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Analysis of Incentive Mechanism of Prefabricated and Assembled Urban Tunnels based on Evolutionary Game Theory

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Abstract

In order to promote the rapid development of tunnel prestressed assembly city, on the basis of natural person limited rational point of view, selection of the government, the building side and the construction party are selected as the research objects, the evolutionary game model is constructed, finally it is concluded that tripartite equilibrium solution of dynamic game model, and analyzes the tripartite between steady state and strategy choice behavior, in order to promote the development of prefabricated city tunnels provide certain theoretical guidance and reference.

Keywords

Evolutionary game; Prefabricated and assembled urban tunnels; Incentive policies; Game model.

1. Introduction

At present, prefabricated structures have been widely used in urban underground engineering and traffic construction all over the world, and are developing rapidly towards the direction of industrial construction. With the increasing demand of urban traffic flow, urban road construction has come into being. The construction of urban tunnels can effectively alleviate traffic pressure, but the traditional cast-in-place construction for a long time has brought a series of urban problems, such as traffic congestion, garbage pollution, noise, etc., so the traditional cast-in-place construction technology of urban tunnels has been unable to meet the needs of social development.

Compared with traditional cast-in-place technology, precast structure has a high degree of industrialization and standardization, high efficiency, high quality, low energy consumption and low pollution, which can greatly shorten the construction period, reduce on-site labor intensity and temporary workload, save construction land, and significantly improve the safety and civilized construction [1].

Game theory mainly studies the decision-making of economic individuals whose behaviors and interests are mutually dependent and relevant market equilibrium issues [2]. After decades of development, game theory has become a widely applied discipline, especially in the fields of economics, management and social sciences [2-4]. Therefore, it is of great significance to introduce game theory into tunnel construction management.

Scholars' studies on prefabricated and assembled tunnels are more focused on the construction technology [5], construction mode [6], seismic performance [7] and other aspects of such projects. By applying game theory to tunnel engineering, scholars now pay more attention to tunnel safety behavior [8], risk response [9], construction scheme [10] and other aspects. Based on the evolutionary game theory, few scholars have discussed the incentive mechanism of relevant stakeholders of prefabricated and assembled urban tunnels, so as to promote the rapid development of prefabricated and assembled urban tunnels. Therefore, it is necessary to establish a game model to discuss the

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incentive mechanism of relevant stakeholders of prefabricated and assembled urban tunnels so as to promote the rapid development of prefabricated and assembled urban tunnels.

2. The evolution game model of the government, the building side and the construction party

2.1 Basic assumptions of evolutionary models.

Hypothesis 1: During the advance of the prefabricated and assembled tunnel, this paper assumes that there are three participants in the game: the government, the building side and the construction party . All the three parties are limited rational subjects with limited learning ability. In the case of incomplete symmetric information, the optimal strategy should be found through continuous learning, identification and adjustment, and repeated evolutionary games, so as to finally reach the stable state of evolutionary games.

Hypothesis 2: The government can choose between "tangible" and "intangible" incentive behavior strategies,The probabilities are x and 1-x,Tangible incentives refer to substantial rewards, such as tax incentives, given to the builder or builder who chooses to prefabricate and assemble urban tunnels.In the case of conforming to the standard, the amount of the reward varies with the prefabrication rate, while the intangible incentive refers to the verbal publicity call;Both the building side and the construction party can choose the two behavior strategies of "prefabricated assembly" and "traditional in-situ" urban tunnel.The building side probability is y and 1-y respectively, and the construction party probability is z and 1-z respectively.

Hypothesis 3: The government encourages the building side and the construction party to choose "prefabricated and assembled" urban tunnels through tangible incentive policies.In this case, the government receives long-term benefits C1 and C2, and needs to pay work cost D3. In addition, the building side and construction party that choose the "prefabricated assembly" strategy will be rewarded with Q1 and Q2. H1 and H2 shall be punished for substandard building side and construction party. When the government chooses the "invisible" incentive strategy, some building sides and construction parties may take the initiative to choose the "prefabricated assembly" strategy to obtain additional incremental income B1 and B2.

