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Research on Collaborative Risk Management Mechanism of Mega Projects: A Tripartite Evolutionary Game Model Considering the Participation of Insurance Institution

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Abstract: The frequent occurrence of mega project accidents has created an issue of risk management and has made its solution highly valued. In the case that the owner is at a regulatory disadvantage, insurance institution can provide a new pattern for risk management of mega projects. The purpose of this paper is to study the impact of insurance institution's participation in mega project risk management on the decision-making of all participants and the promotion of the overall effectiveness of collaborative risk management of all participants. By constructing a tripartite evolutionary game model between the insurance institution, supervision unit and contractor, the conditions of the behavior evolution process of each participant and the important parameters affecting the change in behavior strategies are analyzed. The results indicate that the participation of insurance institution can promote the risk management investment of the supervision unit and contractor, and punitive measures can make participants pay more attention to the losses caused by the occurrence of risks In order to encourage insurance institution to participate in risk management of mega projects, incentive measures need to be taken to dispel their concerns cost surrounding costs. This study is helpful to reduce the probability of risk occurrence so as to realize the sustainable development of mega projects and provides management suggestions for insurance institution to participate in risk management.

Keywords: mega project insurance; risk management; collaborative mechanism; sustainable development; tripartite evolutionary game

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1. Introduction

With increasing competition in the wave of globalization, many countries have adopted mega projects as an important tool to enhance the status of the global political and economic system [1]. Mega projects account for about 8% of global GDP and face a wide range of difficulties and challenges due to their complexity, uncertainty and multi-interface management [2]. In the process of mega project construction, there are not only risks caused by human factors but also some unpredictable risks due to the deep uncertainty of environmental factors [3,4], which brings great difficulties to the risk management of mega projects [5]. For example, in 2012, during the assembly of a tunnel under construction in Nevada, USA, a cement slab became loose under pressure, resulting in a collapse accident, resulting in the death of one worker and the injury of another. In 2023, a newly installed 500 m girder section of a bridge under construction in Bangkok, Thailand, collapsed due to instability of the bridge structure and inadequate on-site risk management, killing an engineer and a worker and injuring 17 others. The frequent occurrence of accidents has exposed the lack of risk management capabilities of all parties involved in the construction and the imbalance of the risk management structure.

The owner, supervision unit and contractor are the main stakeholders in the risk management of mega projects. The temporary nature of mega projects, the uniqueness of the tasks and the diversity of participants increase the difficulty and pressure of the owner's management [6]. Due to the information asymmetry between stakeholders, it is difficult for the owner to directly supervise the risk management work of the supervision unit and the contractor. In order to pursue high profits, the supervision unit and the contractor may take advantage of information asymmetry to collude in rent-setting and rent-seeking [7,8], which lays hidden dangers for risk prevention and runs counter to the goal of achieving the sustainability of mega projects. Therefore, it is of great significance to strengthen the supervision of the supervision unit and contractor for the risk management of mega projects.

Mega projects involve multiple stakeholders in the construction process [9–11], and stakeholders are closely related to risk management [12–14]. At present, mega project insurance is an important risk management means for owner to reduce accident losses, and insurance institution has become the main bearers of project risk losses. However, due to the small number of mega projects, it is difficult for insurance institution to share the risk by undertaking a sufficient number of insurance contracts, and at the same time, it is also unable to obtain data and experience from sufficient historical data to calculate the optimal insurance rate [15]. In order to avoid huge claims, participating in risk management becomes one option for insurance institution. As early as 2003, due to huge losses, the Insurance Institute of the United Kingdom and the British Tunnelling Association jointly published the "British Joint Code of Risk Management for Tunnelling Projects" to jointly manage the risk of insured projects of tunnel engineering. In 2015, China's National Development and Reform Commission issued the "Guiding Opinions of the China Insurance Regulatory Commission on Matters Concerning the Insurance Industry's Support for Mega project Construction", proposing to support insurance companies to give full play to their professional advantages, provide professional risk management advice for mega project construction, take effective disaster prevention and mitigation measures and reduce the incidence of risk accidents. In practice, there have also been many examples of insurance institutions participating in risk management. The Diamer Bhasha project in Pakistan is underwritten by Ping An Property & Casualty Insurance Company of China, with an insurance amount exceeding 2.65 billion US dollars. Ping An Property & Casualty Insurance Company of China not only provides construction risk protection for a project but also provides long-term services such as on-site risk supervision and safety production training. The insured amount of China's Hong Kong-Zhuhai-Macao Bridge is as high as CNY 27.8 billion, which is underwritten by a co-insurance body formed by The People's Insurance Company of China and five other insurance companies and reinsured to the Swiss Reinsurance Company and Zurich Insurance Group. In the process of construction, the insurance industry fully participated, effectively prevented risks, controlled losses and established a global project risk management system. The participation of insurance institution in risk management can not only bring more management experience and management knowledge and make up for the lack of information from the owner but also improve the supervision intensity of the owner and improve the ability to identify and manage misconduct of the supervision unit and contractor. Although participating in risk management will increase the costs of insurance institution, in order to maximize the interests of economic benefits, insurance institution hopes to take regulatory measures to reduce the probability of project risks and avoid huge claims. At the same time, insurance institution participates in risk management and share a part of the risk, reducing the possibility that improper risk allocation will damage the relationship between the owner and the contractor [16]. To sum up, based on mega construction projects such as tunnel projects and bridge projects and the evolutionary game theory, this paper constructs a tripartite evolutionary game model of the insurance institution, supervision unit and contractor based on the maximization of self-interest as the behavior orientation of each subject and solves the following problems: Firstly, how will the changes in key parameters affect the dynamic behavior decisions of the three parties in the game when an insurance institution participates in risk management? Secondly, how should the collaboration in risk management between the insurance institution, supervision unit and contractor occur?

The remainder of this paper is as follows: Section 2 presents a literature review. Section 3 focuses on the establishment and analysis of the tripartite evolutionary game model. In Section 4, a simulation analysis is carried out. The final part presents the conclusions of the paper.

2. Literature Review

2.1. Collaborative Management of Mega Project Risks

Project stakeholders have proven to be critical to project success [17–19]. Due to different claims, interests and cultural backgrounds, most project risks are relevant to stakeholders [20]. Aladağ et al. [21] identified and determined the role of stakeholder-related risks in mega projects based on literature surveys and case studies and found that "improper partner selection", "insufficient relationship with the employer (public)" and "incompetent contractor selection" were the key risk factors. Therefore, in recent years, scholars have mostly carried out research on risk management of mega projects based on stakeholder theory. Xia et al. [22] found that certain stages of the risk management and stakeholder management processes can be integrated together to achieve mutual benefit of the management process and management results. Castelblanco et al. [12] used multi-layer network analysis to identify potential problems by studying the relationship between stakeholders' interests and risks. In addition, some scholars have conducted research on how stakeholders are involved in risk management. Cuppen et al. [23] created an analytical approach to stakeholders in large-scale energy infrastructure projects to assist risk governance by initiating a participatory process of external stakeholders. Based on literature analysis and clear set qualitative comparative analysis methods, Yang and Cheng [24] found that multi-agent participation can help construction projects cope with risks and crises and promote the success of construction projects. Based on practical experience, promoting cooperation among mega project stakeholders is conducive to improving a project's performance, and efficient cooperation can help to cope with the complexity and uncertainty in the construction of mega projects [25,26]. Mega projects involve multiple stakeholders in the construction process, and how to promote the collaboration and cooperation of multiple stakeholders in the process of risk management of mega projects has always been the core issue of research in related fields. Zhang et al. [27] explored the cascading effect of interaction and co-innovation between mega project stakeholders, and the results showed that collaboration and interaction between stakeholders are essential to address the challenges and risks of innovation. Galvin et al. [28] found that alliance contracts between stakeholders in large-scale projects can limit opportunistic behavior and encourage collaborative behavior and can also improve alignment of goals, risks and rewards. Zheng et al. [29] constructed a qualitative relational behavior model based on the value network of stakeholders and found that stakeholders can adopt appropriate strategies to deal with risks through cooperation. The above studies prove that the collaboration of multiple stakeholders in the process of risk management of mega projects has an obvious positive effect on risk management, but the collaboration mechanism and behavior strategies between stakeholders still need to be further studied.

