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Research on the Loss Rule of the Leakage Problem in Residential Construction Based on Water Spray and Storage Tests

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Abstract: Leakage issues have received increasing attention as the most common and significant source of complaints in residential construction quality problems. In this study, based on the classification of residential construction leakage problems, 1947 water spray tests and 2333 water storage tests were conducted on 18 construction projects. An empirical analysis of 432 leakage cases was conducted to determine the loss law for a single leakage point as well as the loss laws for different grades of leakage problems. Through empirical analysis, it can be concluded that more than 90% of the leakage problems are third-level. To better understand the quantitative law of the residential construction leakage problem, a total loss law model was developed. Finally, the law of leakage loss in residential construction is summarized, and measures to reduce leakage loss in residential construction are proposed. This research can provide a theoretical basis and model tools for inherent defect insurance and help insurance companies control insurance risks and drive the promotion of inherent defect insurance.

Keywords: residential construction; water spray and storage tests; leakage; loss rule

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1. Introduction

With the continuous development of the economy and continuous improvement of living standards, higher requirements have been proposed for the quality of residential construction. As an organization that carries out social supervision on goods and services and protects the legitimate rights and interests of consumers, the China Consumers Association (CCA) is an important institution to undertake consumer complaints. Housing is also a commodity, and the occupants of housing are also consumers. Complaints about the quality of housing will also be received by the CCA as consumer complaints. Therefore, CCA's consumer complaints can well reflect the quality of residential constructions. According to data on the acceptance of complaints published by the CCA, the proportion of quality complaints in housing and building material complaints in 2018, 2019, and 2020 was 35.51%, 31.05%, and 25.28%, respectively, indicating a high proportion of complaints [1]. In 2018–2020, the proportion of leakage-related complaints decreased slightly, due to the rise in the total number of complaints caused by the awakening of residents' awareness of rights protection. High proportion of leakage-related complaints in residential constructions is caused by the universality of leakage problems, so the proportion of leakage-related complaints is always high. In addition, among all types of quality problems in residential construction, the leakage problem is universal and repetitive and is a difficult problem that affects the project quality [2]. According to the Beijing Municipal Commission of Housing and Urban-Rural Development's quality complaint data for residential construction in

2020, the proportion of complaints regarding leakage from residential construction (roofs, external walls, kitchen toilets, and other parts) was 33.3%, and all types of residential construction were involved [3]. To propose a more scientific and effective solution to the leakage problem in residential construction, we must first determine the internal law of the loss of leakage problems in residential construction. However, no research has been conducted on the loss law of leakage in residential construction, necessitating a quantitative analysis. The proportions of the main problems identified in Beijing's residential construction quality complaints in 2020 are shown in Figure 1.

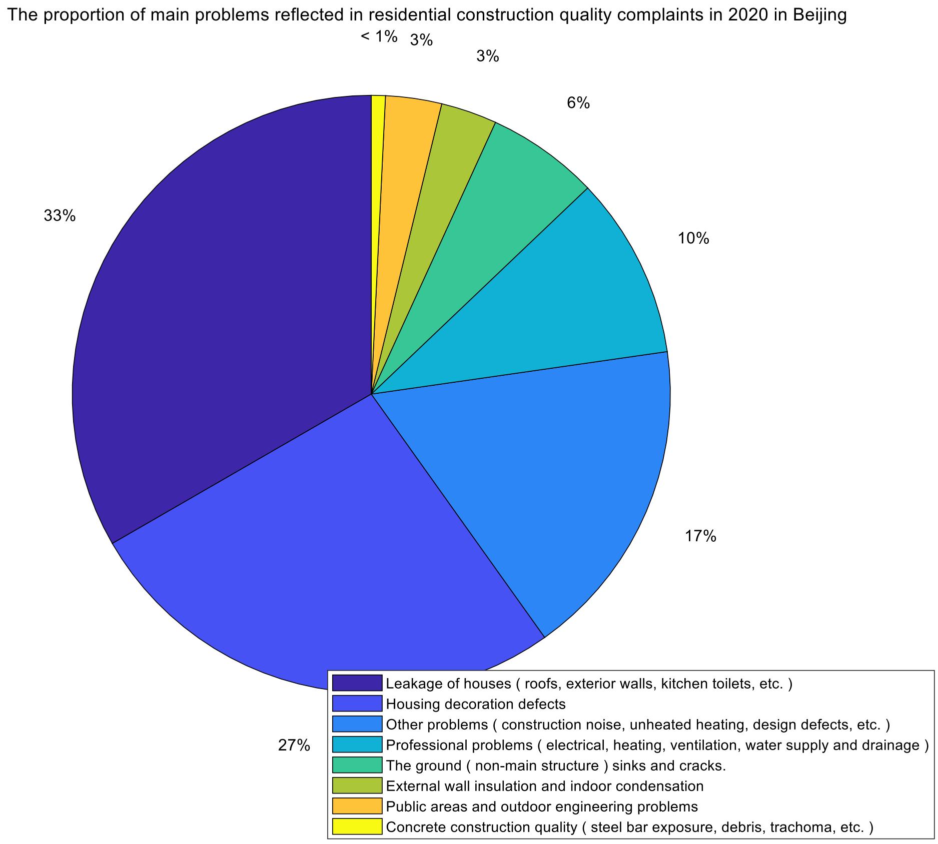

Figure 1. The proportion of main problems reflected in Beijing's residential construction quality complaints in 2020.

The quality of residential constructions has always been the focus of scholars' research. Lekan argues that one of the parameters that has contributed immensely to the management of construction quality in the era of Industry 4.0 is the Internet of Things (IoT), alongside lean thinking concepts, and tries to apply these tools to the quality management system of residential construction projects [4]. Sivanantham proposed special confining reinforcement on slopes to improve the performance of RCC frames and proved, through experiments, that the displacement of the special confined RCC frame with a short column also improved due to ductile reinforcement [5]. At the same time, Sivanantham represented an experimental and analytical investigation of the behavior of reinforced concrete frames and their response in sloped regions of hills and found that the reinforced concrete structure's lateral strength and energy dissipation capacity were increased by 2.45 times with the addition of a solid infill [6]. These studies have expressed a good vision for improving the quality of construction projects. In this context, inherent defect insurance is introduced as a specific means of financial services to the real economy to ensure the interests of the occupants.

Table 1 lists the number and amount of inherent defect insurance claims for each subproject in Shanghai in 2021. According to the practical data from inherent defect insurance, the claim frequency for five-year waterproofing and thermal insulation projects can reach

65.73%, which is significantly higher than that of other sub-projects [7,8]. Therefore, to better prevent and control insurance risk, promote inherent defect insurance, quickly solve the problem of residential leakage, and improve the quality of residential construction, targeted research on residential leakage is required.

Table 1. Claims details of each engineering division and subdivision in Shanghai in 2021.