Hypothesis 4: When the building side chooses the "traditional cast-in-place" urban tunnel, the revenue and cost are N1 and M1 respectively. When the building side chooses the "prefabricated and assembled" urban tunnel, the incremental revenue N2 will be obtained, such as corporate image and brand value, and the incremental cost M2 will be paid.

Hypothesis 5: When the construction party chooses "traditional in-place" urban tunnel, the revenue and cost are P1 and K1, respectively. When the construction party chooses "prefabricated and assembled" urban tunnel, the incremental revenue N2 will be obtained, such as corporate image and brand value, and the incremental cost M2 will be paid.

2.2 The construction of evolutionary Game model

Based on the above assumptions and definitions, the income matrix of the three participants is obtained in summary analysis. The results are shown in Table 1 and Table 2.

Table 1 Revenue matrix of tripartite game under the government's tangible incentive strategy

		Building side	
		Prestressed assembly	Traditional cast-in-situ
Construction party	Prestressed assembly	C1+C2-D3-Q1-Q2 P1+P2-K1-K2+Q2 N1+N2-M1-M2+Q1	C2+H1-D1-D3-Q2 P1-K1-H2 N1+N2-M1-M2+Q1
	Traditional cast-in-situ	C1+H2-D2-D3-Q1 P1+P2-K1-K2+Q2 N1-M1-H1	H2+H1-D1-D2-D3 P1-K1-H2 N1-M1-H1

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Table 2 Revenue matrix of tripartite game under the government's intangible incentives strategy

		Building side	
		Prestressed assembly	Traditional cast-in-situ
Construction party	Prestressed assembly	B1+B2 P1+P2-K1-K2 N1+N2-M1-M2	B2-D1 P1-K1 N1+N2-M1-M2
	Traditional cast-in-situ	B1-D2 P1+P2-K1-K2 N1-M1	D1-D2 P1-K1 N1-M1

Expected benefits of government's "tangible" incentive strategy:

$$Ex1=y(z(C1+C2-D3-Q1-Q2)+(1-z)(C1+H2-D2-D3-Q1))+(1-y)(z(C2+H1-D1-D3-Q2)+(1-z)(H2+H1-D1-D2-D3))=H2+H1-D1-D2-D3+z(C2+D2-Q2-H2)+y(C1+D1-Q1-H1) \quad (1)$$

Expected Benefits of the Government's "invisible" incentive strategy:

$$Ex2=y(z(B1+B2)+(1-z)(B1-D2))+(1-y)(z(B2-D1)+(1-z)(-D1-D2))=-D1-D2+z(B2+D2)+y(B1+D1) \quad (2)$$

Average government revenue:

$$Ex=xEx1+(1-x)Ex2 \quad (3)$$

Expected Benefits of the building side's "prefabricated assembly" strategy:

$$Ey1=x(z(N1+N2-M1-M2+Q1)+(1-z)(N1+N2-M1-M2+Q1))+(1-x)(z(N1+N2-M1-M2)+(1-z)(N1+N2-M1-M2))=N1+N2-M1-M2+xQ1 \quad (4)$$

Expected Benefits of the building side's choice of "traditional cast-in-place" strategy:

$$Ey2=x(z(N1-M1-H1)+(1-z)(N1-M1-H1))+(1-x)(z(N1-M1)+(1-z)(N1-M1))=N1-M1-xH1 \quad (5)$$

Average income of the building side:

$$Ey=yEy1+(1-y)Ey2 \quad (6)$$

Expected Benefits of the construction party's "Prefabrication" strategy:

$$Ez1=x(y(P1+P2-K1-K2+Q2)+(1-y)(P1+P2-K1-K2+Q2))+(1-x)(y(P1+P2-K1-K2)+(1-y)(P1+P2-K1-K2))=P1+P2-K1-K2+xQ2 \quad (7)$$