2.2. The Role of Project Insurance in Risk Management

Under the severe form of risk management, the insurance of project construction entities from insurance institution has become an important means of risk management. Kokkaew et al. [30] proposed a new model of dynamic risk insurance that can improve risk management practices for large-scale construction projects full of uncertainty. Akinradewo et al. [31] evaluated the factors influencing insurance as a contractor's risk response tool, found that insurance is effective in managing external risks and suggested that construction team participants and stakeholders should encourage the use of different insurance coverage in construction projects.

At present, scholars have carried out fruitful research on project insurance. Chen and Wang [32] concluded that the contractor's insurance model is more suitable for EPC contracts than the owner's insurance model, which can control risks more effectively. Liu et al. [33] constructed an extended theoretical model of planning behavior and found that risk perception and past experience have a significant impact on contractor's attitudes and behavior control regarding construction insurance purchase intentions. Owusu-Manu et al. [34] investigated the insurable risks affecting the operation of complex construction projects in developing countries to help contractors determine which risks they are more willing to insure. In view of the deep uncertainty risk and high loss of mega projects, the insurance institution, as the transferor of risks, has sufficient motivation to participate in the risk management of mega projects. Zhu et al. [15] found that the involvement of insurance companies in risk management can motivate contractors to be willing to carry out more comprehensive risk management work and have a good externality effect on the owner. At present, the existing research on project insurance mainly focuses on the project insurance method, insurance coverage, insurance willingness and other aspects, and there are few studies on how insurance institution participates in the risk management of mega projects and the impact mechanism of participation. Therefore, this paper will make up for the above research shortcomings and conduct research on insurance institution as participants in the risk management of mega projects, so as to provide a theoretical reference and policy suggestions for insurance institution to participate in risk management and achieve the sustainable development goals of mega projects.

3. Evolutionary Game Model Construction

3.1. Model Assumptions

Due to the large scale, long duration, large number of stakeholders and far-reaching impact of the project, mega projects have a high degree of uncertainty and complexity compared with other projects [35]. The risks faced by traditional projects are mostly familiar, predictable and controllable, while the interrelationships between mega project risks are complex, and the risk consequences caused by one risk factor may in turn become new risk factors and lead to the occurrence of other risks [36]. At the same time, it is difficult to assess the overall risk management capability of mega projects because of the huge investment amount and strong uniqueness compared with traditional projects. Unlike general project insurance, the uniqueness of mega project insurance makes it difficult for insurance institution to diversify risks by undertaking a large number of similar insurance contracts. Based on this, it is very difficult for insurance institution to increase the intensity of risk management through conventional risk management methods, which makes the insurance institution more inclined to participate in the risk management of mega projects to avoid huge claims caused by accidents.

At present, the ways in which insurance institution participates in risk management are still in the exploratory stage in the relevant literature. Based on the actual situation, this paper reasonably analyzes the decision-making behavior and interest demands of each participant in the risk management of mega projects, allows insurance institution to participate in the risk management of mega projects by cooperating with the owner, supervises the risk management of the supervision unit and contractor and implements corresponding punitive measures while making up for the information disadvantages of the owner, so as to establish a collaborative risk management mechanism between the insurance institution, supervision unit and contractor.

On the basis of this mechanism, this paper constructs a tripartite evolutionary game model including the insurance institution, supervision unit and contractor and analyzes the impact of the insurance institution's participation in the risk management of mega projects and the complex dynamic evolution mechanism of tripartite participants. The game relationship is shown in Figure 1.

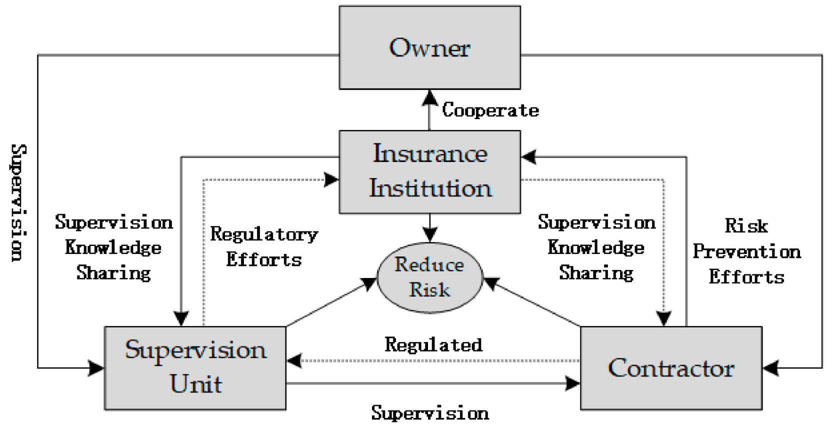

Figure 1. The relationship between the owner, insurance institution, supervision unit and contractor.

Assumption 1. *Suppose the insurance institution's strategy is "participation" and "non-participation", the supervision unit's strategy is "normal supervision" and "abnormal supervision", and the contractor's strategy is "strong prevention" and "weak prevention". The probability of participation of the insurance institution is $x(0 \le x \le 1)$, and the probability of non-participation is $1 - x$. The probability of normal supervision by the supervision unit is $y(0 \le y \le 1)$, and the probability of abnormal supervision is $1 - y$. The probability of the contractor taking strong precautions is $z(0 \le z \le 1)$ and the probability of taking weak precautions is $1 - z$.*

Assumption 2. *If the accident occurs and the insurance institution needs to pay the L_i, the supervision unit will pay L_s reputation and economic loss, and the contractor will pay the reputation and economic loss L_c. The probability of an accident is related to the strategic choice and uncertainty factors of the insurance institution, the supervision unit and the contractor. When the insurance institution chooses to participate, the supervision unit chooses normal supervision and the contractor chooses strong prevention, and the probability of accident is P_1; when the insurance institution chooses not to participate, the supervision unit chooses normal supervision and the contractor chooses strong prevention, and the probability of accident is P_2; when the insurance institution chooses to participate, the supervision unit chooses abnormal supervision and the contractor chooses strong prevention, or the supervision unit chooses normal supervision and the contractor chooses weak prevention, and the probability of accident is P_3; when the insurance institution does not participate, the supervision unit chooses abnormal supervision and the contractor chooses strong prevention, or the supervision unit chooses normal supervision and the contractor chooses weak prevention, and the probability of accident is P_4; when the insurance institution chooses to participate, the supervision unit chooses abnormal supervision and the contractor chooses weak prevention, and the probability of accident is P_5; when the insurance institution chooses not to participate, the supervision unit chooses abnormal supervision and the contractor chooses weak prevention, and the probability of accident is $P_6(0 < P_1 < P_2 < P_3 < P_4 < P_5 < P_6 < 1)$. Assuming that the positive impact of insurance institution involvement on the prevention of risk is the same, there is $P_2 - P_1 = P_4 - P_3 = P_6 - P_5$.*

