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Evolutionary Game Analysis of Construction Suspension Supervision under Persistent Disasters in the Greater Bay Area

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ABSTRACT

This study aims to provide a methodological contribution by demonstrating how to incorporate exogenous environmental temporal dynamics into evolutionary game models. Unlike existing adaptive Evolutionary Game Theory (EGT) models that primarily capture endogenous behavioral feedback (e.g., adjusting penalties based on violation rates), this framework mathematically formalizes how external environmental duration structurally alters the payoff matrix over time. Using the persistent typhoons in the Greater Bay Area (GBA) purely as a narrative device, this study examines how disaster duration alters the cost-benefit structure of suspension supervision and identifies conditions to prevent regulatory failure. We built a tripartite evolutionary game model among government regulatory departments, construction units, and third-party subjects. A disaster persistence index (D) was explicitly embedded into compliance costs, accident losses, and governance

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benefits. We also treated detection probability as a dynamic variable. Replicator dynamics and numerical simulations were used to analyze equilibrium stability and parameter sensitivity. The system reaches an ideal safety equilibrium (compliant suspension, diligent performance, strict supervision) when compliance returns and diligence benefits outweigh violation and collusion gains. However, as disaster duration (D) extends, accumulating compliance costs quickly erode compliance incentives. This shift can drive the system into a dangerous state of "violation and dereliction" despite strict supervision. Sensitivity analysis reveals that compliance costs have a critical threshold effect. While higher fines promote compliance, their marginal utility diminishes. Furthermore, excessive collusion rent induces third-party dereliction, and rising regulatory costs threaten supervision sustainability. The model theoretically supports a shift toward dynamic governance. While mechanisms like duration-linked penalties or targeted compensation align with the mathematical conditions for safety equilibrium, these remain theoretical pathways requiring empirical validation before practical application.

Keywords: Construction Safety; Evolutionary Game Theory; Disaster Persistence; Suspension Supervision; Guangdong–Hong Kong–Macao Greater Bay Area

1. Introduction

At the global level, climate change has significantly accelerated the frequency and intensity of extreme weather events, inflicting catastrophic damages on urban infrastructure and residential areas worldwide. With the increase of climate change, extreme weather has changed from "occasional disturbances" to a "regular risk" which includes repeatable occurrences and progressive damage. Therefore, the engineering safety management has been transformed from the control of individual accidents to the overall problem of risk management concentrating on system resilience [1,2]. This change is due to definite policy directions. At the national stage, great importance has always been attached to enhancing the ability of climate adaptation and strengthening the urban resilience. The National Strategy for Climate Change Adaptation 2035 regards risk recognition, early warning measures and the improvement of adaptive capacity as important tasks. At the regional level, the Development Plan for the Guangdong–Hong Kong–Macao Greater Bay Area considers the Greater Bay Area (GBA) as a significant carrier for a first-class city cluster and an international center for technological advancement. The safety and stability of the infrastructure and construction works in the GBA not only influence the relevant industry but are also closely related to the operational resilience and governmental credibility of the national strategic area [3]. Consequently, the GBA serves as an ideal motivating context for this theoretical study. Situated in an area vulnerable to various disasters, including typhoons, heavy rain and high temperatures, the dense construction in the GBA highlights how the suspension and resumption of work during disasters have a great influence on urban operational safety, the continuity of the supply chain and the spread of public risks. Relevant studies have already provided an important evidence base in directions such as urban-scale resilience construction [4,5] and site-scale disaster indicator identification [6].

In specific regulatory practices, the core challenge typically lies not in the emergency response at the moment of a disaster outbreak, but in the persistent characteristics of disaster weather. Cumulative effects in the time dimension dynamically reshape the cost-benefit structure of all parties. Unlike instantaneous shocks, prolonged peripheral circulation of typhoons or persistent rainstorms exposes construction sites to suspension costs that grow exponentially, such as idle equipment, labor downtime, contract defaults, and cash flow ruptures [7,8]. Furthermore, this persistence results in a "cost-compliance inversion": as the duration of work stoppage for risk prevention prolongs, the additional costs of unutilized equipment, delayed schedules and labor expenses rise greatly, while the physical and mental health and working efficiency of the workers decrease in difficult conditions [9]. Under heavy economic strain, the risk attitude of construction units might change, leading them to prefer opportunistic behaviors like concealment or early resumption of work. At this point, traditional static regulatory models, often constrained by limited resources, struggle to maintain high-frequency on-site verification, thereby exacerbating interest conflicts within the multi-party regulatory system [10]. This dynamic risk driven by disaster persistence exposes traditional regulatory mechanisms—based on fixed penalties and static game assumptions—to the risk of failure, easily inducing a governance paradox where "regulatory fatigue" coexists with "enterprise risk-taking."