Expected benefits of the construction party's choice of "traditional cast-in-place" strategy:

$$Ez2=x(y(P1-K1-H2)+(1-y)(P1-K1-H2))+(1-x)(y(P1-K1)+(1-y)(P1-K1))=P1-K1-xH2 \quad (8)$$

Average earnings of the construction party:

$$Ez=zEz1+(1-z)Ez2 \quad (9)$$

According to the replication dynamic equation formula of evolutionary game, the replication dynamic equation of the government strategy can be obtained as follows:

$$F(x)=x(Ex1-Ex)=x(1-x)(Ex1-Ex2)=x(1-x)(H2+H1-D3+z(C2-Q2-H2-B2)+y(C1-Q1-H1-B1)) \quad (10)$$

According to the replication dynamic equation formula of evolutionary game, the replication dynamic equation of the building side strategy can be obtained as follows:

$$F(y)=y(Ey1-Ey)=y(1-y)(Ey1-Ey2)=y(1-y)(N2-M2+x(Q1+H1)) \quad (11)$$

According to the replication dynamic equation formula of evolutionary game, the replication dynamic equation of the construction party strategy can be obtained as follows:

$$F(z)=z(Ez1-Ez)=z(1-z)(Ez1-Ez2)=z(1-z)(P2-K2+x(Q2+H2)) \quad (12)$$

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3. Model evolution and stability analysis

3.1 Stability analysis of stakeholder's unilateral strategy

3.1.1 Stability analysis of government unilateral strategy

According to formula (10), the replication dynamic equation of government strategy is:

$$F(x)=x(1-x)(H2+H1-D3+z(C2-Q2-H2-B2)+y(C1-Q1-H1-B1))$$

If $y=[z(C2-Q2-H2-B2)+H2+H1-D3]/(Q1+H1+B1-C1)$, then $F(x)\equiv 0$, that means that no matter what y is, the government policy is stable at all levels.

If $y\neq[z(C2-Q2-H2-B2)+H2+H1-D3]/(Q1+H1+B1-C1)$, When $F(x)=0$, $x=0$ and $x=1$ are the two stable points for government strategy replication dynamic equation, and the derivative of F(x) is obtained：

$$F'(x)=(1-2x)(H2+H1-D3+z(C2-Q2-H2-B2)+y(C1-Q1-H1-B1))$$

When $C1-Q1-H1-B1>0$, it can be divided into two situations:

a, If $y<z(C2-Q2-H2-B2)+H2+H1-D3]/(Q1+H1+B1-C1)$, $F'(x)|x=1>0$, $F'(x)|x=0<0$, At this point, x= 0 is the only evolutionary stability strategy;When the willingness of the building side to develop prefabricated and assembled urban tunnels fails to reach a certain extent and shows a downward trend, the possibility of the government to choose tangible incentive strategy gradually decreases, and intangible incentive strategy is the best choice. Obviously this kind of state does not conform to the reality, is an invalid state.

b, If $y>[z(C2-Q2-H2-B2)+H2+H1-D3]/(Q1+H1+B1-C1)$, $F'(x)|x=0>0$, $F'(x)|x=1<0$, At this point, x= 1 is the only evolutionary stability strategy;When the willingness of the building side to develop prefabricated and assembled urban tunnels reaches a certain degree and increases, the possibility of the government to choose tangible incentive strategy gradually increases, and the final tangible incentive strategy is the best choice. Obviously this kind of state does not conform to the reality, is an invalid state.