Scope of Claims	Claims Number	Proportion	Claim Amount (CNY)	Proportion	Average Claim Amount (CNY)
10-Year-Term Foundation and Main Structure	10	0.80%	134,444.00	1.25%	13,444.40
5-Year-Term Waterproofing and Insulation	817	65.73%	7,219,099.04	67.30%	8836.11
5-Year-Term Window and Door	1	0.08%	6150.00	0.06%	6150.00
5-Year-Term Wall and Ceiling Plastering Layer	2	0.16%	8366.00	0.08%	4183.00
2-Year-Term Electrical, Water Supply and Drainage	145	11.67%	1,842,486.87	17.18%	12,706.81
2-Year-Term Window and Door	83	6.68%	241,773.00	2.25%	2912.93
2-Year-Term Wall and Ceiling Plastering Layer	44	3.54%	282,834.99	2.64%	6428.07
2-Year-Term Renovation	141	11.34%	990,910.30	9.24%	7027.73
Total	1243	100.00%	10,726,064.20	100.00%	8629.17

It can be seen from Table 1 that there is a significantly higher claim frequency for five-year and thermal insulation projects compared to other sub-projects. The frequency of insurance claims is also an embodiment of the quality of residential constructions, which shows that the leakage problem is a major difficulty in the daily life of residents. Therefore, in order to better protect the basic rights and interests of residents, it is necessary to introduce and promote inherent defect insurance. The data in Figure 1 and Table 1 reflect that the leakage problem is a common problem in the operation of residential constructions. However, due to the diversity of the causes of leakage, the research on the leakage of residential constructions often lies in finding the causes of leakage to guide the construction, which ignores the study of the leakage law itself.

Considering the leakage problem in residential construction, many scholars have conducted relevant studies. Wang et al. and Sun et al. analyzed the influencing factors of waterproofing performance and the operating environment of underground engineering through practical engineering and concluded that non-standard design, construction, and material properties affect the leakage of residential construction [9,10]. Although these studies discussed the possible causes of leakage in residential constructions, their findings were not substantiated by relevant quantitative analysis tests. In addition, from the perspective of occupants, they do not pursue an understanding of the causes of leakage and the internal mechanism but often care about the loss caused by the leakage problem and how to solve it. We propose the requirements for a quantitative model of the loss law of leakage in residential construction. Scientifically determining the loss law of leakage in residential construction is an urgent problem that needs to be solved for the future development of the construction industry.

In addition, the location and detection of leakages have gradually become the focus of current leakage research. Many scholars have proposed new concepts for leak detection and location using acoustic technology, multi-sensor technology, and high-resolution pressure sensors, whose performance and overall accuracy have also been significantly improved [11–13]. In their respective studies, Cody, Agrawal, and Fezai proposed the use of linear prediction, maximum likelihood estimation, and kernel principal component analysis models to exclude outliers in feature information, which can improve the accuracy of leak location [14–16]. Machine learning models are also widely used for the detection and recognition of leakage sites. Many scholars have developed and verified existing machine learning models and improved and optimized their detection performances [17–20]. Thus, the leakage detection and response times can be effectively reduced, and the leakage can be accurately detected and located.

It can be seen that most scholars' research on residential leakage problems focuses on the related technologies of leakage location and detection, especially the introduction of deep learning models. Through a large number of iterative learning, they can effectively enhance the accuracy of leak detection and location in residential construction. These studies are highly technical, but they do not involve the solution of the leakage problem. However, the causes of leakage problems in residential constructions are diverse. Before the inherent defect insurance began to be promoted, many scholars did not pay attention to the summary and analysis of the loss law of leakage problems, and related research focused on the search for leakage causes and deep mechanism analysis. With the implementation of inherent defect insurance and the introduction of insurance perspective, the correlation between insurance claims and the internal mechanism of the problem is low. On the contrary, the distribution of losses has a greater impact on insurance claims, which puts forward requirements for the establishment of a scientific quantitative model of leakage losses in residential constructions.

Water spray and storage tests are a basic method to determine whether a waterproof roof, exterior wall, kitchen, toilet, or balcony are qualified, and the results can effectively reflect the degree of leakage. Therefore, water spray and storage tests are required before the residential construction can be completed and accepted [2]. Many scholars have introduced or compared water spray and storage tests as a traditional method of detecting the leakage of residential construction in the study of intelligent quality inspection of residential construction, with the goal of improving the system of intelligent quality inspection of residential construction [21–24].

Most studies on residential leakage problems have focused on technologies related to leakage location and detection. Although these studies were highly technical, no additional measures were proposed to solve this leakage problem. Inherent defect insurance can help households solve the problem of residential leakage quickly. However, there is no scientific quantitative model for the loss law of residential construction leakage to guide insurance practices. As the primary method of leakage quality detection, it is necessary to conduct an empirical analysis of the leakage problem of residential construction using water spray and storage tests to construct a loss law model of the leakage problem of residential construction. This helps systematically sort the system design for inherent defect insurance. While promoting inherent defect insurance, it also plays a role in improving the quality of residential construction from multiple perspectives by introducing an insurance perspective to meet people's yearnings and expectations for a better life.

2. Empirical Analysis of Residential Construction Leakage

2.1. Classification of Residential Construction Leakage

Senarathne et al. used the Best Worst Method to evaluate the best waterproof selection criteria, which can improve the watertightness of high-rise buildings from the perspective of waterproof material specification selection, and proposed corresponding office building waterproof solutions [25]. Krause discovered defective and easily damaged structures through self-compacting tests of concrete sealing functions and systematically evaluated the waterproofing performance of actual projects [26]. An et al. highlighted the necessity and superiority of the adjacent layer-dependent waterproof method through an experimental evaluation of multi-unit residential buildings and observed that the difference in installation method and material performance between sheet and coil waterproof methods directly determined the difference in waterproof performance grade [27]. In another study, the researchers proposed composite and self-adhesive board waterproofing as an effective method for waterproofing structures and experimentally evaluated the structural leakage defects of large apartment projects in South Korea, which have similar waterproofing performance levels to existing apartments [28]. However, most of these studies are qualitative analyses, and there is no clear quantitative standard for classifying the leakage problem levels in residential construction. Therefore, according to the requirements of the Code for Acceptance of Construction Quality of Underground Waterproofing (GB50208-2016), the waterproofing situation is divided into four grades based on the different requirements and actual situation of waterproof engineering in China [29]. The first level is the most serious leakage, and the fourth level is the least serious leakage. The standards for each grade are listed in Table 2. The symbol '-' in the table indicates that the grade requirements for the corresponding index in the standard are not clearly defined, and the default is greater than the upper limit of the corresponding index by one grade lower than it.

Table 2. Table of waterproof grade standard.

Waterproof Grade	The Proportion of Total Leakage Area	Number of Leakage Points	Area of Leakage Point (m^2)
First-level	-	-	-
Second-level	-	<7	<0.3
Third-level	<1/1000	<2	<0.1
Fourth-level	No leakage on the surface	0	0

The classification grade provided by the Code for Acceptance of Construction Quality of Underground Waterproof is clear, and the selection of indicators is representative. Because there may be differences in the occurrence of different levels of leakage, such a classification helps to construct a more accurate distribution model of total leakage loss in residential constructions. In insurance practice, insurance companies can also make targeted repair preparations according to this classification, such as staffing, repair time and material preparation. However, because the leakage points are often irregular, it is difficult to calculate the area accurately. In addition, due to the structural structure and material, the area of leakage point of many leakage problems will not be fully presented, and the area of leakage point cannot fully reflect the damage size of the leakage problem. Therefore, in the following empirical analysis, the number of leakage points was selected as the main grade evaluation standard, and the area of the leakage points was used as an auxiliary.