Existing literature has made key contributions in engineering risk identification and resilience assessment. However, there is still a lack of a unified framework for the "persistence-driven suspension supervision failure mechanism" that can simultaneously characterize time-cumulative costs, multi-party strategy evolution, and the dynamic adjustment of regulatory tools. As digital supervision accelerates, current research focuses more on technical solutions themselves, such as digital twin early warning and management for tunnel construction [11], or discussing the reliability of improved detection algorithms in complex weather within other high-risk scenarios [12]. Some studies have also explored game strategies in prefabricated construction [13] and safety education promotion [14]. Yet they did not have any one framework for all time and cumulative and multiple-party strategies. Recent EGT literature has certainly introduced dynamic parameters, such as linking penalty intensities to violation rates or modeling time-dependent learning. However, these mechanisms primarily capture endogenous behavioral feedback. They assume the external environment acts as a static backdrop, with parameter shifts driven entirely by internal strategic interactions. The core scientific problem here is that these endogenous models cannot account for the exogenous temporal accumulation of persistent environmental shocks. When a disaster continues for days, the compounding compliance costs systematically invert the cost-benefit structure of the construction unit, regardless of how government regulatory departments adapt their strategies. If a regulatory model only responds to human behavior while ignoring the independent duration of the disaster, it misses the primary driver of compliance failure. To address this, the principal methodological contribution of this study is the explicit integration of an exogenous temporal variable—the disaster persistence index (D)—into the endogenous strategic evolution process. This shows how external time accumulation, rather than just player interaction, triggers regime shifts in regulatory systems.

To address this gap, this study is positioned as a methodological contribution demonstrating how to embed temporal dynamics into evolutionary game theory. Using the tripartite supervision system in the GBA purely as a narrative device rather than an empirical case study, the model examines how persistent disaster conditions affect strategic choices among the three actors and under what theoretical conditions regulatory failure can be avoided. The omission of temporal accumulation in existing literature represents a critical theoretical lacuna rather than a mere incremental gap. Because static frameworks cannot mathematically explain the 'cost-compliance inversion' observed during prolonged disasters, the main theoretical contribution of this study is the explicit incorporation of a disaster persistence index (D) into both the payoff structure and the dynamic detection mechanism. This ensures the model captures how prolonged exposure systematically alters the relative returns of compliant and non-compliant behavior. Specifically, we pose the following falsifiable research question: How does the disaster persistence index D quantitatively shift the evolutionary equilibrium of the tripartite supervision system? While the basic premise that prolonged disasters increase costs is intuitive, the exact algebraic thresholds where static regulation fails, and how third-party behaviors adapt to these shifts, remain undefined. To address this, we propose a core research hypothesis: there exists a critical disaster duration threshold, D^*. We hypothesize that when $D < D^*$, the system can maintain an ideal safety equilibrium (E_8) through strict supervision; however, when $D > D^*$, the exponential accumulation of compliance costs will inevitably breach the regulatory defense line, driving the system into a state of regulatory failure (E_4) regardless of static penalty intensities. By proving this hypothesis, this study aims to provide a theoretical foundation for shifting from static enforcement to dynamic, duration-linked regulatory mechanisms in the GBA.

2. Literature Review

2.1. Construction Safety Resilience and Suspension Mechanisms under Extreme Weather

Extreme weather events triggered by global climate change are breaking the traditional boundaries of construction safety management. At a macro level, continuous climate variability profoundly alters hydrological and environmental conditions, triggering cascading catastrophic effects on adjacent cities and residential villages (e.g., the spatiotemporal environmental changes observed in Lake Urmia)[15,16]. Consequently, engineering construction in different regions can no longer rely on generic defense standards but must establish adaptive strategies matched to local climate characteristics[17]. This emphasis on "adaptability" has been further corroborated in large-sample literature reviews. The current frontier of international disaster risk management has shifted toward comprehensive governance in the context of climate change; in particular, how to cope with the cascading effects triggered by disaster chains has become an urgent problem to be solved in the field of engineering safety[1].

Shifting focus from macro strategies to specific engineering practices, one of the greatest threats facing construction under extreme weather is flood risk. Green infrastructure plays a key role in mitigating urban flood risks. Research conducted in Beijing shows that this regional drainage and storage capacity effectively becomes the external safety baseline for work suspension and risk avoidance in individual projects[18]. At more micro construction nodes, for underground projects sensitive to hydrological environments, risk evolution is typically non-linear. A set pair analysis model established for subway tunnel construction under extreme rainfall scenarios points out the dynamic coupling relationship between rainfall intensity and surrounding rock stability. This indicates that during continuous disasters, judging the time for work suspension merely based on experience has considerable limitations, requiring the use of quantified dynamic indicators[19]. To overcome the constraints of the current assessment techniques, advanced studies have started to focus on deep learning techniques, aiming to discover the hidden relationships between the indicators of natural disasters and the accident records in building sites by using algorithms. This data-oriented method not only enhances the detail of risk detection but also offers a novel technique for carrying out precise monitoring under complicated and variable meteorological conditions[6]. Empirically, recent field investigations and case analyses in coastal regions confirm that prolonged exposure to typhoons directly correlates with increased unauthorized work resumptions. As construction units' financial buffers deplete over consecutive days of suspension, practical compliance rates drop significantly. However, these empirical realities of temporal cost accumulation have rarely been formalized into behavioral game models.

2.2. Multi-Party Behavioral Interactions and Interest Conflicts in Construction Safety Supervision

Safety control for big construction works is not a straightforward passage of official instructions, but a complicated social relationship composed of various participants. The internal power organization and trust systems in this network have a direct influence on the effectiveness of regulation. By studying large-scale projects like the Hong Kong–Zhuhai–Macao Bridge, it has been found that the conflicts among the involved parties have an evolutionary nature. During the process from planning to construction, the emphasis of each group changes, thus leading to continuous transformation of the main and secondary nodes in the regulatory network[20]. This structural complexity is particularly pronounced in the safety governance of special equipment such as tower cranes. Currently, China's construction industry suffers from a structural imbalance where "government power is excessive, while on-site supervision power is insufficient." This suppresses the collaborative governance effects among owners, supervisors, and construction units, making it difficult for regulatory pressure to effectively penetrate to the operational end[21]. Beyond power structures, psychological contracts and trust are equally critical factors in maintaining network stability. Misalignment often occurs between individual-level risk perception and organizational-level governance policies. If a trust-based communication framework is lacking between frontline workers and management, even perfect institutions cannot prevent violations from slowly breeding within the organization due to cognitive biases[22].

