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Supervision Strategy of PPP Project in Urban Underground Integrated Pipe Gallery

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Supervision Strategy of PPP Project in Urban Underground Integrated Pipe Gallery

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Abstract. The choice of government and social capital partner cooperation strategy in PPP mode has an important impact on the operation of the whole project, and the change of strategy of either party will be affected or influence the choice of the other party's strategy. Therefore, the construction of the urban underground integrated pipe gallery PPP project is a process of a dynamic game between the government and social capital. It is impossible to use a single regulatory strategy throughout the life cycle of the project. This paper takes government supervision as the starting point, based on the evolutionary game theory, constructs the evolutionary game model according to the characteristics of the urban underground integrated pipe gallery PPP project, and mainly analyzes the equilibrium stability of the evolutionary game, which provides strong support for the improvement of the PPP project supervision strategy for urban underground integrated pipe gallery.

1. Introduction

The urban underground integrated pipe gallery PPP project is developing late in China, and there are many difficulties and challenges in the actual promotion process [1]. In particular, China has not yet established a relatively comprehensive regulatory environment for integrated pipe gallery, which has caused major problems in the management of cost, quality, and efficiency of such projects. The construction of urban underground integrated pipe gallery is conducive to solving the problems of repeated excavation of pavements, intensive aerial network and frequent pipeline accidents caused by traditional underground direct buried pipelines. It is an inevitable trend of the comprehensive development of urban public pipeline construction [2].

In the PPP project of urban underground integrated pipe gallery, although the government does not directly participate in the construction and operation of PPP projects, as a PPP project manager, it plays an important role in supervision and management of the project schedule, quality and cost. Therefore, for the government, the conflict between the trading role and the regulatory role is an important reason for the lack of a PPP project supervision system[3]. If the government can adjust the supervision strategy in a timely manner on the premise of taking into account the overall stability according to the actual situation of the project, the final income of the project can be improved[4].

2. Rationality analysis of evolutionary game model

Evolutionary game theory is different from traditional game theory. Evolutionary game is a theory that combines game theory analysis with dynamic evolution process, emphasizing a dynamic equilibrium [5]. In the process of evolutionary game, the game object is not required to be completely rational, and the player cannot find the optimal strategy and equilibrium point at the beginning. Instead, in the process of continuous learning, the error strategy is gradually improved, so as to achieve a stable equilibrium point after a period of replication dynamics [6].

The construction process of the urban underground integrated pipe gallery PPP project is a dynamic game process involving both the government and social capital. Therefore, there is no single regulatory strategy that can penetrate the entire life cycle of the project. From a government perspective, any regulatory action needs to consider cost and efficiency. The government hopes that through the formulation and improvement of a series of regulatory strategies, social capital can participate in PPP projects as actively as possible so that PPP projects can create more project benefits while achieving the intended goals.

3. Construction and analysis of evolutionary game model

3.1 Basic assumptions

Hypothesis 1: Both the government and social capital are bounded rational. Among them, the probability of the government's choice of incentive supervision strategy is x in the PPP project, and the probability of choosing not to strengthen the supervision strategy is $(1-x)$. Correspondingly, the social capital is in the PPP project, the probability of choosing to work together to improve the project's revenue strategy is y, and the probability of choosing an opportunistic strategy is $(1-y)$.

Hypothesis 2: R_G is the various social benefits that the government obtains in the PPP project. R_S is the basic income that social capital obtains in the PPP project, from user payment, government payment or feasibility gap subsidy. C_G is the government's various costs of expenditure during the implementation of the project. C_S is the input of social capital in terms of capital and tax in each stage of the project.

In the implementation process of PPP projects, when the government chooses the incentive supervision strategy, E_G represents the government's supervision cost. At this time, if social capital chooses a positive cooperation strategy, V_G represents the additional benefits that the government obtains from the incentive supervision strategy. A represents the government's reward for social capital's active cooperation in completing projects. When the social capital party chooses opportunism to benefit and gives up the overall benefit of the project, E_S represents the cost of social capital, L_G represents the loss to the government when social capital adopts opportunism. V_S is the additional project benefit that social capital obtains through opportunism. D indicates that under the supervision of the government, social capital chooses opportunism to trigger penalties for various irregularities.