2.2. Data Acquisition

To perform a better empirical analysis of the leakage problem in residential construction, water spray and storage tests were conducted on 18 construction projects to be completed in Shenzhen, and the leakage situations were counted. These construction projects were newly completed residential communities in Shenzhen in the past half year. The project size and construction type involve multiple types, which indicates that the selected residential constructions are representative. Since these data are the data in the actual project, the projects for water spray and water storage test are all construction projects that have been completed and are to be delivered. Therefore, these data can be used to analyze the basic situation of leakage problems in residential constructions and summarize the loss law of leakage problems in residential constructions according to the frequency and degree of leakage problems in actual projects, which is helpful for the formulation and promotion of inherent defect insurance policy.

The test was conducted in strict accordance with the requirements of the Technical Code for Insite Testing of Building Waterproof Engineering (JGJ/T299-2013). The water spray and water storage test times were set to 30 min and 24 h, respectively, and the infrared thermal image method was used to compare the measured areas after the test [30]. In the water spray test, the water pressure was set to 0.3 MPa, and a uniform water curtain was formed on the surface of the area to be measured [30]. In the water storage test, we ensured that the shallowest water storage depth exceeded 25 mm and immediately stopped the water storage test when the test leaked to avoid accidents [30]. Since each water spray and water storage test is not long, environmental factors and testing conditions can be considered constant.

To ensure the universality of the test for different construction projects, according to the size of the project, a number of houses were selected proportionally as pilots to conduct the water spray and storage tests to eliminate the influence of randomness on the test. Generally, the proportions of residential construction selected for the water spray and storage tests were the same. Water spray and storage tests are often performed for the same residential construction to ensure the reliability and stability of the test. Some construction projects have conditions that are not suitable for water spray or water storage tests because of their own requirements, resulting in different times for water spray and water storage tests.

2.3. Water Spray and Storage Tests

A total of 1947 water spray tests and 2333 water storage tests were conducted in 18 residential buildings in Shenzhen. Table 3 lists the basic situation of the water spray and storage tests and obtains the proportion of unqualified times based on the number of water spray and storage tests involved in each project and the number of leakages.

Table 3. Statistical table of the water spray and storage tests.

Residential Constructions Number	Percentage of Unqualified Water Spray Test Times	Percentage of Unqualified Water Storage Test Times	Residential Constructions Number	Percentage of Unqualified Water Spray Test Times	Percentage of Unqualified Water Storage Test Times
1	13.10%	2.38%	10	30.83%	3.75%
2	6.06%	1.52%	11	29.05%	0.00%
3	17.59%	7.41%	12	/	19.44%
4	9.47%	0.53%	13	65.28%	5.56%
5	32.11%	2.38%	14	11.11%	19.44%
6	19.44%	16.11%	15	18.75%	1.00%
7	30.67%	1.52%	16	35.74%	5.11%
8	6.67%	4.55%	17	26.92%	20.63%
9	2.48%	16.11%	18	0.00%	0.00%

To further illustrate the reliability of water spray and storage tests, completion acceptance scores for 18 residential constructions were taken. Since the failure rate of completion acceptance scores and water spray and storage tests is inversely related, the number of points deducted for completion acceptance is taken as the consideration index of residential construction quality. According to the numbering order of residential constructions, the percentage of unqualified water spray test times and the number of points deducted for completion acceptance are introduced in turn for completion acceptance, and the line chart is drawn as shown in Figure 2.

It can be seen from Figure 2 that the percentage of unqualified water spray tests and the number of points scored for completion acceptance are synchronized, and residential constructions with poor water spray test results have lower results. Although the magnitude of variation is not consistent due to other factors, the reliability of the water spray tests is unquestionable.

The leakage of the water spray tests is mainly manifested as the leakage at the contact between the window and ground, leakage at the contact between the window and inner wall, and leakage at the contact between the window and roof (as shown in Figure 3). Leakage in the water storage tests mainly manifested as small balcony anti-seepage and kitchen threshold seepage (as shown in Figure 4).

It can be observed from the water spray and storage tests that the leakage problems in residential construction were more common and different. Further quantitative analysis of the loss caused by leakage problems in residential construction requires further empirical analysis.

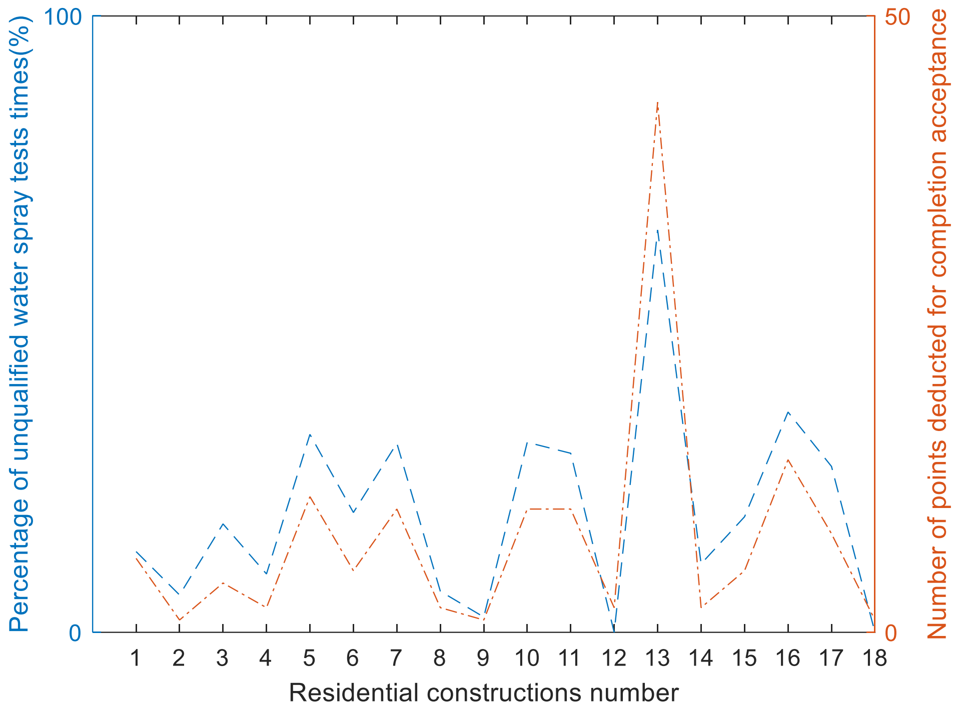

Figure 2. Comparison between the results of water spray test and the quality of residential constructions.

(**a**) (**b**) (**c**)

Figure 3. Leakage problems in the water spray tests. (**a**) Leakage at the contact between the window and the ground; (**b**) leakage at the contact between the window and the inner wall; (**c**) leakage at the contact between the window and the roof.