In complex network structures, the strategic choices of each game subject are essentially rational or boundedly rational behaviors based on cost-benefit calculations. A four-party game model points out the decisive role of "implicit costs" and "implicit benefits" in decision-making. Enterprises not only focus on explicit expenditures like fines but also care about implicit costs such as reputation loss and schedule delays. Meanwhile, government regulatory departments are constrained by the trade-off between regulatory costs and accident accountability risks when making decisions[10]. This game of economic rationality is often alienated by information asymmetry, especially when third-party subjects face interest temptations. Once the "collusion rent" offered by the contractor exceeds the supervisor's "dereliction cost," the third-party regulatory defense line disintegrates from within. Dealing with this issue, linking safety performance to economic benefits and penalties through different incentive systems can modify the payoff matrix for all parties and effectively discourage opportunistic behaviors [23]. Furthermore, the increased information transparency brought by digital technologies can effectively compress rent-seeking space, forcing construction units to re-evaluate the trade-off between "safety investment" and "violation risk" [24].

To cope with the aforementioned structural imbalances and conflicts of interest, the design of regulatory mechanisms is shifting from static administrative penalties to dynamic evolutionary game strategies. Traditional fixed penalty models are often lagging and inefficient when facing the constantly evolving violation methods of enterprises. Establishing a "dynamic penalty mechanism" linked to violation probability can more effectively lock the system's Evolutionarily Stable Strategy (ESS), keeping enterprises in a long-term state of compliance [23]. On this basis, introducing public supervision as a supplementary variable can effectively compensate for the insufficiency of government regulatory forces, forming an evolutionary path of "government-led, society-co-governed" [25]. Simultaneously, reasonable risk-sharing and compensation mechanisms can reduce the pressure of compliance costs on enterprises under extreme environments, preventing the game system from falling into a deadlock of "regulatory failure" [26]. Multiple studies consistently indicate that only when regulatory strategies can be adjusted in real-time based on the opponent's behavior, forming a self-adaptive feedback loop, can construction safety supervision truly escape the dilemma of the "cat-and-mouse game" and achieve a Pareto improvement in the interests of all parties [27,28].

2.3. Application of Evolutionary Game Theory in Engineering Safety Supervision

Evolutionary Game Theory (EGT) accurately describes the strategy changes and learning processes of boundedly rational agents in changing environments; hence, it is an important method for studying the complicated interest connections in construction safety supervision. Previous studies mainly established static payoff matrices among the government, construction unit and third-party subjects to find Evolutionarily Stable Strategies (ESS) in multi-agent games. In the present Chinese construction market, the internal mechanism of "supervision failure" is usually related to interests; if the rent-seeking advantages for third-party subjects are greater than the expected penalties they should bear, the third-party supervisory barrier will definitely break down [2]. Handling this regulatory problem by depending entirely on raising penalties cannot definitely enhance the compliance rate and might rather promote more hidden collusive behaviors. Incorporating reputation systems as additional restrictions usually leads to better administrative results [27]. Changing the emphasis from macro-control to micro-management, the safety behavior competition between general construction units and front-line workers shows distinct features. The violations of workers are usually short-sighted but rational decisions motivated by "saving effort" and "luck," while the construction unit's determination to spend on safety mainly relies on the deterrent effect of governmental supervision [29]. To break through the limitations of traditional static parameter models, recent studies have expanded the EGT framework by incorporating cognitive, structural, and technological variables. For instance, researchers have introduced Metaverse safety training [30], complex network structures [31], Prospect Theory for asymmetric risk perception [32], and Leader-Member Exchange (LMX) dynamics [33] to better reflect real-world heterogeneity. While alternative dynamic modeling approaches exist—such as Agent-Based Modeling (ABM) for micro-heterogeneity, stochastic games for probabilistic state transitions, or reinforcement learning for adaptive behaviors—EGT remains the preferred method in these advanced studies. This is because EGT uniquely derives explicit analytical thresholds under bounded rationality without requiring the massive empirical training datasets demanded by machine learning. Furthermore, dynamic mechanism designs utilizing digital empowerment have been proposed to adjust payoff matrices in real-time [34].

A critical synthesis of the literature reveals a methodological disconnect between environmental and behavioral modeling. Macro-resilience models capture the cumulative nature of environmental shocks well, but often treat regulatory behavior as a static boundary condition. Conversely, advanced EGT models successfully map complex strategic interactions and adaptive mechanisms—such as dynamically adjusting fines based on violation probabilities [23]—yet their payoff matrices rely on static environmental assumptions.

This highlights a specific theoretical limitation: current dynamic EGT models simulate how players react to one another over time, but not how they respond to an environment that compounds in severity. External weather shocks are still largely treated as isolated, instantaneous events rather than persistent processes that accumulate costs. The research gap lies in this incompatibility. Bridging it requires embedding an exogenous time-cumulative variable, such as the disaster persistence index (D), directly into the EGT payoff structure. This step separates our approach from existing adaptive models. It demonstrates that external temporal accumulation can unilaterally force a regulatory failure, even if the endogenous adaptive mechanisms function exactly as designed.