Assumption 3. *The basic income of the insurance institution is E_i. The insurance institution participates in risk management, cooperates with the owner, supervises the supervision unit and contractor and pays a certain amount of supervision and knowledge sharing costs D_i. When the supervision unit chooses abnormal supervision, the supervision unit is fined F_s, and when the supervision unit chooses normal supervision, the knowledge sharing brought by the participation of the insurance institution enables the supervision unit to save supervision costs R_s. When a contractor chooses weak prevention, a fine of $F_{c1}(F_s < F_{c1})$ is imposed on the contractor, and when the contractor chooses strong prevention, the knowledge sharing brought about by the involvement of the insurance institution allows the contractor to save the cost of prevention R_c. In order to encourage the participation of the insurance institution, the owner will give the insurance institution a subsidy for the punishment of non-standard behavior of supervision unit and contractor.*

Assumption 4. *The basic income of the supervision unit is E_s. If the supervision unit chooses normal supervision, it means that it will supervise the contractor's risk management work in accordance with regulations during the construction of the project, and the supervision unit will pay D_s more supervision costs than abnormal supervision. When the contractor takes weak prevention, the supervision unit will order the contractor to carry out rectification, making it pay the cost of rectification $F_{c2}(F_{c2} < F_{c1})$. If the supervision unit chooses the abnormal supervision strategy, the supervision unit will have opportunistic behavior, and if the contractor chooses the weak prevention strategy at this time, the supervision unit and the contractor will reach an agreement and obtain the agreement benefit $B(B < D_c)$.*

Assumption 5. *The basic income of the contractor is E_c. When the contractor chooses strong prevention, it will carry out risk management in strict accordance with the standards and scientifically manage and control the potential risk factors and related details in the construction process of the project; at this time, the contractor pays more prevention costs than weak prevention D_c. If the contractor chooses weak prevention, there may be opportunistic behaviors such as mitigating the intensity of prevention and not following the regulations, and if the supervision unit chooses abnormal supervision, the contractor and the supervision unit will reach an agreement, and the contractor will pay the agreement cost $B(B < D_c)$.*

The parameters and their meanings are shown in Table 1.

Table 1. Model parameters and their meanings.

Parameter	Meaning
x	Probability of the insurance institution choosing the "participation" strategy $x \in [0,1]$
y	Probability of the supervision unit choosing the "normal supervision" strategy $y \in [0,1]$
z	Probability of the contractor choosing the "strong prevention" strategy $z \in [0,1]$
E_i	The basic income of the insurance institution
E_s	The basic income of the supervision unit
E_c	The basic income of the contractor
D_i	The cost of insurance institution participation
D_s	The cost paid by the supervision unit for normal supervision over abnormal supervision
D_c	The cost paid by the contractor for strong prevention over weak prevention
P_1	The probability of an accident when the insurance institution participates, and the supervision unit and the contractor all choose an active strategy.
P_2	The probability of an accident when the insurance institution does not participate, and the supervision unit and the contractor all choose an active strategy.
P_3	The probability of an accident when the insurance institution chooses to participate and one of either the supervision unit or contractor chooses a negative strategy.
P_4	The probability of an accident when the insurance institution chooses not to participate and one of either the supervision unit or contractor chooses a negative strategy.
P_5	The probability of an accident when the insurance institution chooses to participate and the supervision unit and contractor choose a negative strategy.
P_6	The probability of an accident when the insurance institution chooses not to participate and the supervision unit and contractor choose a negative strategy.
L_i	The amount that the insurance institution needs to pay in the event of an accident

Table 1. *Cont.*

Parameter	Meaning
L_s	The reputation and economic losses to be paid by the supervision unit if accident occurs
L_c	The reputation and economic losses to be paid by the contractor if accident occurs
B	The rent-seeking costs paid by the contractor after reaching an agreement with the supervision unit or the agreement income obtained by the supervision unit
R_s	The participation of insurance institution enables the supervision unit to save supervision costs
R_c	The participation of insurance institution enables the contractor to save prevention costs
F_s	The owner's fine against the supervision unit
F_{c1}	The owner's fine against the contractor
F_{c2}	When the supervision unit chooses normal supervision and the contractor chooses weak prevention the rectification cost is to be paid by the contractor

3.2. Establishment of the Evolutionary Game Model

According to the assumptions of the model, the evolutionary game income matrix of the insurance institution, supervision unit and contractor is shown in Table 2.

Table 2. Evolutionary game tripartite return matrix.

Strategy Combination	Return Matrix		
	Insurance Institution	Supervision Unit	Contractor
{participation, normal supervision, strong prevention}	$E_i - D_i - P_1L_i$	$E_s - D_s + R_s - P_1L_s$	$E_c - D_c + R_c - P_1L_c$
{participation, normal supervision, weak prevention}	$E_i - D_i + F_{c1} - P_3L_i$	$E_s - D_s + R_s - P_3L_s$	$E_c - F_{c1} - F_{c2} - P_3L_c$
{participation, abnormal supervision, strong prevention}	$E_i - D_i + F_s - P_3L_i$	$E_s - F_s - P_3L_s$	$E_c - D_c + R_c - P_3L_c$
{participation, abnormal supervision, weak prevention}	$E_i - D_i + F_s + F_{c1} - P_5L_i$	$E_s + B - F_s - P_5L_s$	$E_c - B - F_{c1} - P_5L_c$
{non-participation, normal supervision, strong prevention}	$E_i - P_2L_i$	$E_s - D_s - P_2L_s$	$E_c - D_c - P_2L_c$
{non-participation, normal supervision, weak prevention}	$E_i - P_4L_i$	$E_s - D_s - P_4L_s$	$E_c - F_{c2} - P_4L_c$
{non-participation, abnormal supervision, strong prevention}	$E_i - P_4L_i$	$E_s - P_4L_s$	$E_c - D_c - P_4L_c$
{non-participation, abnormal supervision, weak prevention}	$E_i - P_6L_i$	$E_s + B - P_6L_s$	$E_c - B - P_6L_c$

According to evolutionary game theory and expected utility theory, calculate the average expected returns and replicate dynamic equations of the insurance institution, supervision unit, and contractor.