(**a**) (**b**)

Figure 4. Leakage problems in the water storage tests. (**a**) Leakage at the small balcony anti-seepage; (**b**) leakage at the kitchen threshold seepage.

2.4. Analysis of Leakage Problem in Residential Construction

It can be observed from Table 3 that there were some differences in the unqualified situations of the water spray and water storage tests in different projects. From the overall test situation, the water spray and water storage tests were conducted 1947 and 2333 times, respectively, of which the number of leakages was 432 and 136, respectively. It can be concluded that the total unqualified times for the water spray and water storage tests were 22.19% and 5.83%, respectively. The main reason for this phenomenon is that the water spray tests have stronger water mobility than the water storage tests, and the wall materials often have pores, particularly around windows. Therefore, there are higher leakage occurrences in water spray tests compared to water storage tests and around windows compared to the water spray tests elsewhere. According to these data, the possibility of leakage caused by water spray tests is higher than that caused by water storage tests, which also shows that in an actual project, the leakage of walls, doors, and windows caused by rainfall is the main cause of leakage. Water storage in residential construction is often caused by water spray, and with the increase in regional rainfall, the gap in leakage occurrences between the water spray and the water storage will be more obvious. Therefore, in the process of empirical analysis of the leakage in residential construction, an in-depth analysis of the leakage caused by water spray tests was conducted. To better explore the leakage problem in residential construction, it is necessary to analyze the leakage loss from the perspective of the number of leakage points in combination with the classification level provided by the Code for Acceptance of Construction Quality of Underground Waterproofing.

2.4.1. Analysis of Leakage Degree in Residential Construction

The number of leakage points was obtained by counting 432 leakages in the water spray tests, as shown in Figure 4. Because a count of more than 10 leakage points is no longer continuous, only individual test cases appear. Therefore, in the classification process, leakage points greater than 10 are listed as a class.

It can be observed from Figure 5 that, in the leakage test, more than 90% of the cases were microleakages formed by a single leakage point, and the leakage area of most leakage problems was far less than 0.1 m^2. Because there are numerous leakage problems with a single leakage point, the statistical law for more than two leakage points is not well reflected in Figure 5. Therefore, it is necessary to draw a statistical figure for the number of leakage points in a residential construction with two or more leakage points, as shown in Figure 6.

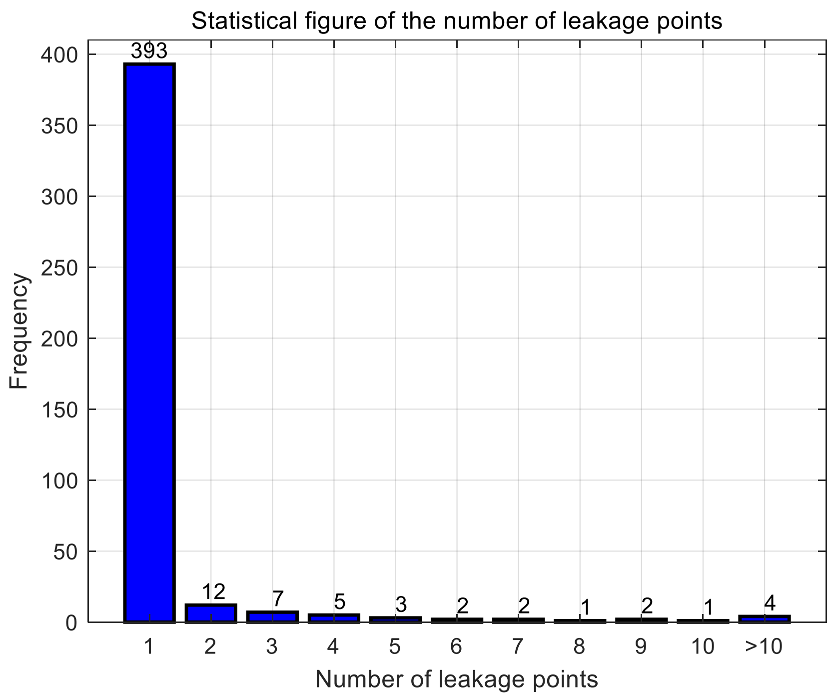

Figure 5. Statistical figure of the number of leakage points.

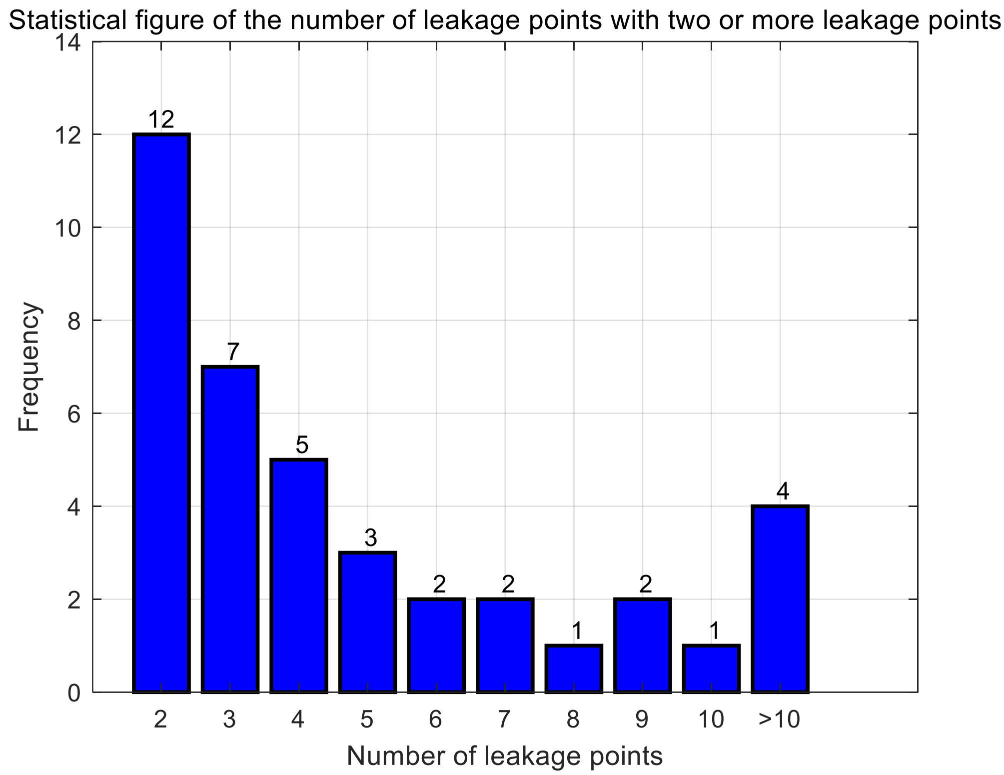

Figure 6. Statistical figure of the number of leakage points with two or more leakage points.

It can be observed from Figure 6 that the distribution of the number of leakage points in residential constructions with two or more leakage points decreases, with the characteristics of gradually leveling off from high to low. This feature is consistent with a real-life situation, indicating that the test data conform to the law of random distribution and are effective.