3. Evolutionary Model Assumptions and Description

3.1. Motivating Context: The Greater Bay Area

Guangdong–Hong Kong–Macao Greater Bay Area (GBA) is in southern coastal China, consisting of 9 cities from Guangdong province plus 2 special administrative regions of HK & Macau. As one of the world's most economically prosperous and densely crowded mega-city conglomerates, the GBA has a large amount of existing infrastructure and urban buildings. Nevertheless, it is located at the border of a subtropical monsoon climate with very frequent and heavy weather disasters, such as stormy weather, especially typhoons. In such conditions of intensive activity within a small volume of space where many things happen at once, GBA becomes a highly representative conceptual background to explore construction suspension supervision under persistent extreme weather. It is crucial to clarify that the GBA is utilized in this study as a theoretical motivating context rather than an empirical case study. The model abstracts the region's typical regulatory challenges—such as high compliance costs due to dense supply chains and severe expected losses from extreme wind loads—into mathematical parameters to explore generalizable evolutionary dynamics, rather than relying on specific regional meteorological datasets. Its geolocation and location are shown in **Figure 1**.

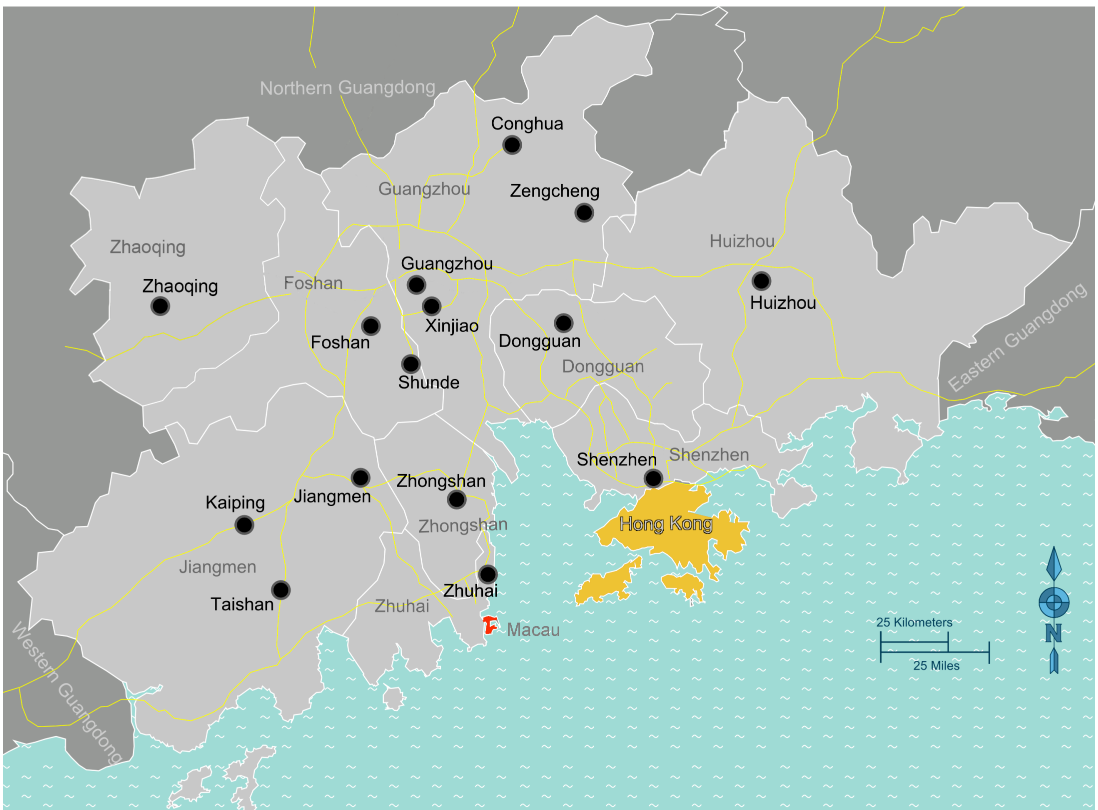

Figure 1. Location of the GBA, serving as the conceptual background for the theoretical model.

3.2. Method Statement and Data Collection

This study adopts a theoretical mechanism design approach combined with numerical simulation to analyze construction suspension supervision under persistent disasters. Rather than relying on empirical datasets such as questionnaire surveys or project-level accident statistics, the model's structural logic is derived from national climate adaptation policies, regional emergency management frameworks, and evolutionary game theory. As such, this study is not an empirical predictive framework. The GBA serves purely as a narrative device to contextualize the theoretical mechanisms. This study does not attempt to provide empirically calibrated findings for the region; rather, it uses the GBA's characteristics to demonstrate the proposed methodological framework for handling persistent external shocks. Specifically, the model does not utilize GBA-specific typhoon frequency statistics, actual fine amounts from local regulations, or real compliance cost estimates. Instead, the numerical simulations are designed to verify the mathematical stability of the replicator dynamics and demonstrate qualitative behavioral shifts. Consequently, the derived thresholds (such as the critical compliance cost $Cs*$) serve as structural algebraic boundaries that explain how variables interact, rather than providing absolute numerical targets for immediate policy deployment. Based on this theoretical foundation, we define the three game subjects, their strategy sets, and payoff variables to construct the tripartite evolutionary game model.