When $C1-Q1-H1-B1<0$, it can be divided into two situations:

a, If $y>[z(C2-Q2-H2-B2)+H2+H1-D3]/(Q1+H1+B1-C1)$, $F'(x)|x=1>0$, $F'(x)|x=0<0$, At this point, x= 0 is the only evolutionary stability strategy; When the willingness of the building side to develop prefabricated and assembled urban tunnels reaches a certain degree and increases, the possibility of the government to choose tangible incentive strategy gradually decreases, and intangible incentive strategy is the best choice.

b, If $y<[z(C2-Q2-H2-B2)+H2+H1-D3]/(Q1+H1+B1-C1)$, $F'(x)|x=0>0$, $F'(x)|x=1<0$, At this point, x= 1 is the only evolutionary stability strategy; When the willingness of the building side to develop prefabricated and assembled urban tunnels fails to reach a certain extent and shows a downward trend, the possibility of the government to choose tangible incentive strategy gradually increases, and the final tangible incentive strategy is the best choice.

3.1.2 Stability analysis of unilateral strategy of building side

According to formula (11),the replication dynamic equation of the building side strategy is:

$$F(y)=y(1-y)(N2-M2+x(Q1+H1))$$

(1) If $x=[N2-M2]/(-Q1-H1)$, then $F(y)\equiv 0$.That means that no matter what x is, the building side strategy is stable at all levels.

(2) If $x\neq[N2-M2]/(-Q1-H1)$, When $F(y)=0$, $y=0$ and $y=1$ are the two stable points of the dynamic equation replication in the building side strategy. The derivative of F(y) is:

$$F'(y)=(1-2y)(N2-M2+x(Q1+H1))$$

Obvious, $Q1+H1>0$, it can be divided into two situations:

a, If $x>[N2-M2]/(-Q1-H1)$, $F'(y)|y=1>0$, $F'(y)|y=0<0$, At this point, y=0 is the only evolutionary stability strategy; When the government selects the tangible incentive strategy to a certain extent and

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the trend is increasing, the possibility of the building side choosing the prefabricated and assembled urban tunnel strategy gradually decreases, and the traditional cast-in-situ urban tunnel strategy is the best choice. Obviously this kind of state does not conform to the reality, is an invalid state.

b, If $x < [N2-M2]/(-Q1-H1)$, $F'(y)|y=0 > 0$, $F'(y)|y=1 < 0$, At this point, y= 1 is the only evolutionary stability strategy; When the government chooses a tangible incentive strategy that does not reach a certain degree and shows a downward trend, the possibility of the building side choosing to develop a prefabricated and assembled urban tunnel strategy gradually increases, and the final choice to develop a traditional cast-in-situ urban tunnel is the best choice. Obviously this kind of state does not conform to the reality, is an invalid state.

3.1.3 Stability analysis of construction party's unilateral strategy

According to formula (12),the replication dynamic equation of construction party strategy is:

$$F(z)=z(1-z)(P2-K2+x(Q2+H2))$$

(1) If $x=(P2-K2)/(-Q2-H2)$, then $F(z) \equiv 0$, It means that regardless of any value of X, all levels of construction strategy are in a stable state.

(2) If $x \neq (P2-K2)/(-Q2-H2)$, When $F(z)=0$, z=0 and z=1 are the two stability points of the construction strategy replication dynamic equation. The derivative of F(z) is:

$$F'(z)=(1-2z)(P2-K2+x(Q2+H2))$$

Obvious, $Q2+H2>0$, it can be divided into two situations:

a, If $x>(P2-K2)/(-Q2-H2)$, $F'(z)|z=1>0$, $F'(z)|z=0<0$, At this point, z=0 is the only evolutionary stability strategy; When the government selects tangible incentive strategies to a certain extent and the trend is increasing, the possibility of the construction party choosing to build prefabricated and assembled urban tunnels gradually decreases, and the final choice to build traditional cast-in-situ urban tunnels is the best choice. Obviously this kind of state does not conform to the reality, is an invalid state.

b, If $x<(P2-K2)/(-Q2-H2)$, $F'(z)|z=0>0$, $F'(z)|z=1<0$, At this point, z= 1 is the only evolutionary stability strategy; When the government chooses a tangible incentive strategy that fails to reach a certain degree and shows a downward trend, the possibility of the construction party choosing to construct the prefabricated and assembled urban tunnel gradually increases, and the final choice to construct the prefabricated and assembled urban tunnel is the best choice. Obviously this kind of state does not conform to the reality, is an invalid state.

