Risk Evaluation Indicator System for Lightning Disaster in Oil Storage Depots

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Abstract. Since oil storage depots typically hold large quantities of oil or gas, they are prone to the build-up of high energy and density levels. This paper established a lightning disaster risk assessment index system for oil storage depots that considered the primary causes for accidental explosions due to lightning and included four first-level, 13 second-level, and 13 third-level indexes. Furthermore, this index system was based on the analysis of the mechanism underlying lightning-causing accidents in different types of storage tanks. Furthermore, it involved the establishment principle for the comprehensive evaluation indicator system, denoting a "comprehensive system, distinct layering, and simplicity." This system includes four first-level evaluation index, 13 second-level evaluation index and 13 third-level evaluation index. It visualizes the affiliation relationship between different risks that may cause lightning accidents in oil storage depots, introduces the method used to obtain each underlying risk indicator and lays a theoretical foundation for assessing the lightning disaster risk in oil storage depots.

1. Background
Continuous industrial, scientific, and technological progress has seen an increase in oil usage and the construction of oil storage depots. High storage energy and density can cause severe accidental explosions, with lightning as one of the primary causes. Therefore, lightning protection is vital to the operational safety of contemporary petrochemical enterprises and requires an adequate risk assessment of the areas likely to be affected. The evaluation process must include a complete lightning disaster, risk assessment index system for oil storage, ensuring the accuracy of the results, and subsequent operational safety.

Various countries have a series of mature lightning protection standards and specifications, among which the standards for lightning risk assessment mainly include IEC62305-2 Protection Against Lightning-Part 2: Risk Management [1] issued by the International Electrotechnical Commission (IEC) and the ITU-TK.39 Assessment of Lightning Damage Risk of Communication Offices and Stations issued by the International Telecommunication Union (ITU). Considering the actual situation in China and based on IEC62305, GB/T21714 Lightning Protection [2] represents the mainstream lightning risk assessment reference method. Gong and Li et al. [3] evaluated the risk of personnel loss caused by lightning disasters in large oil depots. They calculated each lightning risk component according to
IEC62305-2 and other standards. They proposed various remedial measures regarding lightning monitoring and early warning options, relevant safety management measures, lightning protection equipment detection, and emergency plans. Combining the risk assessment method highlighted in the GB/T21714 Lightning Protection with Delphi 7.0, Jiao and Feng et al. [4] developed a lightning disaster risk assessment system capable of project location, lightning data analysis, building facilities, and regional assessment. In conclusion, most current standards are based on a single typical building as the research object, which does not apply to oil storage depots regarding the scope, type, and risk level. In addition, since some of the required evaluation factors can only be dealt with qualitatively, the evaluation displays a certain subjectivity. Therefore, the analysis of the current situation and the specificity of oil storage depots indicate the necessity for establishing a set of risk assessment indicators to prevent lightning disasters in oil storage depots.

2. Examining the lightning risk mechanism in storage tanks

To perform an effective scientific lightning risk assessment of oil depots, it is necessary to analyze the disaster mechanism of lightning accidents in different types of storage tanks while exploring various causative factors in combination with lightning risk, disaster bearing body (tank zone) risk, regional risk, and defense risk. Therefore, according to the "comprehensive system, distinct layering, and simplicity" principle, an effective, scientific risk assessment index system is constructed for lightning disaster in oil storage depots.

2.1. Analysis of the lightning accident mechanism of the external floating roof storage tank

2.1.1 Cause analysis of oil and gas leakage. The external floating roof storage tank is equipped with a sealing device between the floating plate and the tank body, which is mainly used to inhibit the volatilization of oil and gas. The current sealing devices use "primary and secondary sealing." During the construction and operation of external floating roof storage tanks, improper operation or poor maintenance may lead to the failure of the sealing system. The main reasons are as follows:

a. The deviation in roundness and perpendicularity, as well as the local concavity and convexity of the tank wall, reduce the performance of the mechanical seal.

b. Due to the settlement operation of the floating plate and the corrosion of the medium on the tank wall, the change in the geometry and size of the storage tank and floating plate also weakens the tightness of the seal.

c. The sealing rubber ages and cracks due to sun exposure and wind erosion, causing deformation that results in the failure of the sealing film, affecting the sealing effect.

d. Wind, as well as the constant entry and exit of the medium from the tank, and various other factors cause the floating plate to "drift" in the tank.