3.3. Model Description

The research model of this study is grounded in Evolutionary Game Theory (EGT), which assumes that participants are boundedly rational and dynamically adjust their strategies through continuous learning and imitation under information asymmetry. Based on this theoretical framework, this study focuses on the supervision of work suspension for risk avoidance in construction projects under the frequent occurrence of meteorological disasters in the Guangdong–Hong Kong–Macao Greater Bay Area (GBA). A tripartite evolutionary game model is constructed involving the government regulatory department, construction units, and third-party subjects (such as engineering supervision or safety monitoring agencies). During persistent disaster weather such as typhoons and rainstorms, the strategic choices of the three parties are collectively driven by the disaster persistence impact index, regulatory costs, and violation risks, ultimately forming a game equilibrium through dynamic adjustment. All variables used in the model and their meanings are presented in **Table 1**.

Table 1. Variables and Definitions.

Game Subject	Code	Variable	Definition
Government Regulatory Department	S_g	Subsidy/Incentive	Financial subsidies or credit points granted by the government to compliant construction units and diligent third parties.
	F_c	Construction Penalty	Fines and credit punishment costs for construction unit behaviors such as unauthorized work continuation and false reporting.
	F_t	Third-Party Penalty	Fines and industry punishment costs for third-party dereliction of duty and fraud.
	C_g	Regulatory Cost	Costs for on-site inspections, manpower investment, and information platform operation incurred by the government.
	$W(D)$	Social Governance Benefit	Benefits from accident reduction and urban resilience enhancement due to strict supervision; an increasing function of disaster index D.
Construction Unit	B	Project Revenue	Engineering output value or performance revenue from normal construction (baseline revenue).
	C_s	Compliance Cost	Key variable: Costs of suspension losses, personnel evacuation, and reinforcement, accumulating as D increases.
	$L_c(D)$	Accident Loss	Key variable: Expected losses (personnel/property) from accidents caused by violations, increasing as D increases.
	R_c	Reputation Benefit	Implicit benefits such as credit points and market reputation enhancement from compliant suspension.
Third-Party Subject	C_t	Diligence Cost	Labor and material costs required for increasing inspection frequency, re-testing, and data collection.
	$L_t(D)$	Joint Liability Loss	Joint compensation and impacts on professional qualification following an accident caused by dereliction, increasing as D increases.
	R_t	Reputation Benefit	Industry reputation, renewal opportunities, and credit evaluation enhancement from diligent performance.
Associated Variables	D	Persistence Impact	Core indicator: A composite index reflecting the duration and intensity of disaster weather.
	q	Detection Probability	The probability of violations being discovered and held accountable, influenced by regulatory strategies and disaster visibility.

The government regulatory department acts as the guardian of public safety. During persistent disaster weather, the government aims to maximize social governance benefits, i.e., reducing accidents through supervision. The variable $W(D)$ represents the social governance benefits brought by strict supervision, which is positively correlated with the disaster persistence index D; that is, the longer the duration and the greater the intensity of the disaster, the higher the social value of successful risk avoidance. Institutionally, this reflects the government's mandate to prevent cascading infrastructure failures as disasters prolong. The government adopts two policies: "strict control" and "relaxation of control." The policy of strict control involves a greater expenditure on regulation, Cg. In case of violation of rules by the construction unit or neglect by the third party, the government will impose fines, Fc and Ft, respectively. Moreover, the government spends on publicizing and training, Pg, to improve the compliance awareness of the industry and offers rewards, Sg, to the units which comply with the rules.

The construction unit is the executor of work stoppage for risk prevention, which involves the contradiction between "safety" and "profit." Its policies are "complying stoppage" and "violating construction." Variable B denotes the basic construction income under normal conditions. If the complying stoppage is selected, the construction unit will incur compliance costs Cs, which mainly consist of stoppage losses, personnel relocation and resettlement, and idle time costs. Furthermore, Cs will increase with the prolongation of the disaster period D. If we select unauthorized construction, for example, by continuing work without stopping or by giving false reports, although the loss due to suspension can be avoided, there will be risks of accidents. Economically, as deterministic suspension costs compound, the immediate pressure for financial survival often outweighs the probabilistic deterrence of accident risks, driving boundedly rational construction units to violate. The loss of variable $Lc(D)$ represents the expected losses resulting from an accident caused by violation, which includes compensation and damage to reputation. This loss is a function of D. The detection probability q of a violation is not a constant but depends on the degree of government supervision and the duration of the disaster.

The third-party subject, such as an engineering supervision or testing agency, serves as a critical bridge between the government and construction units. This entity is responsible for on-site monitoring and hazard mitigation. Its strategy space consists of 'Diligent Performance' and 'Dereliction'. Diligent performance incurs a cost Ct (e.g., increased inspection frequency and personnel deployment) but yields reputation benefits Rt and potential government subsidies Sg. Conversely, dereliction involves reducing inspection frequencies to save costs or colluding with construction units to conceal violations. Under typical fixed-fee contracts, the elevated physical costs of extreme weather inspections make such collusion an economically rational, albeit illegal, strategy to offset exposure. If an accident occurs or the dereliction is detected, the third party faces a joint liability loss $Lt(D)$ and an administrative fine Ft.