The expected return E_{x1} of the insurance institution choosing the "participation" strategy, the expected return E_{x2} of choosing the "non-participation" strategy and the average expected return $\overline{E}_x$ are as follows:

$$\begin{aligned} E_{x1} = yz(E_i - D_i - P_1L_i) + y(1-z)(E_i - D_i + F_{c1} - P_3L_i) + (1-y)z(E_i - D_i + F_s - P_3L_i) \\ +(1-y)(1-z)(E_i - D_i + F_s + F_{c1} - P_5L_i) \end{aligned} \tag{1}$$

$$E_{x2} = yz(E_i - P_2L_i) + y(1-z)(E_i - P_4L_i) + (1-y)z(E_i - P_4L_i) + (1-y)(1-z)(E_i - P_6L_i) \tag{2}$$

$$\overline{E}_x = xE_{x1} + (1-x)E_{x2} \tag{3}$$

The replication dynamic equation of insurance institution is

$$\begin{aligned} F(x) = \frac{dx}{dt} = x(E_{x1} - \overline{E}_x) = x(1-x)(-D_i + (1-y)F_s + (1-z)F_{c1} - yzP_1L_i + yzP_2L_i \\ -(y+z-2yz)P_3L_i + (y+z-2yz)P_4L_i - (1-y)(1-z)P_5L_i + (1-y)(1-z)P_6L_i) \end{aligned} \tag{4}$$

The expected return E_{y1} of the supervision unit choosing the "normal supervision" strategy, the expected return E_{y2} of choosing the "abnormal supervision" strategy and the average expected return $\overline{E}_y$ are as follows:

$$E_{y1} = xz(E_s - D_s + R_s - P_1L_s) + x(1-z)(E_s - D_s + R_s - P_3L_s) + (1-x)z(E_s - D_s - P_2L_s) + (1-x)(1-z)(E_s - D_s - P_4L_s) \quad (5)$$

$$E_{y2} = xz(E_s - F_s - P_3L_s) + x(1-z)(E_s + B - F_s - P_5L_s) + (1-x)z(E_s - P_4L_s) + (1-x)(1-z)(E_s + B - P_6L_s) \quad (6)$$

$$\overline{E}_y = yE_{y1} + (1-y)E_{y2} \quad (7)$$

The replication dynamic equation of supervision unit is

$$F(y) = \frac{dy}{dt} = y(E_{y1} - \overline{E}_y) = y(1-y)(-D_s + xR_s + xF_s - (1-z)B - xzP_1L_s - (1-x)zP_2L_s - x(1-2z)P_3L_s - (1-x)(1-2z)\,P_4L_s + x(1-z)P_5L_s + (1-x)(1-z)P_6L_s) \quad (8)$$

The expected return E_{z1} of the contractor choosing the "strong prevention" strategy, the expected return E_{z2} of choosing the "weak prevention" strategy and the average expected return $\overline{E}_z$ are as follows:

$$E_{z1} = xy(E_c - D_c + R_c - P_1L_c) + x(1-y)(E_c - D_c + R_c - P_3L_c) + (1-x)y(E_c - D_c - P_2L_c) + (1-x)(1-y)(E_c - D_c - P_4L_c) \quad (9)$$

$$E_{z2} = xy(E_c - F_{c1} - F_{c2} - P_3L_c) + x(1-y)(E_c - B - F_{c1} - P_5L_c) + (1-x)y(E_c - F_{c2} - P_4L_c) + (1-x)(1-y)(E_c - B - P_6L_c) \quad (10)$$

$$\overline{E}_z = zE_{z1} + (1-z)E_{z2} \quad (11)$$

The replication dynamic equation of contractor is

$$F(z) = \frac{dz}{dt} = z(E_{z1} - \overline{E}_z) = z(1-z)(-Dc + xR_c + xF_{c1} + yF_{c2} + (1-y)B - xyP_1L_c - (1-x)yP_2L_c - x(1-2y)P_3L_c - \big(1-x)(1-2y)P_4L_c + x\big(1-y)P_5L_c + (1-x)(1-y)P_6L_c\big) \quad (12)$$

3.3. Analysis of Stability Strategies for Three Participants

According to the stability theorem of differential equations, in order to achieve the optimal state of a dynamic game, when the replicated dynamic equation is zero and its first derivative is less than zero, the choice of each participant is the optimal strategy. Therefore, a stability analysis of the strategies of insurance institution, supervision unit and contractor are carried out as follows:

Calculate the partial derivative of x for the replication dynamic equation of the insurance institution:

$$F'(x) = \frac{d(F(x))}{dt} = x(E_{x1} - \overline{E}_x) = (1-2x)(-D_i + (1-y)F_s + (1-z)F_{c1} - yzP_1L_i + yzP_2L_i - (y+z-2yz)P_3L_i + (y+z-2yz)P_4L_i - (1-y)(1-z)P_5L_i + (1-y)(1-z)P_6L_i) \quad (13)$$

According to the stability theorem of differential equations, the necessary conditions $F(x) = 0$ and $F'(x) < 0$ must be met to reach the evolutionary stability point. According to the replication dynamic equation, it can be obtained: $y_0 = -D_i + F_s + (1-z)F_{c1} - zP_3L_i + zP_4L_i - (1-z)P_5L_i + (1-z)P_6L_i / F_s + zP_1L_i - zP_2L_i + (1-2z)P_3L_i - (1-2z)P_4L_i - (1-z)P_5L_i + (1-z)P_6L_i$. When $y = y_0$, for all x is a steady state and does not change over time, any strategy of the insurance institution is a stable strategy. Because $F_s + zP_1L_i - zP_2L_i + (1-2z)P_3L_i - (1-2z)P_4L_i - (1-z)P_5L_i + (1-z)P_6L_i > 0$, when $y > y_0$, $F'(0) < 0$, $F'(1) > 0$, $x = 0$ satisfies the condition, it is the evolutionary stability point. When $y < y_0$, $F'(0) > 0$, $F'(1) < 0$, $x = 1$ satisfies the condition, it is the evolutionary stability point. Based on the relational y_0, the evolution of the insurance institution's strategy can be drawn, as shown in Figure 2. Under the condition that other parameters remain unchanged, when the D_i increases, the probability of the insurance institution choosing not to participate in the risk management strategy increases. When the F_{c1} increases, the probability of the insurance institution choosing to participate in risk management strategies increases. This shows that the probability of the insurance institution choosing to participate in risk management strategies is inversely proportional to the cost of participation and directly proportional to the punishment of the contractor for weak prevention.

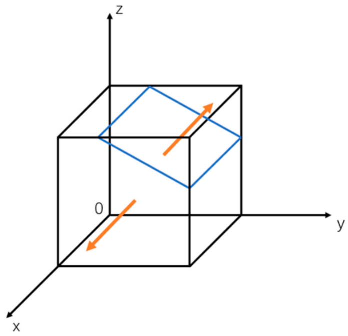

Figure 2. The evolution process of insurance institution strategies.

Calculate the partial derivative of y for the replication dynamic equation of the supervision unit:

$$F'(y) = \frac{d(F(y))}{dt} = y(E_{y1} - \overline{E}_y) = (1-2y)(-D_s + xR_s + xF_s - (1-z)B - xzP_1L_s - (1-x)zP_2L_s \\ -x(1-2z)P_3L_s - (1-x)(1-2z)P_4L_s + x(1-z)P_5L_s + (1-x)(1-z)P_6L_s) \tag{14}$$