According to the above assumptions combined with the evolutionary game theory, the game payment matrix of government and social capital is constructed, as shown in Table 1.

Table 1 Game payment matrix of government and social capital

PPP project		Social capital	
		Active cooperation (y)	Opportunism $(1-y)$
Government	Supervision (x)	$R_G-C_G-E_G+V_G-A$, R_S-C_S+A	$R_G-C_G-E_G-L_G+D$, $R_S-C_S-E_S+V_S-D$
	Not strengthening supervision $(1-x)$	R_G-C_G, R_S-C_S	$R_G-C_G-L_G$, $R_S-C_S-E_S+V_S$

3.2 Replication dynamics and stability analysis

(1) Both government and social capital replicate dynamic equations

The expected return of the government's choice of regulatory strategy is U_{11}, the expected return without strengthening supervision is U_{12}, and the average return is $\overline{U_1}$.

$$U_{11}=y(R_G-C_G-E_G+V_G-A)+(1-y)(R_G-C_G-E_G-L_G+D) \quad (1)$$

$$U_{12}=y(R_G-C_G)+(1-y)(R_G-C_G-L_G) \quad (2)$$

$$\overline{U_1} = xU_{11} + (1-x)U_{12} \quad (3)$$

In the process of participating in the project, the expected return of the social capital effort cooperation strategy is U_{21}, the expected return of social capital adopting opportunism is U_{22}, and the average return is $\overline{U_2}$.

$$U_{21} = x(R_S - C_S + A) + (1-x)(R_S - C_S) \quad (4)$$

$$U_{22} = x(R_S - C_S - E_S + V_S - D) + (1-x)(R_S - C_S - E_S + V_S) \quad (5)$$

$$\overline{U_2} = yU_{21} + (1-y)U_{22} \quad (6)$$

The replication dynamics are the most common dynamic processes in the evolutionary game. By copying the dynamic analysis of the government and the social capital, the replication dynamic equations of both parties can be obtained.

The government's replication dynamic equation:

$$F(x) = \frac{dx}{dt} = x(U_{11} - \overline{U_1}) = x(1-x)(U_{11} - U_{12})$$
$$= x(1-x)[y(V_G - A - D) - (E_G - D)] \quad (7)$$

Take the derivative of $F(x)$ with respect to x:

$$F'(x) = \frac{\partial F(x)}{\partial x} = (1-2x)[y(V_G - A - D) - (E_G - D)] \quad (8)$$

The social capital's replication dynamic equation:

$$F(y) = \frac{dy}{dt} = y(U_{21} - \overline{U_2}) = y(1-y)(U_{21} - U_{22})$$
$$= y(1-y)[x(A+D) - (V_S - E_S)] \quad (9)$$

Take the derivative of $\mathrm{F}(y)$ with respect to y:

$$F'(y) = \frac{\partial F(y)}{\partial y} = (1-2y)[x(A+D) - (V_S - E_S)] \quad (10)$$

(2) Analysis of replication dynamic equations for the government

According to the formula 7, $x^* = 0, x^* = 1$ are all stable states, but only when the derivative of the equation in the steady state is less than 0, the stable evolution strategy can be achieved.

① When $y = \frac{E_G - D}{V_G - A - D}$, there is always $F'(x) = 0$, and all the values of x are the government's stable evolution strategy. This means that when the probability of social capital choosing to work together to improve the project's income strategy is $\frac{E_G - D}{V_G - A - D}$, regardless of whether the government adopts a regulatory strategy, the two effects are the same, and the evolution effect is shown in Figure 1(a).