2.4.2. Analysis of Leakage Rank Distribution in Residential Construction

According to the classification standard for the residential construction leakage problem constructed in the previous section, the non-leakage situation is a four-level leakage. A third-level leakage grade indicates that there is only one leakage point, and the leakage area is much smaller than 0.1 m^2. The second- and first-level leakage grades indicate that there are two to six leakage points and seven or more leakage points, respectively. From the descriptive statistics of the test, it can be observed that the water spray tests were conducted 1947 times, of which the number of leakages was 432, and the probability of a four-level leakage grade without leakage was 0.7781. In the 432 leakage problem tests, there were 393 cases with one leakage point, and the probability of a three-level leakage grade corresponding to a leakage problem in residential construction was 0.2019. This indicates that the three-level leakage grade is still common in real life, which will cause problems for ordinary residents. Objectively, it is necessary to have a set of guarantee mechanisms to solve the problem of residential leakage quickly. There were 29 and 10 instances of two to six leakage points and seven or more leakage points, respectively, and the probabilities of the second- and first-level leakage grades corresponding to the leakage problem of residential construction were 0.0149 and 0.0051, respectively. The probability of multiple leakage points was significantly less than that of a single leakage point, which indicates that the difficulty in solving the leakage problem of residential construction is not due to there being many leakage points and the leakage situation being complex but due to the occurrence rate being high and the claim for damage being higher. This situation is often caused by irregularities in the construction process, demonstrating the importance of strengthening the supervision of the construction process. The distribution law for each grade of the leakage problem in residential construction is listed in Table 4.

Table 4. The distribution law of each grade of leakage problem.

Leakage Grade	First-Level	Second-Level	Third-Level	Fourth-Level
probability	0.0051	0.0149	0.2019	0.7781

Insurance claims are based on the inherent defects identified, so the fourth-level leakage does not involve claims and loss rules. In probability theory, the sum of all possibilities is required to be 1, that is, $\sum p_i = 1$. Therefore, the normalized distribution law of leakage problems in residential construction was selected for an in-depth analysis in the next analysis. First, the leakage grade of residential engineering was recorded as $S_k, k = 1, 2, 3, 4$, and the conditional probability was introduced when analyzing the probability of each leakage level.

Because the fourth-level leakage problem indicates that there is no leakage in residential construction, there are no insurance claims in this case. Therefore, the probability of claim settlement caused by leakage problems in residential construction is $1 - P(x = S_4)$, and the normalized probability calculation formula for the remaining levels is as follows:

$$P^*(x = S_i) = \frac{P(x = S_i)}{1 - P(x = S_4)} \tag{1}$$

After eliminating the four-level leakage grade that does not involve claims, the normalized distribution law was obtained, as listed in Table 5:

Table 5. The normalized distribution law of each grade of leakage problem.

Leakage Grade	First-Level	Second-Level	Third-Level	Fourth-Level
normalized probability (p_i)	0.0230	0.0671	0.9099	-

As listed in Table 5, the leakage problem of residential construction involved a small probability of serious defects, and more serious defects cause heavy claims, most of which are three-level leakage problems with lighter claims. Such microleakages will be completely resolved with the repair of the claim and will not have a cumulative impact on the long-term structural integrity. However, more than 90% of leakage problems will increase the number of claims, resulting in higher personnel and testing costs, which will bring challenges to the implementation of inherent defect insurance. For the leakage problem of multiple leakage points, the repair cost is proportional to the number of leakage points. Therefore, it is necessary to construct a suitable distribution to fit the number of leakage points, so as to obtain the loss of multiple leakage points.

However, there is no research on the loss law of leakage in residential construction that puts forward a test for rate determination and actuarial analysis of inherent defect insurance. The insurance company's ratemaking is often the function of the expectation of the claims process. The lack of accurate leakage problem loss distribution will lead to errors in the determination of the expectation of the claim process. In this way, it is difficult for insurance companies to determine the premium of insurance and quantify the risk in insurance. This phenomenon also largely inhibits insurance companies' willingness to participate, which is not conducive to the promotion of inherently defective insurance. There were significant differences in the distribution of losses and claims for different levels of leakage. Therefore, it is necessary to construct a corresponding loss law model for different leakage grades and sort out the loss law of leakage problems in residential construction to provide a corresponding theoretical basis and model tools for insurance claims.

3. The Loss Law Model of Leakage Problem in Residential Construction

3.1. The Loss Law of Single Leakage Point

It can be observed from the empirical analysis that there were some differences in the distribution probabilities of different grades of leakage points. Therefore, it is necessary to construct a corresponding loss law model for different levels of leakage problems. When constructing a loss law model, it is necessary to first clarify the loss law of a single leakage point. Because the principle of inherent defect insurance is 'to repair instead of claim,' it focuses on solving residents' problems in real life. Therefore, the loss of a single leakage point for the leakage problem of residential construction can be converted into the cost of repairing the leakage point.

The random variable ω was recorded as the cost of repairing a single leakage point. To facilitate the construction of the following model, the random variable ω was set as a constant, and ω was determined by the project cost. Considering the dormitory building of the Laiyang Campus of Qingdao Agricultural University as an example, Li analyzed the maintenance cost of leakage points based on scientifically setting the engineering work amount, and the material maintenance cost of the room with a residential leakage problem was determined to be CNY 2119.52 based on the content of the Shandong Province Construction Project Cost Project Composition and Calculation Rules [31]. Zhou used the earned value method to analyze the cost of leakage maintenance in a residential district in Kunming, Yunnan Province, and identified that the proportion of the material maintenance cost of the leakage problem to the total maintenance cost was approximately 30.28% [32]. The proportion of material maintenance costs in Yunnan Province was extended to Shandong Province, and the total maintenance cost of a room with leakage problems was CNY 6999.83.

Because the water spray and storage tests in this study were conducted in the same room, the results of the tests are also relevant to the number of leakage points in residential constructions with leakage problems. By calculating the mathematical expectation of 432 leakage cases in Figure 4, it can be concluded that the expectation of the number of leakage points in the room with leakage problems was 1.375, which means that the total maintenance cost of a single leakage point was approximately CNY 5091.

Affected by the degree of economic development between regions, the maintenance material cost of single leakage point calculated according to the Shandong Province Construction Project Cost Project Composition and Calculation Rules will also change. Therefore, in order to promote inherent defect insurance throughout China, it is necessary to introduce regional coefficients to adapt to different repair costs between regions. By analyzing the engineering work amount in the Li study, a total of 20 materials involved were considered as variables, and the unit price of each material was recorded as δ_i $i = 1, 2, \ldots, 20$ [31]. Correspondingly, the unit price of the material in the converted region is denoted as δ_i' $i = 1, 2, \ldots, 20$. The conversion coefficient between regions can be expressed as:

$$\delta = \frac{\sum_{i=1}^{20} \alpha_i \delta_i'}{\sum_{i=1}^{20} \alpha_i \delta_i} \quad (2)$$

α_i is a weight coefficient, determined by the amount of work used in the engineering work amount. The introduction of regional coefficients can address regional economic disparities in repair costs.