Similarly, to reach the evolutionary stability point, the necessary conditions $F(y) = 0$ and $F(y) = 0$ must be satisfied. According to the replication dynamic equation, it can be obtained: $z_0 = -D_s + xR_s + xF_s - B - xP_3L_s - (1-x)P_4L_s + xP_5L_s + (1-x)P_6L_s / -B + xP_1L_s + (1-x)P_2L_s - 2xP_3L_s - 2(1-x)P_4L_s + xP_5L_s + (1-x)P_6L_s$. When $z = z_0$, for all y is a steady state, not changing with time, any strategy of the supervision unit is a stable strategy. If $-B + xP_1L_s + (1-x)P_2L_s - 2xP_3L_s - 2(1-x)P_4L_s + xP_5L_s + (1-x)P_6L_s > 0$, when $z > z_0$, $F'(0) < 0$, $F'(1) > 0$, $y = 0$ satisfies the condition, it is the evolutionary stability point. When $z < z_0$, $F'(0) > 0$, $F'(1) < 0$, $y = 1$ satisfies the condition, which is the evolutionary stability point. In the same way, if $-B + xP_1L_s + (1-x)P_2L_s - 2xP_3L_s - 2(1-x)P_4L_s + xP_5L_s + (1-x)P_6L_s < 0$, when $z > z_0$, $F'(0) > 0$, $F'(1) < 0$, $y = 1$ satisfies the condition, it is the evolutionary stability point. When $z < z_0$, $F'(0) < 0$, $F'(1) > 0$, $y = 0$ satisfies the condition, which is the evolutionary stability point. When $-B + xP_1L_s + (1-x)P_2L_s - 2xP_3L_s - 2(1-x)P_4L_s + xP_5L_s + (1-x)P_6L_s < 0$, according to the relational z_0, the evolution process of the supervision unit strategy can be drawn, as shown in Figure 3. When the D_s increases, the probability of the supervision unit choosing abnormal supervision strategies increases. When the R_s or F_s increase, the probability of the supervision unit choosing normal supervision strategies increases. This shows that the probability of the supervision unit choosing the normal supervision strategy is inversely proportional to the cost and is directly proportional to the cost saved by the insurance institution and the penalty obtained by choosing the negative strategy.

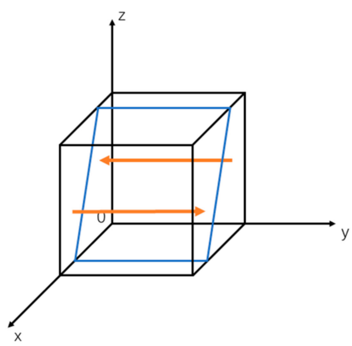

Figure 3. The evolution process of supervision unit strategies.

Calculate the partial derivative of z for the replication dynamic equation of the contractor:

$$\begin{aligned} F\prime(z) = \tfrac{d(F(z))}{dt} = z(E_{z1} - \overline{E}_z) = (1-2z)(-Dc + xR_c + xF_{c1} + yF_{c2} + (1-y)B - xyP_1L_c \\ -(1-x)yP_2L_c - x(1-2y)P_3L_c - \big(1-x\big)(1-2y)P_4L_c + x\big(1-y\big)P_5L_c + (1-x)(1-y)P_6L_c\big) \end{aligned} \quad (15)$$

In the same way, to reach the evolutionary stability point, the necessary conditions $F(z) = 0$ and $F\prime(z) < 0$ must be satisfied. According to the replication dynamic equation, it can be obtained: $x_0 = -Dc + yF_{c2} + (1-y)B - yP_2L_c - (1-2y)P_4L_c + (1-y)P_6L_c / -R_c - F_{c1} + yP_1L_c - yP_2L_c + (1-2y)P_3L_c - (1-2y)P_4L_c - \big(1-y\big)P_5L_c + (1-y)P_6L_c$. When $x = x_0$, for all z is a steady state and does not change over time, any strategy of the contractor is a stable strategy. Because $-R_c - F_{c1} + yP_1L_c - yP_2L_c + (1-2y)P_3L_c - (1-2y)P_4L_c - \big(1-y\big)P_5L_c + (1-y)P_6L_c < 0$, when $x > x_0$, $F'(0) > 0$, $F'(1) < 0$, $z = 1$ satisfies the condition, it is the evolutionary stability point. When $x < x_0$, $F'(0) < 0$, $F'(1) > 0$, $z = 0$ satisfies the condition and is the evolutionary stability point. Based on the relational x_0, the evolution of the contractor's strategy can be plotted, as shown in Figure 4. When the D_c increases, the probability of the contractor choosing weak prevention strategies increases. When the R_c, F_{c1} and F_{c2} increase, the probability of the contractor choosing strong prevention strategies increases. This shows that the probability of the contractor choosing a strong prevention strategy is inversely proportional to the cost and directly proportional to the cost savings of the insurance institution's participation and the penalty obtained by choosing the negative strategy.

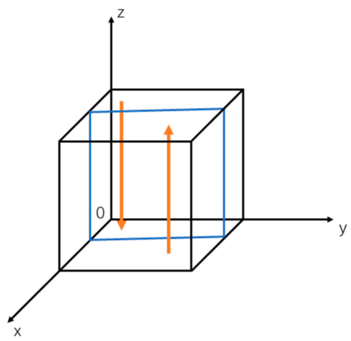

Figure 4. The evolution process of contractor strategies.

3.4. Evolutionary Equilibrium Point and Stability Analysis

According to the method proposed by Friedman, the stability of the equilibrium point of the differential system can be analyzed using a Jacobian matrix (denoted J). The Jacobian matrix of the evolutionary game system is

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \quad (16)$$

Among them,

$$\begin{aligned} \tfrac{\partial F(x)}{\partial x} = (1-2x)(-D_i + (1-y)F_s + (1-z)F_{c1} - yzP_1L_i + yzP_2L_i - (y+z-2yz)P_3L_i \\ +(y+z-2yz)P_4L_i - (1-y)(1-z)P_5L_i + (1-y)(1-z)P_6L_i) \end{aligned} \quad (17)$$

$$\frac{\partial F(x)}{\partial y} = x(1-x)(-F_s - zP_1L_i + zP_2L_i - (1-2z)P_3L_i + (1-2z)P_4L_i + (1-z)P_5L_i - (1+z)P_6) \quad (18)$$

$$\frac{\partial F(x)}{\partial z} = x(1-x)(-F_{c1} - yP_1L_i + yP_2L_i - (1-2y)P_3L_i + (1-2y)P_4L_i + (1-y)P_5L_i - (1-y)P_6L_i) \quad (19)$$

$$\frac{\partial F(y)}{\partial x} = y(1-y)(F_s + R_s - zP_1L_s + zP_2L_s - (1-2z)P_3L_s + (1-2z)P_4L_s + (1-z)P_5L_s - (1-z)P_6L_s) \quad (20)$$

$$\frac{\partial F(y)}{\partial y} = (1-2y)(-D_s + xR_s + xF_s - (1-z)B - xzP_1L_s - (1-x)zP_2L_s - x(1-2z)P_3L_s \\ -(1-x)(1-2z)P_4L_s + x(1-z)P_5L_s + (1-x)(1-z)P_6L_s) \tag{21}$$

$$\frac{\partial F(y)}{\partial z} = y(1-y)(B - xP_1L_s + xP_2L_s + 2xP_3L_s - 2(1-x)P_4L_s - xP_5L_s - (1-x)P_6L_s) \tag{22}$$

$$\frac{\partial F(z)}{\partial x} = z(1-z)(F_{c1} + R_{c2} - yP_1L_c + yP_2L_c - (1-2y)P_3L_c + (1-2y)P_4L_c + (1-y)P_5L_c \\ -(1-y)P_6L_c) \tag{23}$$

$$\frac{\partial F(z)}{\partial y} = z(1-z)(F_{c2} - B + R_{c1} - xP_1L_c + xP_2L_c + 2xP_3L_c + 2(1-x)P_4L_c - xP_5L_c - (1-x)P_6L_c) \tag{24}$$

$$\frac{\partial F(z)}{\partial z} = (1-2z)(-Dc + xR_c + xF_{c1} + yF_{c2} + (1-y)B - xyP_1L_c - (1-x)yP_2L_c - x(1-2y)P_3L_c \\ -(1-x)(1-2y)P_4L_c + x(1-y)P_5L_c + (1-x)(1-y)P_6L_c) \tag{25}$$

Let $F(x) = 0$, $F(y) = 0$ and $F(z) = 0$ to obtain eight pure strategy Nash equilibrium points existing in the game process of the insurance institution, supervision unit and contractor $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(0,1,1)$, $E_5(1,0,0)$, $E_6(1,0,1)$, $E_7(1,1,0)$, $E_8(1,1,1)$. Eight pure strategy equilibrium points are substituted into Equation (16) to obtain the eigenvalues of each equilibrium point, as shown in Table 3.