If the emitted oil and gas accumulate in the sealing cavity due to sealing failure, and external air is allowed to enter, an explosive oil and gas mixture is formed [5-6]. Once the oil and gas mixture concentration in the sealing device reaches the explosion limit, it ignites instantaneously, causing severe fire and explosion accidents when the storage tank is struck by lightning.

2.1.2 Lightning hazard analysis. Since the oil and gas mixture in the explosion limit range is combustible, the discharge gap between metal facilities represents the ignition source and can be analyzed via a lightning strike.

a. Lightning strikes to the top of the tank wall. Because the current diverges along the path of minimum resistance by default and the top of the tank wall is more likely to be struck by lightning, the lightning current mainly diverges along two paths: one discharges directly along the tank wall and the other discharges along the inner tank wall, sealing ring, floating plate, and then through the tank wall.
b. Lightning strike floating plate. For external floating roof storage tanks with a large capacity, the central area of the floating plate is not in the protection range of the tank wall top. Specifically, when the liquid level in the tank is high, lightning is more likely to strike the floating plate directly. The lightning current then disperses along various channels, including via the sliding ladder and tank wall or along the sealing ring and tank wall towards the ground.

![Figure 1. Discharge channel of the lightning current when lightning strikes the tank wall top.](image1)

![Figure 2. Discharge channel of lightning current for the lightning strike floating plate](image2)

Of the lightning strike scenarios mentioned above, the latter may present a more substantial risk, while the lightning current of the former may be discharged directly into the earth along the tank wall, significantly decreasing the probability of an accident. For the latter, the discharging lightning current must pass through the sealing ring, commonly causing the failure of the electrical connection between the sealing ring and the tank wall [7]. The external floating roof storage tank primarily uses an elastic bonding, secondary sealing conductive sheet to ensure the electrical connection between the floating plate and the tank wall. When the bonding becomes unstable due to external factors and the discharge gap is formed, hundreds of amperes of current cause spark discharge, leading to lightning fire, causing explosion accidents in the floating roof storage tank [8].
2.2. Analysis of the lightning accident mechanism of the internal floating roof storage tank

2.2.1 Cause analysis of oil and gas leakage. The roof of the internal floating roof storage tank is manufactured from light material, the structure of which is shown in Figure 3. However, most of the internal floating roof storage tanks are in a disposable sealing form. Thus it is likely to leak oil and gas through the gap of floating plate in operation. The leaked oil and gas accumulate in the space between the floating roof and the top of the tank, forming an oil and gas mixture with the air entering through the vent holes in the top and wall of the tank. As long as its density reaches the explosion limit, two of the three elements of combustion and explosion are available, namely combustibles and combustion supporting materials, and thus there is a great risk.

![Figure 3. A simple structural diagram of the internal floating roof storage tank](image)

2.2.2 Lightning hazard analysis. The tank roof and wall of the internal floating roof are equipped with air vents. Due to the working principle of the air vent, the oil-gas mixture within the explosion limit may appear around the air vent. During the thunderstorm season, the atmospheric pressure is low, the airflow is slow, and the oil and gas near the air vent cannot disperse in time, easily reaching the explosion limit. When a lightning current passes through at this time, discharge and ignition occur, and the flame may rush directly into the tank, resulting in large-area combustion of the accumulated oil and gas mixture. The immediate increase in the internal tank pressure and the sealed internal floating roof tank structure do not allow timeous gas release, causing the tank to be prone to combustion and explosion.

2.3. Analysis of the lightning accident mechanism of the dome roof storage tank

Compared with the internal floating roof tank, the dome roof tank does not have a floating plate. Therefore, it is not expensive to manufacture and is often used to store small quantities of crude oil. Due to its structural characteristics, oil and gas are more likely to accumulate between the oil level and the top of the tank. During use, the breathing valve at the top of the tank opens to maintain its internal pressure balance due to the fluctuating liquid level. Similar to the vent in the internal floating roof storage tank, part of the oil and gas mixture may accumulate within the explosion limit at the vent of the breathing valve during seal failure or thunderstorms. In case of flashover and ignition by lightning, the oil and gas mixture will likely burn, allowing the flame to rush into the tank, causing combustion and explosion.
3. Lightning disaster risk assessment indicator system for oil storage depots

3.1. Risk assessment indicator system

Since the current lightning disaster vulnerability classification research is relatively mature, many provinces and cities in China have performed corresponding lightning risk zoning. Therefore, during the initial stage of the lightning risk evaluation of oil storage, the lightning disaster vulnerability classification can be considered a reference for selecting the assessment indicators [9-12].