3.2. The Loss Law of Different Levels of Leakage Problems

To better understand the distribution law of the leakage, it is necessary to set the random variable distribution of the first-, second-, and third-level leakage grade losses and fit the distribution. Based on the corresponding loss law combined with the loss law of the leakage point, a loss law model of the leakage problem in residential construction was constructed.

3.2.1. First-Level Leakage Grade

As shown in Figure 5, in the water spray and storage tests with more than seven leakage points, except for two cases of seven and nine leakage points, the rest of the tests were conducted once. This shows that in the case of more than seven leakage points, the probability of each number of leakage points is almost equal; therefore, the distribution of the leakage level can be fitted by a uniform distribution. The maximum number of leakage points in the water spray and storage tests was 19, which was significantly different from the number of leakage points in the other watering tests. Therefore, to cover as many situations as possible, the upper limit of the number of leakage points in residential construction was set to 19. By substituting parameters 7 and 19 into the probability density function of uniform distribution, the probability density function of the number of leakage points in the first-level leakage grade of residential construction was obtained as follows:

$$f(x) = \begin{cases} \frac{1}{12}, 7 \leq x \leq 19 \\ 0, \quad other \end{cases} \tag{3}$$

Because water spray and storage tests are carried out in residential constructions that have already been built and are awaiting delivery, there is obviously no significant difference in the status of newly built homes for different types of residential constructions.

By introducing the variable ω of a single leakage point's loss into the probability density function of the number of leakage points in the first-level leakage of residential construction, the loss model of the first-level leakage grade of residential construction leakage problem was obtained. Because the number of leakage points in the first-level leakage grade was determined to be $[7, 19]$ based on the standard and test results, the loss model of the first-level leakage grade of the leakage problem in residential construction is as follows:

$$W_1 = \int_7^{19} x f(x) \cdot \omega dx \approx 66,183 \tag{4}$$

W_1 is the loss expectation of residential construction leakage under the first-level leakage grade. This indicates that the average loss caused by the first-level leakage grade was approximately CNY 66,183.

3.2.2. Second-Level Leakage Grade

As shown in Figure 5, the frequency of the number of leakage points in the second-level leakage grade of residential construction decreased, and the rate of decrease gradually decreased, which is a concave function. According to the central limit theorem, when the number of independent random variables continues to increase, the distribution of its sum tends to be normal distribution, which is in line with the characteristics of large insurance coverage and mutual independence. At the same time, the natural decline law of the second-level leakage conforms to the morphological characteristics of the descending section of the normal distribution, but it is necessary to shift the normal distribution curve to a certain extent, which means that the Gaussian distribution representing the generalized normal distribution is the best fitting function. Therefore, a Gaussian function was selected to fit the second-level leakage grade of the residential construction leakage problem. The fitting results are shown in Figure 7.

As shown in Figure 7, the distribution of the second-level leakage grade of the residential construction leakage problem obeyed the Gaussian function, and the R^2 value of the fitting was 0.98947, indicating that the function fitting effect was good. Therefore, the distribution of the second-level leakage grade of the leakage problem in residential construction can be regarded as a Gaussian function. The basic equation of the Gaussian function used for function fitting is expressed as follows:

$$y = y_0 + \frac{A}{w \cdot \sqrt{\pi/2}} \cdot e^{-2 \cdot \left(\frac{x - x_c}{w}\right)^2} \tag{5}$$

The values of the Gaussian function parameters obtained by MATLAB fitting are listed in Table 6.

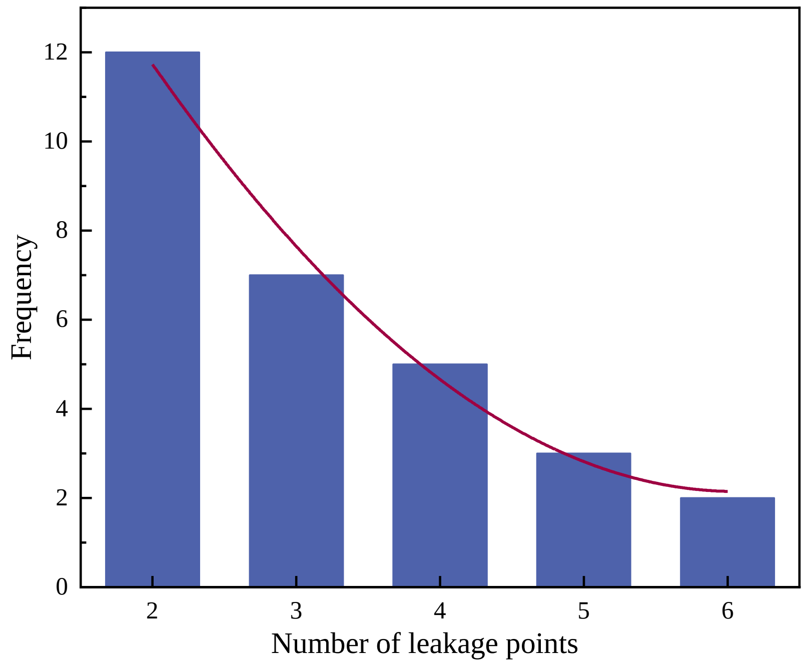

Figure 7. Second-level leakage grade function fitting figure of residential construction.

Table 6. Table of Gaussian function fitting coefficients.

Coefficient	y_0	x_c	w	A
Value	229.08962	6.0649	27.67339	−7871.18296

Because the probability density function requires that the area enclosed by the function and the x-axis is 1, it is necessary to normalize the fitted Gaussian function, which requires processing the Gaussian function and calculating the definite integral on the interval [2, 6]. Figure 7 shows the geometric meaning of the definite integral of the Gaussian function on the interval [2, 6] (as shown in the blue part of the Figure 8).

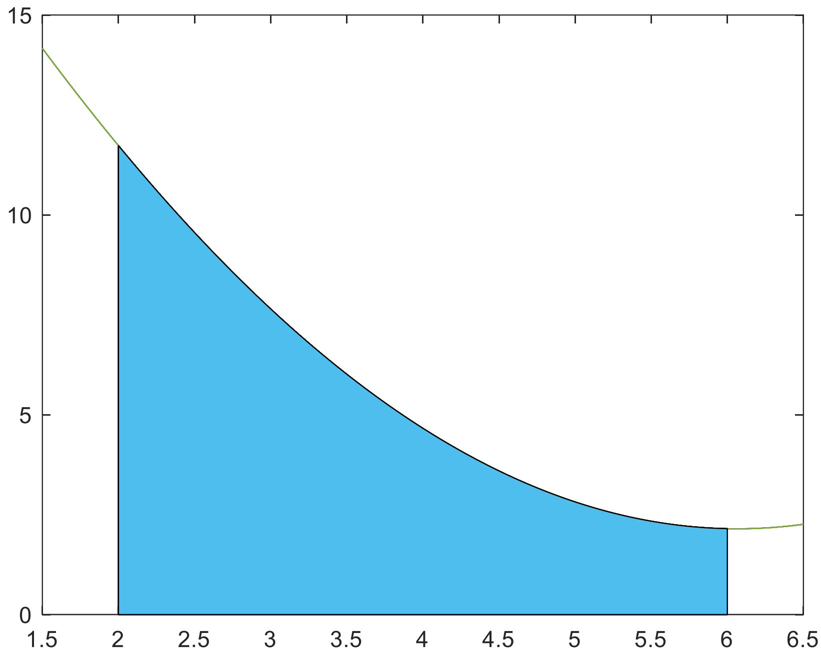

Figure 8. The geometric meaning of the definite integral of the Gaussian function.