Table 3. Eigenvalues for each equilibrium point.

Equilibrium Point	Eigenvalue
$E_1(0,0,0)$	$\lambda_1 = -D_i + F_s + F_{c1} - P_5L_i + P_6L_i$ $\lambda_2 = -D_s - B - P_4L_s + P_6L_s$ $\lambda_3 = -D_c + B - P_4L_c + P_6L_c$
$E_2(1,0,0)$	$\lambda_1 = D_i - F_s - F_{c1} + P_5L_i - P_6L_i$ $\lambda_2 = -D_s - B + F_s + R_s - P_3L_s + P_5L_s$ $\lambda_3 = -D_c + B + F_{c1} + R_c - P_3L_c + P_5L_c$
$E_3(0,1,0)$	$\lambda_1 = -D_i + F_{c1} - P_3L_i + P_4L_i$ $\lambda_2 = D_s + B + P_4L_s - P_6L_s$ $\lambda_3 = -D_c + F_{c2} - P_2L_c + P_4L_c$
$E_4(0,0,1)$	$\lambda_1 = -D_i + F_s - P_3L_i + P_4L_i$ $\lambda_2 = -D_s - P_2L_s + P_4L_s$ $\lambda_3 = D_c - B + P_4L_c - P_6L_c$
$E_5(1,1,0)$	$\lambda_1 = D_i - F_{c1} + P_3L_i - P_4L_i$ $\lambda_2 = D_s + B - F_s - R_s + P_3L_s - P_5L_s$ $\lambda_3 = -D_c + F_{c1} + F_{c2} + R_c - P_1L_c + P_3L_c$
$E_6(1,0,1)$	$\lambda_1 = D_i - F_s + P_3L_i - P_4L_i$ $\lambda_2 = -D_s + F_s + R_s - P_1L_s + P_3L_s$ $\lambda_3 = D_c - B - F_{c1} - R_c + P_3L_c - P_5L_c$
$E_7(0,1,1)$	$\lambda_1 = -D_i - P_1L_i + P_2L_i$ $\lambda_2 = D_s + P_2L_s - P_4L_s$ $\lambda_3 = D_c - F_{c2} + P_2L_c - P_4L_c$
$E_8(1,1,1)$	$\lambda_1 = D_i + P_1L_i - P_2L_i$ $\lambda_2 = D_s - F_s - R_s + P_1L_s - P_3L_s$ $\lambda_3 = D_c - F_{c1} - F_{c2} - R_c + P_1L_c - P_3L_c$

According to the Lyapunov discriminant method, if all the eigenvalues of the Jacobian matrix of an equilibrium point are less than 0, then this equilibrium point is the evolutionary game stability point (ESS) of the system. In order to enable the insurance institution, supervision unit, and contractor to better manage risks and promote the sustainable development of mega projects, $E_8(1,1,1)$ is an ideal stabilizing point.

4. Simulation Analysis of Tripartite Evolutionary Game

4.1. Evolution Path of Three Participants in Game

The value of the simulation model lies not in its authenticity but in its usefulness and the depth of revealing the laws of change [8]. Therefore, based on the interviews of the Nanjing Metro project in China, this paper mainly selects the initial values of all parameters by weighing how the changes in these parameters affect the strategy selection of different participants. In order to verify the effectiveness of evolutionary stability analysis and more intuitively show the impact of the participation of the insurance institution on the evolutionary path and steady state of the risk management of mega projects, the initial values of parameters are set on the basis of the ideal stable state $E_8(1, 1, 1)$, as shown in Table 4.

Table 4. Initial values of model parameters.

Parameter	Value	Parameter	Value	Parameter	Value
D_i	2	P_4	0.16	B	1
D_s	3	P_5	0.3	R_s	2
D_c	6	P_6	0.36	R_c	3
P_1	0.01	L_i	60	F_s	4
P_2	0.07	L_s	8	F_{c1}	5
P_3	0.1	L_c	15	F_{c2}	4

The above initial values were substituted into the model for numerical simulation, and the simulation results are shown in Figure 5.

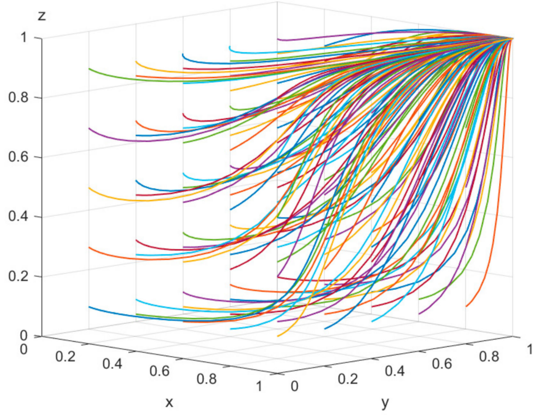

Figure 5. System evolution path diagram.

According to the results obtained by the simulation analysis, the evolutionary steady state of the system is $E_8(1, 1, 1)$, which is consistent with the results of the strategy stability analysis of the game agent, which verifies that the model is effective.

4.2. Sensitivity Analysis

In order to further analyze the impact of changes in the main parameters on the evolution of the strategies of insurance institution, supervision unit and contractor, this part is more intuitively presented through numerical simulations. Because the participation of the insurance institution in risk management is still in the initial stage, the initial probability of each party's strategy is 0.5 by default.

4.2.1. The Influence of the Initial Strategy Probability of the "Participation" Strategy of the Insurance Institution on the Strategy Choice of the Supervision Unit and the Contractor

The initial strategy probability x of the insurance institution is 0, 0.5 and 1, respectively, and the influence of the initial strategy probability of the "participation" strategy of the insurance institution on the strategy choice of the supervision unit and the contractor is shown in Figure 6. When the insurance institution chooses the "non-participation" strategy, and the initial strategy probability is $x = 0$, the strategy probability of the supervision unit and the contractor shows a downward trend, indicating that the supervision unit and the contractor are more inclined to choose the negative strategy when there is a lack of external supervision. With the increase in the initial strategy probability x of insurance institution from 0.5 to 1, the external supervision and knowledge sharing brought by the insurance institution make the supervision unit and the contractor more inclined to choose the active strategy, and with the increase in the initial strategy probability x, the strategic probability of the supervision unit and the contractor to choose the active strategy increases faster, which indicates that the participation of the insurance institution can drive the supervision unit and the contractor to be more active in the risk management of mega projects, and the collaborative risk management between the three is more effective than the traditional risk management cooperation model established between the supervision unit and the contractor.