② When $y > \frac{E_G - D}{V_G - A - D}$, $F'(1) < 0$, which means that the probability of social capital selection efforts cooperation strategy is higher than $\frac{E_G - D}{V_G - A - D}$. The government should adjust the strategy to active supervision. At this time, $x = 1$ is the stable evolution strategy of the government in the process of supervision of the PPP project, and the evolution effect is shown in Figure 1(b).

③ When $y < \frac{E_G - D}{V_G - A - D}$, $F'(0) < 0$, which means that the probability of social capital selection efforts cooperation strategy is lower than $\frac{E_G - D}{V_G - A - D}$. The government should adjust the strategy to not strengthen supervision. At this time, $x = 0$ is the stable evolution strategy of the government in the PPP project. The evolution effect is shown in Figure 1(c).

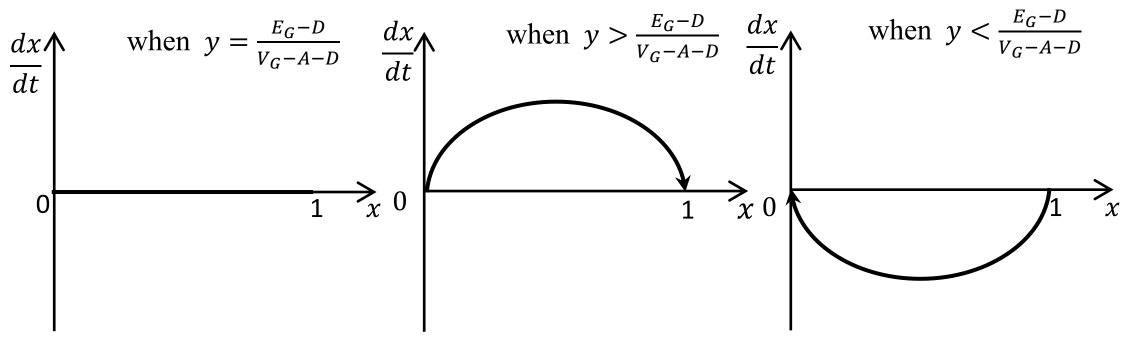

Figure 1 Government replication dynamic phase diagram

(3) Analysis of replication dynamic equations for social capital

In the same way, the replication dynamic equation of social capital can be analyzed, and the evolution effect is shown in Figure 2.

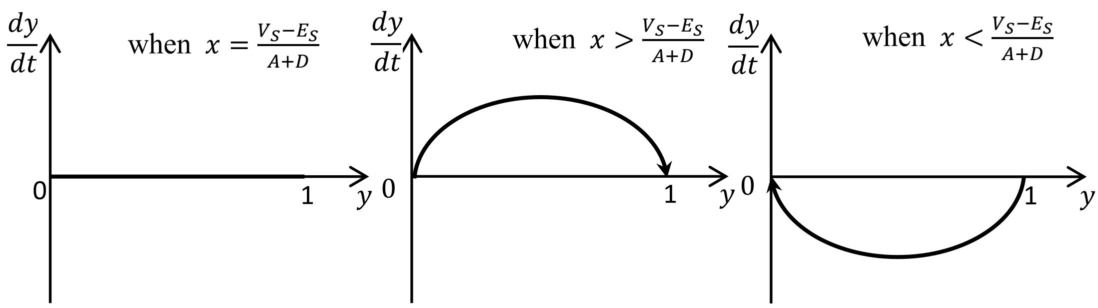

Figure 2 Replication dynamic phase diagram of social capital

3.3 Analysis of equilibrium stability of evolutionary game

The analysis process of evolutionary game stability can be described by the system composed of the partial derivative of formula 7 and formula 9 with respect to variable *x* and *y*. By analyzing the system, when $F(x) = 0, F(y) = 0$, there are five partial equilibrium points between government and social capital, which are $(0,0)$、$(0,1)$、$(1,0)$、$(1,1)$ and (x, y), where $x = V_S - E_S/A + D$, $y = E_G - D/V_G - A - D$. For a group dynamics described by differential equations, the stability of the equilibrium point can be obtained according to the structural analysis of the Jacobian matrix[7]. The Jacobian matrix J of the system, the determinant $Det(J)$ of the matrix, and the trace $Tr(J)$ of the matrix, is as follows.