To better calculate the value of the definite integral, $B = \frac{A}{w \cdot \sqrt{\pi/2}}$, $t = \frac{x - x_c}{w}$, $\bar{t} = \frac{6 - x_c}{w}$, $\underline{t} = \frac{2 - x_c}{w}$, and the definite integral of the fitted Gaussian function on the interval $[2, 6]$ is expressed as follows:

$$\int_2^6 y dx = \int_2^6 y_0 dx + B \int_2^6 e^{-2(\frac{x - x_c}{w})^2} dx = \int_2^6 y_0 dx + \frac{1}{w} \int_{\underline{t}}^{\bar{t}} e^{-2t^2} dt \quad (6)$$

$\int_{\underline{t}}^{\bar{t}} e^{-2t^2} dt$ is expanded using the Taylor formula to obtain:

$$\begin{aligned} \int_{\underline{t}}^{\bar{t}} e^{-2t^2} dt &= \int_{\underline{t}}^{\bar{t}} \left[1 + \left(-2t^2\right) + \frac{\left(-2t^2\right)^2}{2!} + \ldots + \frac{\left(-2t^2\right)^n}{n!} + \ldots \right] dt \\ &= \int_{\underline{t}}^{\bar{t}} \sum_{n=0}^{\infty} \frac{\left(-2t^2\right)^n}{n!} dt \\ &= \int_{\underline{t}}^{\bar{t}} \sum_{n=0}^{\infty} \frac{(-2)^n}{n!} \cdot t^{2n} dt \\ &= \sum_{n=0}^{\infty} \frac{(-2)^n}{n!} \cdot \frac{t^{2n+1}}{2n+1} + C|_{\underline{t}}^{\bar{t}} \end{aligned} \quad (7)$$

The value of $\int_{\underline{t}}^{\bar{t}} e^{-2t^2} dt$ obtained by the interpolation method was approximately 21.684. By substituting the results into the fitted Gaussian function equation, the normalized probability density function of the second-level leakage grade of the residential construction leakage problem was obtained as follows:

$$f(x) = \begin{cases} 10.565 - 10.467 e^{-2 \cdot (\frac{x - 6.0649}{27.67339})^2}, 2 \leq x \leq 6 \\ 0, \quad other \end{cases} \quad (8)$$

The variable ω of a single leakage point's loss was introduced into the probability density function of the number of leakage points in the second-level leakage grade of residential construction, and the loss model of the second-level leakage grade of residential construction leakage was obtained. The loss model of the second-level leakage grade of the leakage problem of the residential construction was constructed as follows:

$$W_2 = \int_2^6 x f(x) \cdot \omega dx \approx 17,273.37 \quad (9)$$

W_2 is the loss expectation of residential construction leakages under the second-level leakage grade. This indicated that the average loss caused by the second-level leakage grade was approximately CNY 17,273.37.

3.2.3. Third-Level Leakage Grade

According to the classification level provided by the Code for Acceptance of Construction Quality of Waterproof, the three-level leakage grade of residential construction leakage problems only involves one leakage point. Therefore, it was unnecessary to convert the data into a continuous distribution to fit this trend. Because this grade is regarded as other cases, except for one leakage point, the distribution of this grade can be represented by a 0–1 distribution. The loss model for the three-level leakage grade of the residential construction leakage problem was obtained as follows:

$$W_3 = \omega \approx 5091 \quad (10)$$

W_3 is the loss expectation of residential construction leakages under the third-level leakage grade. This indicates that the average loss caused by the third-level leakage grade was approximately CNY 5091.

3.3. The Loss Law of Leakage Problem in Residential Construction

From the previous analysis, it can be observed that $W_i, i = 1, 2, 3$ was the average loss that could be caused at each level of leakage problems in residential construction. Through an analysis of the loss of each leakage grade, the probability p_i of each leakage grade obtained by water spray and storage tests can be introduced, and the loss law of all levels of the leakage problems can be integrated. Table 7 lists the distribution law of the leakage loss for each grade.

Table 7. The distribution law of leakage loss of each grade.

Leakage Grade	W_1	W_2	W_3
Probability (p_i)	0.0230	0.0671	0.9099

Finally, by introducing the regional coefficients obtained in the previous section, the loss expectation of the residential construction leakage problem is obtained by weighting as follows:

$$E(W) = \delta \cdot \sum_{i=1}^{3} p_i \cdot W_i \approx 7328\delta \tag{11}$$

According to the data on inherent defect insurance claims in Shanghai, the average claim amount for five-year waterproof and thermal insulation projects in this area was CNY 8836.11 [7,8]. This is of the same order of magnitude as the leakage loss calculated in this study, and the losses are essentially the same, which shows that the model constructed in this study is reasonable and effective. Compared with the Shanghai IDI insurance claims data, the leakage loss calculated in this study was smaller. On the one hand, because thermal insulation projects involve many dangerous situations, such as the shedding of the external thermal insulation layer, the average claim amount of the thermal insulation project is greater than that of the leakage problem. On the other hand, this is ascribable to the higher cost of materials and labor in Shanghai compared with Shandong and Yunnan Provinces selected in this study.

To better reflect the loss of leakage problems in residential construction, the total leakage loss law of residential construction was further summarized based on the loss law of each grade to provide model tools and theoretical support for insurance companies. Because the modeling of the first and second leakage levels is based on the occurrence number of the leakage point number as the dependent variable, it was deemed necessary to transform it into the distribution of the leakage point number as the dependent variable in the total loss law of the leakage problem of residential construction. Linear interpolation was used to replace the missing parts of the function between each level. The probability function of the leakage problem in residential construction is as follows:

$$f(x) = \begin{cases} 0.9099 & , x = 1 \\ -0.8827x + 1.7926 & , 1 < x < 2 \\ 0.53 - 0.525e^{-2 \cdot \left(\frac{x - 6.0649}{27.67339}\right)^2} & , 2 \le x \le 6 \\ -0.0027x + 0.0212 & , 6 < x < 7 \\ 0.0023 & , 7 \le x \le 19 \\ 0 & , other \end{cases} \tag{12}$$

Figure 9 shows the probability figure drawn based on the loss function of the leakage problem in residential construction. As shown in Figure 9, the probability of the number of leakage points in residential construction decreased sharply in two or more cases, indicating that the leakage problem of a single leakage point was the main part of the leakage problem of residential construction. It can also be observed from the loss model for each level of the leakage problem that the loss expectation $p_3 \cdot W_3$ of the third-level leakage grade with only one leakage point accounted for more than half of the total leakage distribution.