According to the existing theoretical research of lightning disaster vulnerability, the lightning risk, the sensitivity of the assessment area, and the vulnerability of the disaster-bearing body are considered reference objects. Therefore, on this basis and combined with the relevant lightning standards domestically and abroad, the mechanism behind oil tank lightning disaster, and the knowledge and experience of relevant experts, a lightning risk assessment indicator system with oil storage characteristics is established. This system includes four first-level evaluation indicators: lightning risk, disaster bearing-body risk, regional risk, and defense risk; 13 second-level evaluation indicators: lightning current intensity, annual thunderstorm days, lightning density, thunderstorm path, project attributes, tank characteristics, electrical instrument system, topography, soil conditions, surrounding environment, sealing device form, equipotential bonding, and grounding resistance; 13 third-level indicators: number of personnel, grade of oil depot, floor area, oil risk, combustible gas concentration, instrument system, electrical system, soil resistivity, vertical soil stratification, horizontal soil stratification, safety distance, relative height, and electromagnetic environment.

The specifically selected explanation of each indicator is shown in Table 1.

Table 1. Description of the Lightning Disaster Risk Safety Evaluation Indicators for Oil Storage Depots

| First-level indicators | Second-level indicators | Indicator description                                                                 | Third-level indicators | Indicator description                                                                 |
|------------------------|-------------------------|---------------------------------------------------------------------------------------|------------------------|---------------------------------------------------------------------------------------|
| Lightning strike risk  | Lightning current intensity | The average value of the lightning current in an area throughout the year is an important indicator of how much damage may be caused by lightning in the area. |                        |                                                                                       |
|                        | Annual thunderstorm days | The number of days of lightning discharge in an area in a year is used to indicate the frequency of lightning discharge in the local area. |                        |                                                                                       |
|                        | Lightning strike density | The average number of lightning strikes per unit area in an area in a year is an important indicator of the frequency of lightning activity in the region. |                        |                                                                                       |
|                        | Thunderstorm path       | The movement direction of thunderstorms in an area represents the concentration of lightning activity in the area. |                        |                                                                                       |

(Continued)

| First-level indicators | Second-level indicators | Indicator description                                                                 | Third-level indicators | Indicator description                                                                 |
|------------------------|-------------------------|---------------------------------------------------------------------------------------|------------------------|---------------------------------------------------------------------------------------|
| Hazard-bearer risk     | Project properties      | According to the basic principle that disasters mainly cause economic losses and casualties, the impact of two factors, namely the size of the oil depot and the activities of personnel, on the potential risk after lightning strikes is mainly considered. | Number of personnel    | Evaluating the number of regular workers in the oil depot is directly related to the degree of casualties caused by lightning. |
|                        |                         |                                                                                        | Oil depot grade         | The higher the risk level of an oil depot, the more serious the consequences of lightning |
## First-level indicators

| Second-level indicators | Indicator description | Third-level indicators | Indicator description |
|-------------------------|-----------------------|------------------------|------------------------|
| Area                    | This includes oil product risk and combustible gas concentration and mainly considers the sensitivity of the oil tank characteristics to lightning strikes and the degree of impact after lightning strikes. | Oil risk | Reaching the explosion limit is the leading cause of lightning accidents, and the concentration of combustible gas in the risk zone is a vital indicator that directly affects lightning accidents. |
| Tank characteristics    | This includes two aspects of the instrument system and the electrical system and primarily considers the sensitivity of the disaster-bearing body to lightning strikes. | Combustible gas concentration | Oil depot instrument systems such as liquid level gauges, flow meters, and other high-precision equipment often suffer from lightning damage. Therefore, the integrity of their lightning protection measures needs to be considered. Also known as low-voltage distribution systems, the power supply and distribution system of the project directly affect the severity of lightning accidents. |
| Instrument electrical system | This includes soil resistivity, vertical soil layering, and horizontal soil layering, which are analyzed from the three perspectives, namely the different levels of soil resistivity affecting lightning strike points, soil resistivity mutations affecting lightning strikes, and horizontal multilayered soil affecting soil resistivity changes. | Soil resistivity | The resistance between the opposite surfaces of the soil in the unit cube displays conductivity and comprehensive dispersion. |