To resolve conceptual ambiguity, the disaster persistence index (D) is defined in this model as a dimensionless theoretical parameter. In practical regulatory contexts, it can be operationalized as a composite index: the cumulative hours a severe weather warning remains active (duration), multiplied by the specific warning level (intensity). In GBA construction projects, the interactions among the three parties exhibit dynamic game characteristics. For instance, during the prolonged impact of a typhoon (as the D value increases), the government faces escalating social management pressure, prompting stricter supervision. Simultaneously, the construction unit's compliance cost (Cs) rises sharply, strengthening the economic incentive for unauthorized resumption of work. Under these conditions, if the third-party subject fails to perform diligent on-site monitoring, the safety defense line is highly likely to collapse. By incorporating these variables, the proposed model captures how disaster duration alters the decision-making processes of the three stakeholders through compounding compliance costs and expected accident losses, thereby providing a theoretical foundation for dynamic regulatory strategies.

3.4. Evolutionary Model Assumptions

The three major game subjects in this study—the construction unit, the third-party subject, and the government regulatory department—are all boundedly rational participants. Under the premises of information asymmetry and the dynamic changes of the disaster environment, each party adjusts its strategies through continuous learning and imitation. To ensure the scientific nature and solvability of the model, the following assumptions are proposed:

Assumption 1: The strategy spaces of the three game parties are clearly defined. The strategy space for the Government Regulatory Department (G) is (Strict Supervision, Loose Supervision). The proportion of choosing strict supervision is z, and the proportion of choosing loose supervision is $1-z$. Strict supervision implies that the government incurs the full regulatory cost (Cg) to maintain high-frequency inspections and strictly enforces penalties and subsidies. Conversely, loose supervision involves maintaining only basic, routine inspections at a reduced cost, which consequently lowers the probability of detecting violations.

Assumption 2: The disaster persistence index D has a nonlinear amplification effect. It is assumed that the construction unit's compliance cost Cs and the expected accident loss $Lc(D)$ are both positively correlated with D. Specifically, drawing upon supply chain disruption literature and organizational resource depletion, the economic strain of prolonged suspension is rarely linear; as buffers deplete, costs compound. To capture the exponential accumulation of costs over time (e.g., contract defaults, supply chain disruptions), the compliance cost is formally modeled as an exponential function of duration: $C_s(D) = C_{base} \times e^{\alpha D}$, where C_{base} is the baseline unit cost and α is the disaster amplification coefficient ($\alpha > 0$). This exponential specification is deliberately selected over linear or polynomial forms to reflect the cascading nature of construction delays. While short suspensions primarily incur linear daily expenses (e.g., basic idle labor and equipment rental), prolonged stoppages typically trigger non-linear compounding financial penalties, such as critical path schedule overruns, breach of contract fines, and severe supply chain bottlenecks. This means the longer the disaster lasts, the greater the economic cost of suspension, which serves as the core driver for the construction unit's violation. Simultaneously, the social governance benefit $W(D)$ also increases nonlinearly with the increase of D, reflecting the high value of government supervision in the face of major disasters.

Assumption 3: The probabilistic structures of detection (q) and accidents (p) are bounded, monotonic, and strategy-dependent. First, the detection probability q ($0 \leq q \leq 1$) depends on the joint regulatory intensity. Mathematically, these state-dependent probabilities satisfy the following inequality: $q_{RD}(D) > max(q_{RN}(D), q_{LD}(D)) > min(q_{RN}(D), q_{LD}(D)) > q_{LN}(D)$. Furthermore, as disaster duration D extends, the physical manifestation of violations (e.g., deep water accumulation, obvious loosening of scaffolding) becomes more visible, meaning all detection probabilities are monotonically increasing with D ($\frac{\partial q}{\partial D} > 0$). To operationalize these probabilities for numerical simulation, we deliberately adopt a bounded exponential growth model (e.g., $q_{ij}(D) = q_{ij}^{max} - (q_{ij}^{max} - q_{ij}^{min}) \cdot e^{-\beta D}$). This specific functional form is chosen over linear or polynomial specifications for two fundamental reasons: mathematically, it ensures that probabilities strictly asymptote to a maximum limit (≤ 1) rather than growing infinitely to violate probability axioms; behaviorally, it accurately captures the 'diminishing marginal visibility' of hazards, where the physical manifestation of violations (e.g., site flooding) becomes obvious quickly but eventually plateaus. Second, the accident probability p ($0 \leq p \leq 1$) depends on the third party's performance. A diligent third party effectively mitigates on-site risks, ensuring$p_D(D) < p_N(D)$. Simultaneously, the cumulative destructive force of persistent disasters implies that accident probabilities also monotonically increase over time ($\frac{\partial p}{\partial D} > 0$). Similarly, the functional form used in the simulation is defined as: $p_k(D) = p_k^{max} - (p_k^{max} - p_k^{min}) \cdot e^{-\gamma D}$, where $k \in \{D, N\}$ and γ is the risk accumulation coefficient.

Assumption 4: The profit and loss transfer logic for each party's strategic choice is clearly defined. When the construction unit chooses compliant suspension, it incurs a compliance cost Cs, but gains reputation benefits Rc and government subsidies Sg. If it chooses violation construction and is detected, it faces expected accident losses $Lc(D)$ and an administrative fine Fc. For the third-party subject, choosing diligent performance incurs a cost Ct. If it chooses dereliction and an accident occurs or the violation is detected, it bears joint liability losses $Lt(D)$ along with the fine Ft.

Assumption 5: All game parties are boundedly rational and risk-neutral, pursuing the maximization of their expected utility. The government's subsidy budget and fine income are included in its overall utility function, reflecting a balance between financial expenditure and social security benefits.