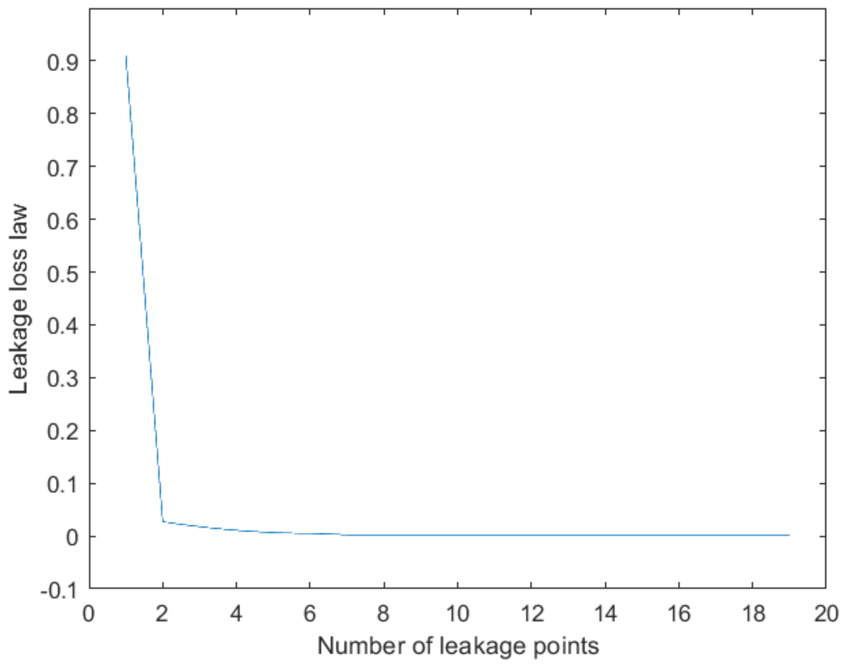

Figure 9. Probability function figure of leakage point.

By multiplying the number of leakage points by its probability function, the loss law function of the leakage problem of random variable residential construction was obtained, which can be regarded as $g(x) = x \cdot f(x)$. Because the intervals $(1,2)$ and $(6,7)$ were functions fitted by linear interpolation, a new linear interpolation was performed on these two intervals to ensure the continuity of the loss function. The change in the regular function X of the loss of leakage problem in residential construction is shown in Figure 10:

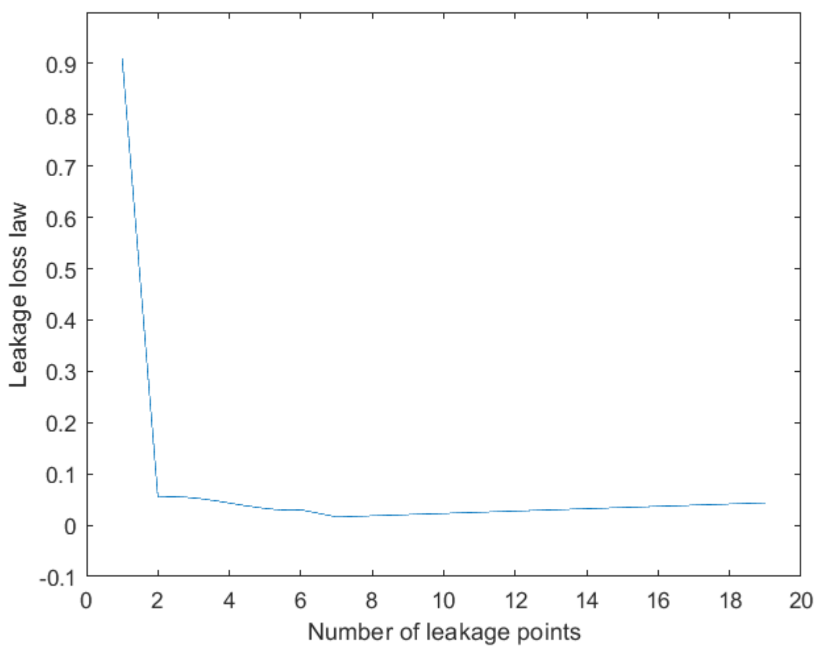

Figure 10. Function figure of leakage loss law.

As shown in Figure 10, the loss of residential construction leakage was primarily concentrated in the case of a single leakage point. In the case of multiple leakage points, the loss first decreased and then increased, and the minimum loss occurred when the number of leakage points was seven. This situation belonged to the case where the number of leakage points was the least in the first-level leakage grade. In this case, the probability of occurrence was low and the number of leakage points was relatively small.

4. Conclusions

As the most common problem in terms of the quality of residential construction, leakage has the highest proportion of complaints, and there has been no research on quantitative law. In this study, to address the leakage issue in residential construction, 1947 water spray tests and 2333 water storage tests were conducted on 18 construction projects to be built, and 432 leakage cases were analyzed empirically. These leakage conditions were graded based on the classification grade provided by the Code for Acceptance of Construction Quality of Underground Waterproofing, and their distribution rules were statistically analyzed. Subsequently, a loss law model of the leakage problem in residential construction was constructed, which provided model tools and a theoretical basis for the promotion and implementation of inherent defect insurance.

From the loss law model of the residential construction leakage problem, it can be observed that the single leakage point of the residential construction leakage problem was in the majority, and the proportion of the three-level leakage grade was relatively large, which also led to the loss of residential construction leakage problem, primarily concentrated on the single leakage point problem. It can be observed that the leakage problem in residential construction is frequently uncomplicated, mostly caused by irregularities in the construction process, such as uncompacted concrete vibrating at construction joints and non-compact sealing at scaffold holes and large die bolt holes. Therefore, it is necessary to strengthen the supervision and management of the construction process and the effect of project completion and acceptance to reduce the frequency of the three-level leakage problem with slight losses. In addition, standardized regulations also help to constrain specific construction irregularities, which can effectively reduce the impact of personnel quality on construction quality on the basis of clear construction steps. And then, strengthening the punishment for the detected construction irregularities also helps to reduce these construction irregularities from the standard level.

To reduce the leakage loss of residential projects and improve the quality of residential construction, this study proposes suggestions based on clarifying the responsibilities of all parties and strengthening inspection and punishment. Combined with the policy background of the Chinese government's current promotion of inherent defect insurance, insurance companies and their TIS agencies as third parties can better supervise and manage the construction processes of construction projects. As there is no interest between a third party and the parties involved in the construction, it is helpful to better identify the problems and risk points in the construction process. Simultaneously, insurance companies and TIS agencies will test the overall quality of the construction project before its completion, which also strengthens the acceptance of residential construction. Thus, the occurrence of three-level leakage problems can be avoided as much as possible to reduce the overall loss of leakage problems in residential construction and improve the overall quality of residential construction.

In addition, because there is no relevant specification or research on the loss of a single leakage point, this study sets the loss of a single leakage point as a constant and assumes that the case of multiple leakage points is linear. However, in an actual project, the average loss of a single leakage point is often higher when the number of leakage points is small, and with an increase in the number of leakage points, it gradually decreases and tends to stabilize. Simultaneously, owing to the differences in the degree of economic development in various regions, the repair cost of the leakage points also needs to set different adjustment coefficients. In future studies, a more scientific and accurate leakage point loss model will be developed to explore the law of leakage loss in residential construction.

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