3.2 Solving the equilibrium points of evolutionary games

According to the evolutionary game theory, the equilibrium point when all eigenvalues of the Jacobian matrix have negative real part is the stable point of the evolutionary system (ESS)[11]. To find its equilibrium point, let:

$$\begin{cases} F(x)=0 \\ F(y)=0 \\ F(z)=0 \end{cases} \tag{13}$$

There are eight special equilibrium points, E1[0,0,0], E2[1,0,0], E3[0,1,0], E4[0,0,1], E5[1,1,0], E6[1,0,1], E7[0,1,1],E8[1,1,1],Constitutes the boundary of the solution domain of evolutionary game [12] :$R=\{(x,y,z)|0<x<1,0<y<1,0<z<1\}$。 And derivation of the replication dynamic equation of evolutionary game can be obtained as follows:

$$\begin{cases} F'(x)=(1-2x)\left[H2+H1-D3+z(C2-Q2-H2-B2)+y(C1-Q1-H1-B1)\right] \\ F'(y)=(1-2y)\left[N2-M2+x(Q1+H1)\right] \\ F'(z)=(1-2z)\left[P2-K2+x(Q2+H2)\right] \end{cases} \tag{14}$$

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3.3 The stability analysis of evolutionary game

According to the conclusions proposed by Ritzberger and Weibull[13],Therefore, only special equilibrium points E1~E8 are discussed, and other points are non-asymptotic stable states. When y=0, that is, the builder chooses to construct traditional cast-in-place tunnels without considering the promotion of prefabricated and assembled tunnels. Therefore, E1, E2, E4 and E6 are not considered [14].

The equilibrium point obtained by the replication dynamic equation is not necessarily the evolutionary stability strategy of the system, but according to Lyapunov's first method, the asymptotic stability of the replication dynamic system of the evolutionary game can be determined by the eigenvalues of the Jacobian matrix of the system, and the necessary and sufficient condition is that all the eigenvalues of the Jacobian matrix are less than 0. The Jacobian matrix of the above evolutionary system is obtained:

$$\begin{bmatrix} (1-2x)\left[H2+H1-D3+z(C2-Q2-H2-B2)+y(C1-Q1-H1-B1)\right] & x(1-x)(C1-Q1-H1-B1) & x(1-x)(C2-Q2-H2-B2) \\ y(1-y)(Q1+H1) & (1-2y)(N2-M2+x(Q1+H1)) & 0 \\ z(1-z)(Q2+H2) & 0 & (1-2z)(P2-K2+x(Q2+H2)) \end{bmatrix} \tag{15}$$

The four equilibrium points were substituted into the Jacobian matrix, and the eigenvalues of the Jacobian matrix corresponding to the equilibrium points were calculated, as shown in Table 3.

Table 3 Equilibrium points and eigenvalues of Jacobian matrix

Equantequation	Characteristic value			Status
	λ1	λ2	λ3	
E3[0,1,0]	H2+C1-D3-Q1-B1	M2-N2	P2-K2	indeterminacy
E5[1,1,0]	D3+Q1+B1-H2-C1	M2-N2-Q1-H1	P2+Q2+H2-K2	indeterminacy
E7[0,1,1]	C1+C2-D3-Q2-B1-B2-Q1	M2-N2	K2-P2	indeterminacy
E8[1,1,1]	D3+Q2+B1+B2+Q1-C1-C2	M2-N2-Q1-H1	K2-P2-Q2-H2	indeterminacy
Let G=H2+C1-D3-Q1-B1, U=C2+C1-D3-Q2-B1-B2-Q1, V=-Q1-H1, J=Q2+H2, I=M2-N2, L=P2-K2.				