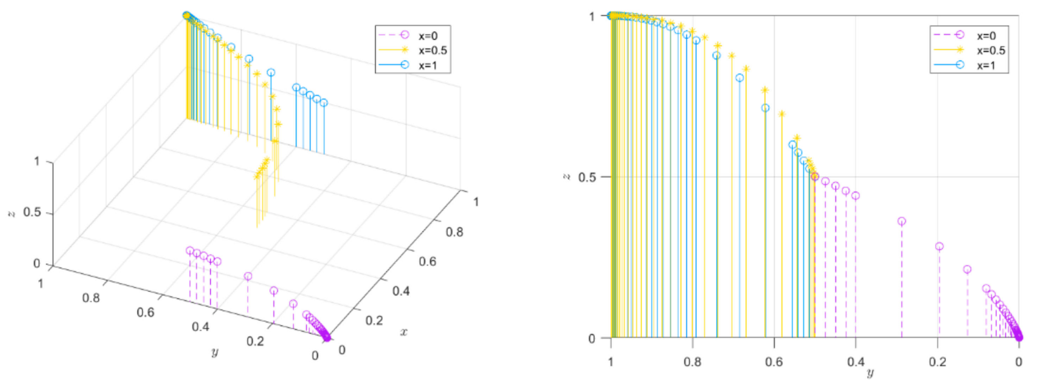

Figure 6. The impact of the initial policy probability of insurance institution choosing "participation" strategy.

4.2.2. The Impact of the Change in the Probability of Risk Occurrence on the Choice of Tripartite Strategies

Reducing the possibility of mega project risks is the main driving force for insurance institution to participate in risk management. The changes in the probability of risk occurrence are 0.03, 0.06 and 0.08, respectively, and the impact of the change in risk probability on the choice of tripartite strategy is shown in Figure 7. For the supervision unit and the contractor, because the loss caused by the accident is relatively small, the change in the risk probability when the insurance institution chooses the "participation" strategy has little impact on their strategy selection probability. For insurance institution, when the change in risk probability is 0.03, the strategy probability of the insurance institution choosing "participation" is mainly affected by the strategy selection probability of the supervision unit and the contractor and the large amount of compensation brought by the risk occurrence. When the strategy selection probability of the supervision unit and the contractor is low, in order to avoid risk loss, the insurance institution will tend to choose the "participation" strategy; when the strategy selection probability of the supervision unit and the contractor is high, the probability of risk occurrence is low. The cost of participating in risk management will make the insurance institution more inclined to choose the "non-participation" strategy; when the change in the probability of risk occurrence is 0.06 to 0.08, the loss mitigated between the two strategy choices of the insurance institution is always greater than the set cost to participate in risk management, and the insurance institution will tend to choose the "participation" strategy to reduce the probability of risk occurrence and avoid large claims.

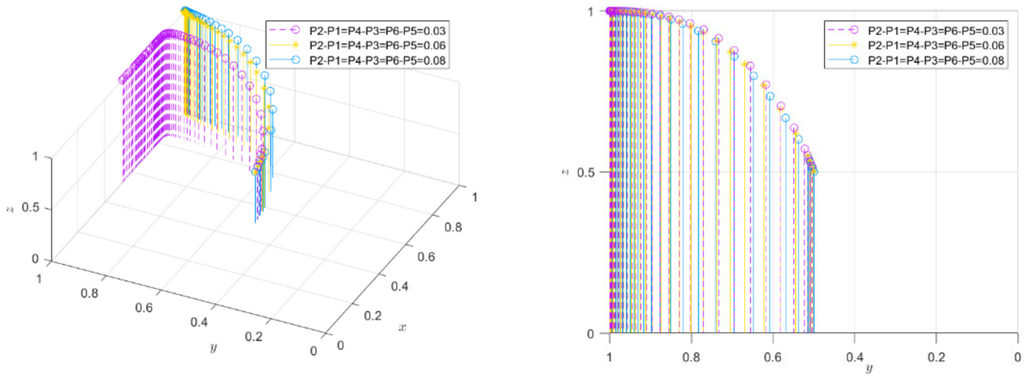

Figure 7. The impact of risk occurrence probability on the choice of tripartite strategies.

The probability of risk occurrence is related to factors such as project category and number of subcontractors, and this study finds that the probability of mega project risk has a significant impact on the strategic choice of insurance institution, supervision unit and contractor. Therefore, the insurance institution, supervision unit and contractor need to take into account the project category and the number of subcontractors when making decisions and fully evaluate and predict the probability of risk occurrence to make strategic choices.

4.2.3. The Impact of Cost Savings on the Choice of Tripartite Strategies

First of all, the value of the regulatory cost R_s of the supervision unit is 0, 2 and 4, respectively, and the impact of the regulatory cost savings of the supervision unit on the tripartite strategy choice R_s is shown in Figure 8. The size of the R_s mainly has an impact on the supervision unit; with the increase in the R_s, the strategic probability of the supervision unit is accelerating, and the reduction in the cost makes the supervision unit more inclined to choose "normal supervision".

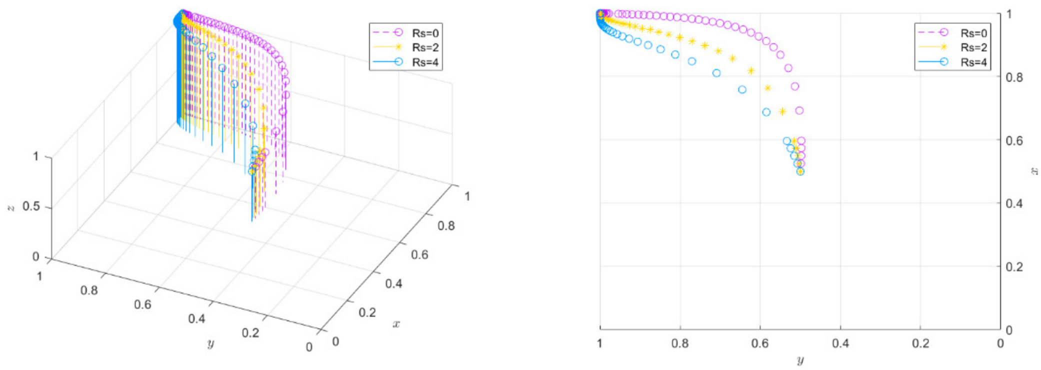

Figure 8. The impact of cost savings of supervision unit on the choice of tripartite strategies.

Secondly, the values of the prevention cost R_c of the contractor are 0, 3 and 6, respectively, and the impact of the contractor's cost saving on the tripartite strategy choice R_c is shown in Figure 9. The size of the R_c mainly has an impact on the contractor, and with the increase in the R_c, the probability of the contractor's strategy will rise faster, and the reduction in the cost will make the contractor more inclined to choose "strong prevention".

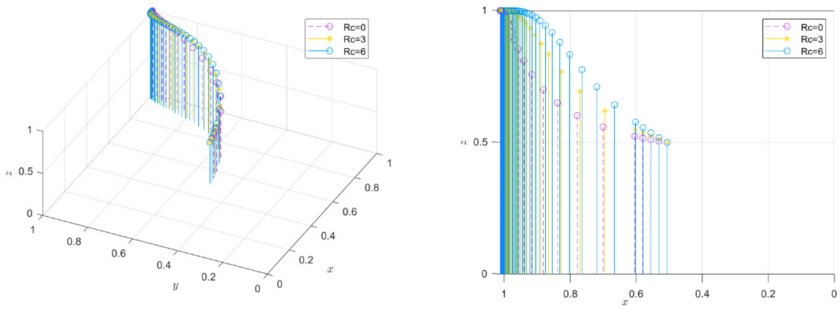

Figure 9. The impact of cost savings of contractor on the choice of tripartite strategies.

