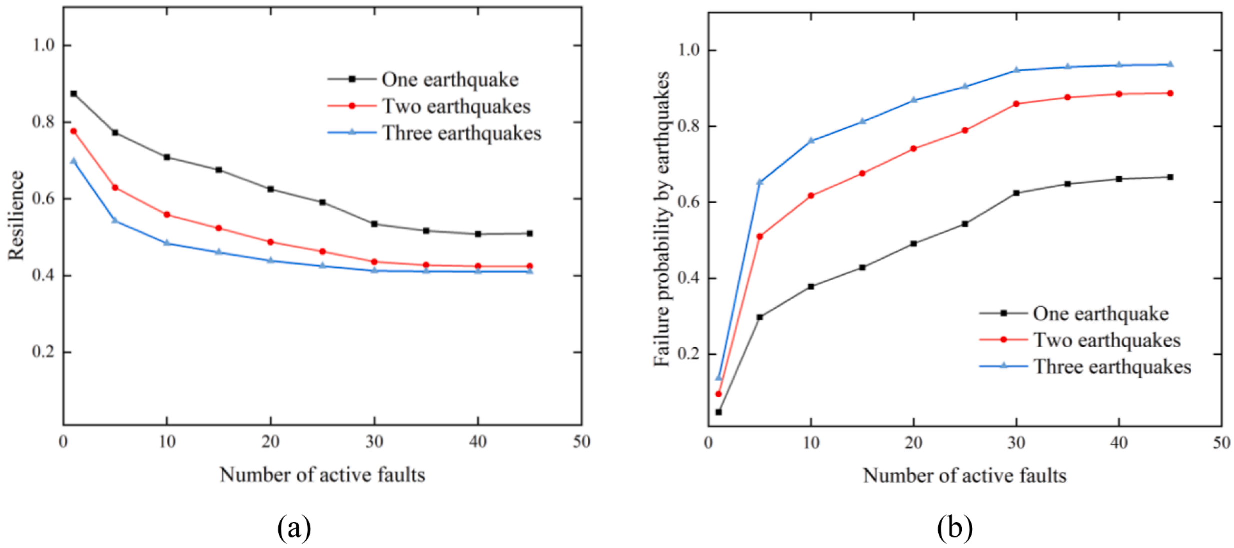

Fig. 10. The influence of the number of active faults on (a) the seismic resilience of the oil tank farm and (b) the failure probability of storage tanks under multiple earthquakes.

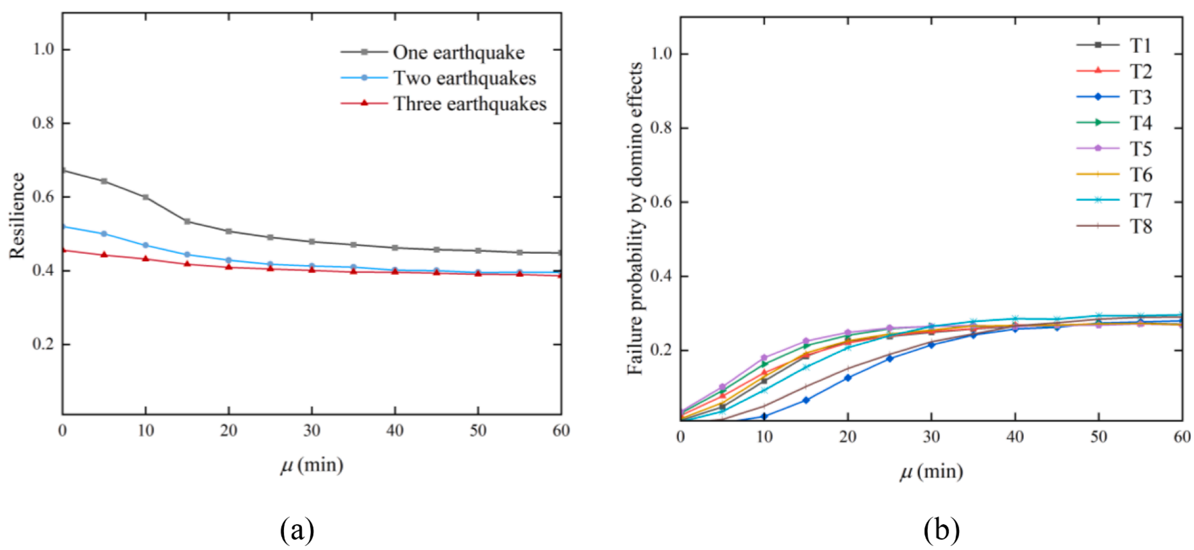

Fig. 11. The influence of the *tte* delay on (a) the seismic resilience of the oil tank farm and (b) the failure probability of storage tanks under multiple earthquakes.

damage to emergency response facilities can accelerate the propagation of domino effects and thus decrease the seismic resilience. In this study the probit model is used for calculating the failure probability of tanks exposed to earthquakes while this model neglects many factors such as tank volume, tank thinness, tank materials. In the future, the probit model may be improved by experiments or statistic data. Besides, vapor cloud explosion and the interaction between different active faults may also be considered in further research work.

CRediT authorship contribution statement

Xinxin Tan: Writing – original draft. **Shenbin Xiao:** Writing – original draft. **Yu Yang:** Visualization, Data curation. **Nima Khakzad:** Writing – review & editing. **Genserik Reniers:** Writing – review & editing. **Chao Chen:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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