The Jacobian matrix J is:

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

$$= \begin{bmatrix} (1-2x)[y(V_G - A - D) - (E_G - D)] & x(1-x)(V_G - A - D) \\ y(1-y)(A+D) & (1-2y)[x(A+D) - (V_S - E_S)] \end{bmatrix} \tag{11}$$

The determinant $Det(J)$ of the Jacobian matrix is:

$$Det(J) = \frac{\partial F(x)}{\partial x} \cdot \frac{\partial F(y)}{\partial y} - \frac{\partial F(x)}{\partial y} \cdot \frac{\partial F(y)}{\partial x}$$

$$= (1-2x)[y(V_G - A - D) - (E_G - D)](1-2y)[x(A+D) - (V_S - E_S)]$$

(12)

$$-x(1-x)(V_G-A-D)y(1-y)(A+D)$$

The trace $Tr(J)$ of the Jacobian matrix is:

$$Tr(J)=\frac{\partial F(x)}{\partial x}+\frac{\partial F(y)}{\partial y}$$

$$=(1-2x)[y(V_G-A-D)-(E_G-D)]+(1-2y)[x(A+D)-(V_S-E_S)] \quad (13)$$

According to the local stability analysis, the five equilibrium points can be calculated into the matrix determinant $Det(J)$ and the trace $Tr(J)$ of the matrix, and the stability of the equilibrium point can be judged by calculating the positive and negative of the result. If a certain equilibrium point can make the determinant of the Jacobian matrix greater than zero ($Det(J)>0$), and the trace of the Jacobian matrix is less than zero ($Tr(J)<0$), then the point corresponds to the value of x, y is the probability of a stable evolutionary strategy of government and social capital. The analysis results of the Jacobian matrix can be shown in Table 2.

Table 2 System Jacobian Matrix Analysis

Equilibrium point	$Det(J)$	$Tr(J)$
(0,0)	$(D-E_G)(E_S-V_S)$	$(D-E_G)+(E_S-V_S)$
(0,1)	$-(V_G-A-E_G)(E_S-V_S)$	$(V_G-A-E_G)-(E_S-V_S)$
(1,0)	$-(D-E_G)(A+D-V_S+E_S)$	$(E_G+A)+(E_S-V_S)$
(1,1)	$(V_G-A-E_G)(A+D-V_S+E_S)$	$-(V_G-A-E_G)$ $-(A+D-V_S+E_S)$
$(\frac{V_S-E_S}{A+D},\frac{E_G-D}{V_G-A-D})$	$\frac{-(E_S-V_S)(A+D-V_S+E_S)(D-E_G)(V_G-A-E_G)}{(A+D)(V_G-A-D)}$	0

It can be seen from the analysis of Table 2 that the positive and negative results of the Jacobian matrix determinant $Det(J)$ and the Jacobian matrix trace $Tr(J)$ are mainly related to the four combined variables of $D-E_G$ 、 E_S-V_S 、 V_G-A-E_G and $A+D-V_S+E_S$, among which $D-E_G$ and E_S-V_S mainly determine the local stability of the equilibrium point. Therefore, the relationship between the value of the variable and the local stability will be discussed below.

(1) When $D-E_G<0$，$E_S-V_S<0$, the government's supervision cost is greater than the punishment cost of social capital opportunistic behavior, and the additional project income obtained by social capital through opportunism is greater than the opportunity cost. At this time, there are two results of V_G-A-E_G and $A+D-V_S+E_S$, and the local stability analysis is shown in Table 3.