The parameter settings adopted in this study are mainly intended to reflect the relative strength of incentives, penalties, and losses among the three parties in a stylized decision environment, rather than to represent empirically calibrated policy estimates. In the same spirit, the functional forms introduced above are used to capture several basic features relevant to construction safety supervision under persistent disasters, including the cumulative increase in compliance cost and the bounded variation of detection and accident probabilities as disaster persistence changes.

4. Construction and Analysis of the Evolutionary Model

4.1. Model Construction

In the game model, it is assumed that the probability of the Construction Unit choosing the 'Compliant Suspension' strategy is x, and the probability of choosing the 'Violation Construction' strategy is $1-x$. The probability of the Third-party Subject choosing the 'Diligent Performance' strategy is y, and the probability of choosing the 'Dereliction/Collusion' strategy is $1-y$. The probability of the Government Regulatory Department choosing 'Strict Supervision' is z, and the probability of choosing 'Loose Supervision' is $1-z$. Based on the assumptions and variable definitions above, the tripartite mixed-strategy game payoff matrix involving the government regulatory department, the construction unit, and the third-party subject is constructed, as shown in **Table 2**.

Table 2. Tripartite Mixed-Strategy Game Payoff Matrix.

Construction Unit Strategy	Third-Party Strategy	Government: Strict Supervision (*R*)	Government: Loose Supervision (*L*)
Compliant Suspension (*S*)	Diligent (*D*)	Construction: $-C_s(D)+R_c+S_g$ Third-Party: $-C_t+R_t+S_g$ Gov: $W(D)-C_g-2S_g$	Construction: $-C_s(D)+R_c+S_g$ Third-Party: $-C_t+R_t+S_g$ Gov: $\theta W(D)-\kappa C_g-2S_g$
	Dereliction (N)	Construction: $-C_s(D)+R_c+S_g$ Third-Party: $M-p_N(D)L_t(D)-q_{RN}(D)F_t$ Gov: $W(D)-C_g-S_g+q_{RN}(D)F_t$	Construction: $-C_s(D)+R_c+S_g$ Third-Party: $M-p_N(D)L_t(D)-q_{LN}(D)F_t$ Gov: $\theta W(D)-\kappa C_g-S_g+q_{LN}(D)F_t$
Violation Construction (V)	Diligent (*D*)	Construction: $B-p_D(D)L_c(D)-q_{RD}(D)F_c$ Third-Party: $-C_t+R_t+S_g$ Gov: $W(D)-C_g-S_g+q_{RD}(D)F_c-p_D(D)L_g(D)$	Construction: $B-p_D(D)L_c(D)-q_{LD}(D)F_c$ Third-Party: $-C_t+R_t+S_g$ Gov: $\theta W(D)-\kappa C_g-S_g+q_{LD}(D)F_c-p_D(D)L_g(D)$
	Dereliction (N)	Construction: $B-p_N(D)L_c(D)-q_{RN}(D)F_c$ Third-Party: $M-p_N(D)L_t(D)-q_{RN}(D)F_t$ Gov: $W(D)-C_g+q_{RN}(D)(F_c+F_t)-p_N(D)L_g(D)$	Construction: $B-p_D(D)L_c(D)-q_{RD}(D)F_c$ Third-Party: $M-p_N(D)L_t(D)-q_{LN}(D)F_t$ Gov: $\theta W(D)-\kappa C_g+q_{LN}(D)(F_c+F_t)-p_N(D)L_g(D)$

Note: $q_{RD}(D)$ = detection probability under strict government supervision and diligent third-party performance; $q_{RN}(D)$ = detection probability under strict government supervision and derelict third-party performance; $q_{LD}(D)$ = detection probability under loose government supervision and diligent third-party performance; $q_{LN}(D)$ = detection probability under loose government supervision and derelict third-party performance. $p_D(D)$ = accident probability under diligent third-party performance; $p_N(D)$ = accident probability under derelict third-party performance. θ = discount coefficient of social governance benefits under loose supervision ($0<\theta<1$); κ = cost coefficient of loose supervision ($0<\kappa<1$); M = implicit benefit (e.g., cost savings or collusion rent) obtained by the third party when choosing dereliction.

4.2. Game Model Analysis

According to evolutionary game theory, each game subject adjusts their strategy choice by comparing the expected returns of different strategies. If the expected return of a specific strategy is higher than the average return, the proportion of that strategy in the population will increase over time. The following section derives the replicator dynamic equations for the construction unit, the third-party subject, and the government regulatory department, respectively. Specifically, the expected return for each strategy is calculated as the probability-weighted sum of the corresponding payoffs from Table 2, given the mixed-strategy profiles of the other two interacting parties. This ensures all parameters are systematically traced from the static matrix into the dynamic equations.

(1) Expected Revenue and Replicator Dynamics of the Construction Unit

The expected return for the construction unit choosing "Compliant Suspension" is:

$$\begin{gathered}E_x=(-C_s(D)+R_c+S_g)yz\\+(-C_s(D)+R_c+S_g)y(1-z)+(-C_s(D)+R_c\\+S_g)(1-y)z+(-C_s(D)+R_c+S_g)(1-y)(1-z)\end{gathered}$$

The expected return for the construction unit choosing "Violation Construction" is:

$$\begin{gathered}E_{1-x}=(B-p_D(D)L_c(D)-q_{RD}(D)F_c)yz\\+(B-p_D(D)L_c(D)-q_{LD}(D)F_c)y(1-z)\\+(B-p_N(D)L_c(D)-q_{RN}(D)F_c)(1-y)z\\+(B-p_N(D)L_c(D)-q_{LN}(D)F_c)(1-y)(1-z)\end{gathered}$$