According to the above analysis, it is impossible to make a clear judgment of the positive and negative eigenvalues corresponding to the equilibrium points, and there are many and complex parameters in the system model. Therefore, in order to facilitate the judgment of the eigenvalues of the Jacobian matrix corresponding to each equilibrium point, the following four general assumptions are made, as shown in Table 4.

Table 4 Assumptions on stability of equilibrium point of Jacobian matrix

Equantequation	Stability condition			Hypothesis
E3[0,1,0]	G＜0	I＜0	L＜0	Hypothesis1
E5[1,1,0]	-G＜0	I+V＜0	L+J＜0	Hypothesis2
E7[0,1,1]	U＜0	I＜0	-L＜0	Hypothesis3
E8[1,1,1]	-U＜0	I+V＜0	-L-J＜0	Hypothesis4

For example, according to lyapunov's first method, the eigenvalues of the jacobian matrix at the equilibrium point E3[0,1,0] satisfy hypothesis 1,when λ1= D3+Q2+B1+B2+Q1-C1-C2＜0,λ2=M2-N2-Q1-H1＜0,λ3=K2-P2-Q2-H2＜0,equilibrium point E3[0,1,0] is asymptotically stable, that is,

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evolutionary stability strategy; Similarly, the remaining three equilibrium points are also evolutionary stable strategies.

The evolutionary stability strategy of E3[0,1,0], E5[1,1,0] and E7[0,1,1] is a long-term stable state under the action of market mechanism. However, due to the high incremental cost of prefabricated and assembled urban tunnels, it is not the optimal strategy to promote prefabricated and assembled urban tunnels from a practical perspective.

When the jacobian eigenvalues of the equilibrium point E8[1,1,1] meet hypothesis 4, namely D3+Q1+Q2+B1+B2<C1+C2；M2<N2+Q1+H1；K2<P2+Q2+H2, In other words, when the above three conditions are met at the same time, the tripartite game will evolve to an ideal stable state. In the evolution of the steady state, the government, the building side and the construction party of the tripartite main body of prefabricated had a positive effect in the promotion of city tunnels, the obvious leading role of the government and the building side and the construction party jointly promote the system to reach a stable state. the strategy combination among will eventually converge to steady-state will depend on what evolutionary hypothesis 4 each the size of the parameter values, the strategy is the short-term rapid promotion prestressed assembly optimal stable strategy of city tunnel.

4. Conclusion

The development of prefabricated urban tunnel is still in the breakthrough stage, and the game between the government, the building side and the construction party needs to go through a process. The behavioral decisions of the three parties are influenced by their costs and benefits. Compared with the traditional cast-in-place process, the building side is inclined to choose the strategy of developing the precast assembled urban tunnel when the cost and profit of developing the precast assembled urban tunnel are lower and the penalty of environmental pollution caused by traditional cast-in-place is higher. When the government adopts the tangible incentive strategy to obtain high income but low cost, the government chooses the tangible incentive strategy. When the construction party chooses to optimize and improve the advantages of prefabrication during the construction stage, the cost is lower and the income is higher, and the penalty paid due to environmental pollution is higher, it tends to choose to optimize and improve the advantages of prefabrication during the construction stage.

This paper adopts the dynamic game analysis method, selects the government, the building side and the construction party as the three main parties, constructs the stakeholder incentive mechanism model to promote the development of prefabricated and assembled urban tunnels, and finally obtains the equilibrium solution of the dynamic game model. Different stakeholders have different willingness to participate, and each participant is affected by various factors, so different strategies need to be formulated. It is not only necessary to urge government departments to establish tangible incentive strategies, but also to focus on the cultivation of leading consciousness of building sides and construction parties at the present stage. The promotion of prefabricated and assembled urban tunnels is not only the responsibility of the government. It is hoped that the research in this paper will provide some theoretical guidance and reference for promoting the development of prefabricated and assembled urban tunnels, especially those with high prefabricated rate.

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