4.2.4. The Impact of Punishment on the Choice of Tripartite Strategies

First of all, when the insurance institution chooses "participation", the value of the owner's fine F_s for the "abnormal supervision" of the supervision unit is 0, 4 and 8, respectively, and the impact of the owner's fine F_s on the "abnormal supervision" of the supervision unit on the tripartite strategy selection is shown in Figure 10. With the increase in F_s, the probability of the strategy of the three parties increases faster. When $F_s = 0$, the strategy probability of the supervision unit gradually decreases from 0.5, and the lack of punishment makes the supervision unit tend to choose the "abnormal supervision" strategy.

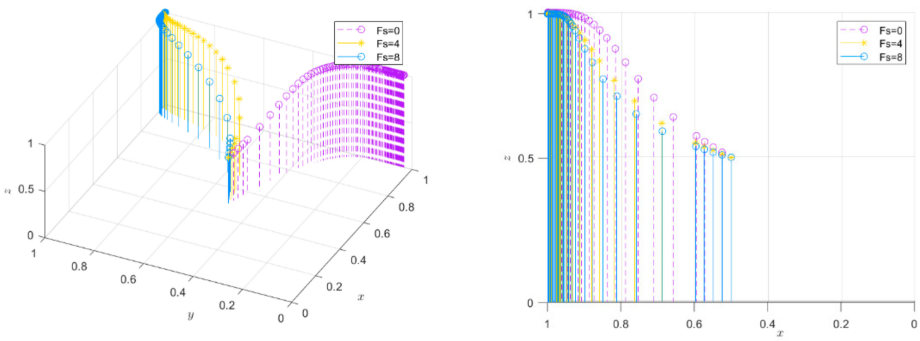

Figure 10. The impact of the punishment of the supervision unit on the tripartite strategy choice.

Secondly, when the insurance institution chooses "participation", the value of the owner's fine F_{c1} for the contractor's "weak prevention" is 0, 5 and 9, respectively, and the impact of the owner's fine F_{c1} on the contractor's "weak prevention" on the tripartite strategy choice is shown in Figure 11. With the increase in F_{c1}, the strategic probability of the insurance institution and contractor rises faster, especially for contractor, and there is a significant gap. The change in F_{c1} has little impact on the supervision unit, but due to the change in the probability of the other two parties' strategies, the supervision unit will also be more inclined to choose "normal supervision".

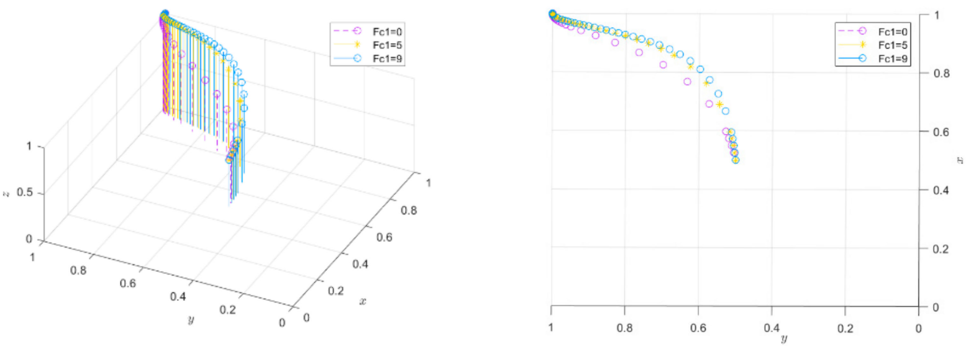

Figure 11. The impact of the punishment of the contractor on the tripartite strategy choice.

5. Conclusions

In order to ensure the stability and sustainability of tunnel projects, bridge projects and other mega construction projects, it is important to give full play to the overall effectiveness of risk management. This paper constructs a collaborative risk management mechanism between the insurance institution, supervision unit and contractor and constructs a tripartite evolutionary game model, analyzing the conditions and important parameters of each party's strategy. The conclusions and recommendations of the study are as follows:

First of all, the participation of the insurance institution has a signaling effect on the realization of sustainable goals for the risk management of mega projects. The high willingness of the insurance institution to participate in risk management will increase the initiative of the supervision unit and contractor and increase risk management investment. The management experience and management knowledge brought by the insurance institution to participate in risk management can help the supervision unit and the contractor save the cost of supervision and prevention, and the amount of cost savings may be determined by the degree or method of sharing the management experience and management knowledge with the insurance institution, so the insurance institution needs to effectively grasp the experience and knowledge sharing plan of the supervision unit and the contractor, reduce the cost concerns of the supervision unit and the contractor and promote the tripartite cooperation in the risk management of mega projects.

Second, the development of a reasonable punishment system is an important way to share costs. For insurance institution, the punishment of the supervision unit and the contractor through the owner will share part of the cost of participating in risk management. For the supervision unit and the contractor, in order to maximize the benefits and avoid penalties, they will be more active in supervision and risk prevention. Reasonable punishment can motivate the supervision unit and contractor to actively carry out risk management, reduce the impact of additional costs and pay attention to the losses caused by risks.

Finally, facilitating the participation of insurance institution in risk management requires addressing the cost concerns of the insurance institution. There will be a certain cost for insurance institution to participate in risk management, and the insurance institution needs to balance the relationship between costs and management effectiveness. Because mega projects are related to regional social and economic development and people's livelihood and well-being, in order to encourage insurance institution to participate in risk management, relevant departments can formulate relevant incentive policies such as financial subsidies or tax reductions and exemptions to assist insurance institution in reducing costs and increasing efficiency in risk management.

The above results show that insurance institution can participate in risk management by cooperating with owners and establishing a collaborative risk management mechanism with other participants. Through the research of this paper, in addition to the impact of insurance institution's participation itself, the cost savings and the implementation of penalties are the decisive factors that affect the tripartite strategy choice. Insurance institution can help participants identify hidden risks by participating in the risk management of the whole life cycle of mega projects and use their rich experience in risk management, such as providing relevant management suggestions for the contractor to determine construction plans in the early participation process. At the same time, the owner, as the main leader of the project, has established a corresponding contractual relationship with all participants, and the owner can promote the establishment of a risk collaborative management mechanism through its own rights to assist insurance institution to participate in risk management. In addition, insurance institution can also establish a more direct risk collaborative management mechanism with other participants by formulating revenue sharing methods and signing relevant contracts, but they need to clarify the responsibilities of all parties when signing contracts. Although promoting more stakeholders to participate in risk management of mega projects can better improve the risk management mechanism of mega projects and increase the effectiveness of risk management; if the management responsibilities of all participants are not clear, it is easy for all participants to pass the buck to each other, resulting in the occurrence of no supervision and no prevention.

This paper provides an important reference for the development of a collaborative management mechanism for mega project risks, but there are still some limitations. Future research can further explore the interaction between various parameters and the participation of insurance institution so as to build a more complete tripartite collaborative risk management strategy system, improve the risk management ability of mega projects and achieve the sustainable development goals of mega projects.

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