### (Continued)

| Second-level indicators | Indicator description | Third-level indicators | Indicator description |
|-------------------------|-----------------------|------------------------|------------------------|
| Vertical soil layering  | The maximum difference in the resistivity of the soil junction. The soil junction is the most vulnerable location to lightning strikes. | Soil conditions | The soil consists of several layers, and the soil resistivity differs from layer to layer. Therefore, the horizontal layering of the soil is also closely related to the distribution of the lightning current. |
| Horizontal soil layering | As in the table above. | Soil conditions | |
First-level indicators | Second-level indicators | Indicator description | Third-level indicators | Indicator description
--- | --- | --- | --- | ---
Topography | | The lightning strike mechanism is related to the differences in topography and landforms. Mountains are more prone to lightning strikes in the rainy season than dry hilly areas. | | Evaluates the presence of dangerous locations within a certain distance around the project that may directly or indirectly pose a risk to the assessed object.

Surroundings | | The surrounding environment in this article mainly refers to the external factors within one kilometer that may indirectly or directly cause the project to suffer lightning disasters. It includes three aspects: safe distance, relative height, and electromagnetic environment. | Safe distance | Evaluates the relationship between the height of the building in the project and the highest point of lightning-prone objects in a specific surrounding area, among which taller buildings are more susceptible to lightning strikes.

Sealing device form | | This is mainly used for external floating roof storage tanks since they are most prone to lightning accidents, while the sealing device is primarily responsible for lightning accidents. When the equipotential connection fails, the lightning current cannot be released in time, causing discharge and ignition, which can easily lead to a fire and the explosion of the oil tank. | Equipotential bonding | (Continued)

3.2. Method for obtaining the indicator parameters
Both qualitative and quantitative indicator parameters are used during lightning disaster risk assessment. The main difference between the two is whether they can be quantified, that is, whether they can be measured in the form of numbers. Therefore, based on the lightning risk indicator system for oil storage established in this paper, the quantitative indicators are divided as follows: lightning current intensity, annual thunderstorm days, lightning density, number of personnel, oil storage grade, floor area, oil risk, combustible gas concentration, soil resistivity, vertical soil stratification, horizontal soil stratification, electromagnetic environment, and grounding resistance. The primary qualitative indicators are thunderstorm path, instrument system, electrical system, topography, safety distance, relative height, sealing device form, and equipotential bonding. The methods used for obtaining the parameters of the two types of indicators are shown in Tables 2 and 3.
Table 2. Methods for obtaining the quantitative indicator parameters