Table 3 $D-E_G<0$，$E_S-V_S<0$. System equilibrium point local stability analysis

Equilibrium point	$V_G-A-E_G>0$ $A+D-V_S+E_S>0$			$V_G-A-E_G>0$ $A+D-V_S+E_S<0$			$V_G-A-E_G<0$ $A+D-V_S+E_S>0$			$V_G-A-E_G<0$ $A+D-V_S+E_S<0$		
	$Det(J)$	$Tr(J)$	Local stability	$Det(J)$	$Tr(J)$	Local stability	$Det(J)$	$Tr(J)$	Local stability	$Det(J)$	$Tr(J)$	Local stability
(0,0)	+	-	ESS	+	-	ESS	+	-	ESS	+	-	ESS
(0,1)	+	+	Unstable	+	+	Unstable	-	±	Unstable	-	±	Unstable
(1,0)	+	±	Unstable	-	±	Unstable	+	±	Unstable	-	±	Unstable
(1,1)	+	-	ESS	-	±	Unstable	+	±	Unstable	+	+	Unstable
(x, y)	-	0	Saddle point	+	0	Saddle point	-	0	Saddle point	-	0	Saddle point

On the basis of Table 3, the evolutionary game phase diagram of the government and social capital under different conditions can be drawn. Since the analysis process is similar, only the complex cases such as $D-E_G<0$，$E_S-V_S<0$，$V_G-A-E_G>0$，$A+D-V_S+E_S>0$ are selected for analysis. In addition, the phase diagram of the system evolution game is shown in Figure 3.

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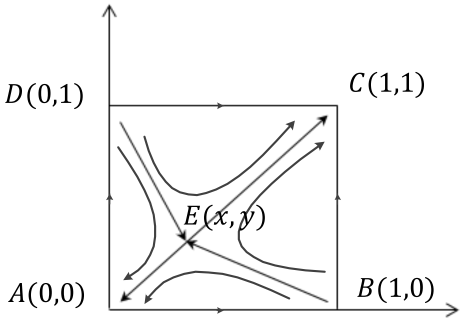

Figure 3 System evolution game phase diagram

It can be seen from Figure 3 that when the initial game falls within the evolutionary area ABCD, both parties learn through continuous game learning, and finally will use (0,0) as the stability point of the evolutionary stability strategy, which indicates that even if the government does not strengthen supervision, the social capital choosing opportunism is an inevitable combination of strategies. However, when the initial game falls within the evolutionary region BCDE, both parties will continue to learn by the game, and finally (1,1) will be the stable point of the evolutionary stability strategy. This shows that the government actively monitors and the social capital actively cooperate, which is an inevitable strategy combination.

According to the phase diagram, it can be analyzed that when the government obtains additional project benefits under the incentive supervision strategy, increases the punishment for social capital opportunism or increases the incentives for social capital to actively cooperate in completing the project. The stability point will shift to the lower left, thereby increasing the area of the quadrilateral region BCDE. Therefore, in the game process, both parties are more likely to evolve toward active supervision and cooperation.

(2) When $D - E_G > 0$, $E_S - V_S < 0$, the government's supervision cost is less than the penalty cost for social capital opportunistic behavior, and the additional project income obtained by social capital through opportunism is greater than the opportunity cost. At this time, if the trends of $V_G - A - E_G$ and $A + D - V_S + E_S$ are consistent, then the evolution of the game tends to be stable toward (1, 1). If the trend is reversed, the system has no stable evolution strategy. The details are shown in Table 4.