| Quantitative indicators                  | Taking as the center                                                                 |
|-----------------------------------------|--------------------------------------------------------------------------------------|
| Lightning current intensity             | The lightning data assignment of the area with a radius of 5 km, expanding outward with the evaluation project area as the center, mainly refers to the lightning monitoring data provided by the local meteorological unit. |
| Annual thunderstorm days                | This information is obtained by querying the average thunderstorm days in the area where the project is located in the artificial thunderstorm data of the local meteorological unit over the years. |
| Lightning strike density                | \[ N_L = \frac{a}{\pi \times 25} = 0.0127a \left( \frac{V}{km^2 \cdot yr} \right) \] Here, \( a \) is the annual average number of lightning strikes in an area with a radius of 5km, expanding outward with the evaluation project area as the center. It refers to the flashpoint location system data provided by the local meteorological unit. |
| Number of personnel                     | This information is mainly obtained via project construction materials and communication with the unit. \[ N_p = \frac{a}{\pi \times 25} = 0.0127a \left( \frac{V}{km^2 \cdot yr} \right) \] |
| Oil depot grade                         | Since the tank level is judged based on the total capacity of the tank in the GB 50074-2014 "Code for Design of Petroleum Depot," obtain it from the actual total tank capacity of the project. |
| Area                                     | Obtained via project construction materials. |
| Oil risk                                 | The flammable gas concentration is determined according to the data provided by the lightning protection test report of the project. |
| Combustible gas concentration           | The measurement method requires establishing a soil resistivity rose diagram at the geometric center of the evaluation project area, as shown on the left. At least one collection point is selected in eight directions to calculate the average value of soil resistivity \( \rho \): \[ \rho = \frac{A + B + C + D + E + F + G + H}{6} (\Omega \cdot m) \] Here, A, B, C, D, E, F, G, and H are the soil resistivity values collected from the measurement points in the eight directions of the evaluation project. According to the specific season and soil, these values must be calculated in conjunction with the seasonal correction coefficient. |
| Soil resistivity                         | The horizontal layering of soil refers to the maximum difference in resistivity in the vertical direction. The soil resistivity is measured using the four-pole method, after which the relationship curve between the grounding electrode spacing \( a \) and soil resistivity is drawn. The turning point on the curve represents the occurrence of horizontal soil layering. The soil resistivity corresponding to all turning points is compared two by one, and the maximum difference is used to represent the horizontal soil layering parameter. |
| Horizontal soil layering                 | The vertical layering of soil refers to the maximum difference in resistivity in different directions. Therefore, eight points, namely A, B, C, D, E, F, G, and H, are selected according to the soil resistivity rose chart and compared in pairs. The maximum difference represents the vertical layering parameter of the soil. |
| Vertical soil layering                   | The site is investigated, and the distance \( L_a \) of the closest building 1 km away from the evaluation project is recorded. The lightning current is considered an infinite current-carrying guideline while calculating the electromagnetic induction intensity caused by the building to the evaluation project: \[ B = \frac{2\mu_i i}{2\pi L_a} \times 10^4 (Gs) \] where \( i \) is the lightning current intensity, \( \mu_0 \) is the vacuum permeability, and the magnitude is \( 4\pi \times 10^{-7} N g A^{-2} \). |
| Electromagnetic environment              | This is obtained from the lightning protection test report regarding the on-site measurement or evaluation project. |
| Ground resistance                        | This information is obtained by querying the average thunderstorm days in the area where the project is located in the artificial thunderstorm data of the local meteorological unit over the years. |
### Table 3. Methods for obtaining the qualitative indicator parameters

| Qualitative indicators | Taking as the center |
|------------------------|----------------------|
| Thunderstorm path      | By querying the thunderstorm data provided by the local meteorological unit, the data of previous years are calculated to determine the main movement direction of thunderstorms. |
| Instrument system      | The grounding of the ground terminal of the meter shell and the installation of the surge protector is reviewed according to the data provided in the lightning protection test report of the project. |
| Electrical system      | The load level of the power system and the laying of outdoor low-voltage power distribution lines are reviewed using project construction materials, feasibility reports, and other data. |
| Topography             | Based on the actual location of the project, on-site surveys are conducted and combined with relevant data to determine the type of topography the project is located in. |
| Relative height        | The actual project situation and engineering plan are used to determine whether an air-termination point exists within a 1 km area surrounding the project. If there is, the specific height and distance from the project must be determined. |
| Safe distance          | The actual project situation and engineering plan are used to determine whether an explosion hazard area exists within a 1 km area surrounding the project. If there is, the specific distance and its scale must be determined. |
| Sealing device form    | The construction data is used to determine the sealing device form of the floating roof oil tank of the project. Should there be no external floating roof oil tank, it should be recorded as none. |
| Equipotential bonding  | The equipotential connection of the metal accessories, such as the breathing valve, oil measuring hole, and light transmission hole on the storage tank, is determined using the data provided in the lightning protection test report of the project. |

### 4. Conclusion

Many factors required consideration during the large-scale lightning risk assessment of oil storage facilities. Therefore, it is vital to establish a scientific risk evaluation indicator system combined with the lightning risk characteristics of oil storage depots to obtain reliable evaluation results. On this basis, scientific, mathematical methods can be used for accurate and reasonable lightning disaster risk assessment. The research involving the lightning disaster mechanism in different types of storage tanks, as well as repeated modification and practice, allows this paper to provide a comprehensive analysis of each factor that may influence the lightning risk in oil storage depots. In addition, the lightning risk evaluation index system for oil storage depots is established according to the basic principles of scientificity, perfection, and operability. Furthermore, the method used to obtain the risk indicator parameters is introduced, laying a theoretical foundation for follow-up risk assessment.

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