Table 4 $D - E_G > 0$, $E_S - V_S < 0$. System equilibrium point local stability analysis

Equilibrium point	$V_G - A - E_G > 0$ $A + D - V_S + E_S > 0$			$V_G - A - E_G > 0$ $A + D - V_S + E_S < 0$			$V_G - A - E_G < 0$ $A + D - V_S + E_S > 0$			$V_G - A - E_G < 0$ $A + D - V_S + E_S < 0$		
	$Det(J)$	$Tr(J)$	Local stability	$Det(J)$	$Tr(J)$	Local stability	$Det(J)$	$Tr(J)$	Local stability	$Det(J)$	$Tr(J)$	Local stability
(0,0)	-	±	Unstable	-	±	Unstable	-	±	Unstable	-	±	Unstable
(0,1)	+	+	Unstable	+	+	Unstable	-	±	Unstable	-	±	Unstable
(1,0)	-	±	Unstable	+	±	Unstable	-	±	Unstable	+	±	Unstable
(1,1)	+	-	ESS	-	±	Unstable	-	±	Unstable	+	-	ESS
(x,y)	+	0	Saddle point	-	0	Saddle point	-	0	Saddle point	+	0	Saddle point

(3) When $E_S - V_S > 0$, there is always $A + D - V_S + E_S > 0$. At this time, the opportunity cost of social capital is greater than the additional project income obtained by opportunism, so it tends to choose active cooperation strategy. For the government, if $V_G - A - E_G < 0$, the government's additional income in the PPP project cannot be guaranteed, and it will tend to choose not to strengthen the supervision strategy; if $V_G - A - E_G > 0$, the government's income in PPP projects is greater than the sum of regulatory and incentive costs. The government has sufficient incentives to implement supervision, so it will choose incentive supervision as the best strategy, as shown in Table 5.

Table 5 $E_S - V_S > 0$. System equilibrium point local stability analysis

Equilibrium point	$D-E_G>0$ $V_G-A-E_G>0$			$D-E_G>0$ $V_G-A-E_G<0$			$D-E_G<0$ $V_G-A-E_G>0$			$D-E_G<0$ $V_G-A-E_G<0$		
	$Det(J)$	$Tr(J)$	Local stability	$Det(J)$	$Tr(J)$	Local stability	$Det(J)$	$Tr(J)$	Local stability	$Det(J)$	$Tr(J)$	Local stability
(0,0)	+	+	Unstable	+	+	Unstable	-	±	Unstable	-	±	Unstable
(0,1)	-	±	Unstable	+	-	ESS	-	±	Unstable	+	-	ESS
(1,0)	-	+	Unstable	-	+	Unstable	+	+	Unstable	+	+	Unstable
(1,1)	+	-	ESS	-	±	Unstable	+	-	ESS	-	±	Unstable
(x,y)	-	0	Saddle point	+	0	Saddle point	+	0	Saddle point	-	0	Saddle point

3.4 Analysis of evolutionary game model

(1) Even if the government's regulatory cost is greater than the penalty cost of social capital opportunistic behavior $(E_G > D)$, the additional project income obtained by social capital through opportunism is greater than the opportunity cost $(V_S > E_S)$. As long as it can increase the additional income V_G obtained by the government in the urban underground integrated pipe gallery PPP project (such as the social benefits and social welfare generated by exceeding the target of the project to increase the user's payment), or when the performance level of social capital exceeds the government's target, the government increases the incentives A for social capital to actively cooperate to complete the project, or increase the punishment D for various types of violations caused by social capital opportunism in the PPP contract. So to a large extent, the two sides will develop towards a stable strategy of active supervision and cooperation.

(2) When the government's regulatory cost is less than the penalty cost for social capital opportunistic behavior $(E_G < D)$, even if the extra project income obtained by social capital through opportunism is greater than the opportunity cost $(V_S > E_S)$, as long as the government's interest change trend is consistent with social capital, the overall profit of social capital can be guaranteed. then win-win cooperation will also become a stable and balanced priority development strategy.

(3) When the opportunity cost of social capital is greater than the additional project benefit obtained by opportunism $(E_S > V_S)$, social capital tends to choose a positive cooperation strategy. At this time, the evolution of the system is mainly led by the government. If the government can reduce the cost of PPP project supervision or increase the projected revenue through its own efforts, the evolution result will also develop toward a stable and balanced strategy of win-win cooperation.

4. The perfect strategy for PPP project supervision of urban underground integrated pipe gallery

Effective regulatory approaches can help achieve regulatory goals and contribute to PPP project implementation. Therefore, through the above analysis, the supervision method of the urban underground integrated pipe gallery PPP project can be improved from the following aspects:

(1) Reduce regulatory costs

Considering that the government's supervision will gradually decrease with the increase of government supervision costs, and the rate of change of supervision will be different at different stages. Therefore, how to reduce unnecessary supervision, reduce supervision costs and improve the efficiency of supervision work in PPP projects is one of the important contents of the government's work. Specifically, the government's supervision work can be improved from the following aspects: ①The government needs to strengthen the dynamic attention to social capital according to the stage of the PPP project, so as to adjust the supervision strategy in time. ②The government should comprehensively upgrade the supervision system and reduce the supervision cost in the process of continuous optimization of the supervision method. ③The government should establish a special PPP management organization to strengthen the management and assessment of the supervision work, so as to effectively improve the efficiency and quality of government supervision.

(2) Strengthen incentives and constraints

The government's setting of the intensity of social capital incentives largely determines the risk aversion attitude and optimal effort level of social capital to PPP projects. Reasonable incentives and constraints can effectively guide social capital to reduce moral hazard and increase the enthusiasm of social capital to participate in project construction. Therefore, the government can adopt effective strategies such as increasing tax reduction and government financial subsidies, improving PPP legislation, standardize the project approval process and other effective strategies to strengthen the set of social capital incentives and constraints. In addition, this incentive regulation has a fair and objective nature and can help PPP projects achieve better economic and social value.

(3) Improve contract supervision

The PPP project contract as an important basis for government supervision work, its integrity and rationality can not only improve the social capital access standards but also maximize the impact of project promotion efficiency. In the process of formulation and improvement of contract supervision, the key is to clarify the responsibilities and obligations of both parties, to ensure the smooth development of PPP projects, and to reduce the breach of contract between the government and social capital, the corresponding punitive measures must be clearly formulated in the contract. Reasonable punishment measures correctly guide social capital's attitude toward opportunism while increasing the enthusiasm of social capital to participate in the project. Of course, in the actual construction process of PPP projects, it is difficult to solve various types of emergencies by relying only on contract supervision. The government also needs to combine PPP project contracts to adopt more flexible, effective and targeted regulatory measures.

(4) Optimize regulatory policies

The ultimate goal of PPP project supervision is to ensure that the project achieves its intended objectives at its best. Therefore, the formulation of regulatory strategies must follow the principle of strictness and moderation. A strict regulatory strategy will not be conducive to improving project income and affecting the enthusiasm of social capital cooperation, and a loose regulatory strategy will affect the smooth implementation of the project and increase the moral hazard of social capital. In the process of formulating regulatory policies, the government must comprehensively determine according to the actual situation of the project. When the project benefits are lower than the expected targets, the government must strictly implement the supervision strategy to promote social capital to be better invested in project construction. When the project returns are good, the government can moderately relax the supervision strategy under the premise of the same regulatory principle, so that social capital can fully exert its own advantages and enhance the overall income of the project.

5. Summary

The construction of PPP project of urban underground integrated pipe gallery is one of the main development directions in the current engineering construction field, the improvement, and selection of its supervision methods affect the economic and social value of the whole project to a large extent. At present, most of the research on the supervision methods of PPP projects in urban underground integrated pipe corridors is a qualitative analysis, and there are few dynamic game analysis that can be combined with the project construction process. Therefore, based on the analysis of the evolutionary game model, this paper mainly discusses from the two perspectives of the government's supervision cost is greater or less than the penalty cost of social capital opportunism behavior and the additional project income obtained by social capital through opportunism is greater or less than the opportunity cost, so as to dynamically adjusts the selection of the supervision mode of the urban underground integrated gallery PPP project. In addition, this paper also combines the relevant analysis of the game model to propose ways to improve the regulatory strategy: reduce supervision costs, strengthen incentives, improve contract supervision and optimize regulatory policies.

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