The average return of the construction unit is:

$$\bar{E} = xE_x + (1-x)E_{1-x}$$

The replicator dynamic equation for the construction unit is:

$$F(x) = \frac{dx}{dt} = x(E_x - \bar{E}) = x(1-x)(E_x - E_{1-x})$$

(2) Expected Revenue and Replicator Dynamics of the Third-Party Subject

The expected return for the third party choosing "Diligent Performance" is:

$$\begin{gathered} E_y = (-C_t + R_t + S_g)xz \\ +(-C_t + R_t + S_g)x(1-z) \\ +(-C_t + R_t + S_g)(1-x)z \\ +(-C_t + R_t + S_g)(1-x)(1-z) \end{gathered}$$

The expected return for the third party choosing "Dereliction/Collusion" is:

$$\begin{gathered} E_{1-y} = (M - q_{RN}(D)F_t)xz \\ +(M - q_{LN}(D)F_t)x(1-z) + (M - p_N(D)L_t(D) \\ -q_{RN}(D)F_t)(1-x)z + (M - p_N(D)L_t(D) \\ -q_{LN}(D)F_t)(1-x)(1-z) \end{gathered}$$

The average return of the third party is:

$$\bar{E} = yE_y + (1-y)E_{1-y}$$

The replicator dynamic equation for the third party is:

$$F(y) = \frac{dy}{dt} = y(E_y - \bar{E}) = y(1-y)(E_y - E_{1-y})$$

(3) Expected Revenue and Replicator Dynamics of the Government Regulatory Department

The expected return for the government choosing "Strict Supervision" is:

$$\begin{gathered} E_z = (W(D) - C_g - 2S_g)xy + (W(D) - C_g - S_g \\ +q_{RN}(D)F_t)x(1-y) + (W(D) - C_g - S_g \\ +q_{RD}(D)F_c - p_D(D)L_g(D))(1-x)y + [W(D) \\ -C_g + q_{RN}(D)(F_c + F_t) \\ -p_N(D)L_g(D)](1-x)(1-y) \end{gathered}$$

The expected return for the government choosing "Loose Supervision" is:

$$\begin{gathered} E_{1-z} = (\theta W(D) - \kappa C_g - 2S_g)xy + (\theta W(D) \\ -\kappa C_g - S_g + q_{LN}(D)F_t)x(1-y) + (\theta W(D) \\ -\kappa C_g - S_g + q_{LD}(D)F_c - p_D(D)L_g(D))(1-x)y \\ +[\theta W(D) - \kappa C_g + q_{LN}(D)(F_c + F_t) \\ -p_N(D)L_g(D)](1-x)(1-y) \end{gathered}$$

The average return of the government is:

$$\bar{E} = zE_z + (1-z)E_{1-z}$$

The replicator dynamic equation for the government is:

$$F(z) = \frac{dz}{dt} = z(E_z - \bar{E}) = z(1-z)(E_z - E_{1-z})$$

4.3. Evolutionary System Equilibrium Analysis

According to the stability principle of replicator dynamic equations, by setting $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$, we obtain eight pure strategy equilibrium points in the three-dimensional space $V = \{(x,y,z) \mid 0 \le x \le 1, 0 \le y \le 1, 0 \le z \le 1\}$: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, and $E_8(1,1,1)$. Furthermore, while mixed strategy equilibrium points may exist, mixed strategies are typically not Evolutionarily Stable Strategies (ESS) in asymmetric games. Therefore, this study focuses on analyzing the asymptotic stability of the eight pure strategy equilibrium points.

The stability of this tripartite evolutionary game system can be analyzed using the Jacobian matrix proposed by Friedman. The Jacobian matrix J is obtained by taking the partial derivatives of the replicator dynamic equations with respect to x, y, and z, respectively. The general Jacobian matrix J is constructed by taking the first-order partial derivatives of the replicator dynamic equations $F(x)$, $F(y)$, and $F(z)$ with respect to x, y, and z:

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

According to Lyapunov's first method, an equilibrium point is an Evolutionarily Stable Strategy (ESS) if and only if all eigenvalues (λ) of the corresponding Jacobian matrix have real parts less than 0. If the signs of the eigenvalues are not all negative, the point is an unstable point or a saddle point.

By substituting the eight pure strategy equilibrium points into the Jacobian matrix and combining them with the payoff matrix in **Table 2**, the eigenvalues corresponding to each equilibrium point can be calculated. Since the Jacobian matrix is typically a diagonal matrix at pure strategy points, its diagonal elements are the eigenvalues λ_1, λ_2, and λ_3. Specifically:

$$\lambda_1 = \frac{\partial F(x)}{\partial x}\Big|_{(1,1,1)} = -(E_x - E_{1-x}) = E_{1-x} - E_x$$

$$\lambda_2 = \frac{\partial F(y)}{\partial y}\Big|_{(1,1,1)} = -(E_y - E_{1-y}) = E_{1-y} - E_y$$

$$\lambda_3 = \frac{\partial F(z)}{\partial z}\Big|_{(1,1,1)} = -(E_z - E_{1-z}) = E_{1-z} - E_z$$

By substituting the specific payoff functions from **Table 2** into these diagonal elements, we obtain the explicit eigenvalue expressions. This identical derivation process is applied to all eight pure strategy equilibrium points. To resolve previous notation inconsistencies, all dynamic variables strictly denote their dependence on the disaster index (D). The complete and standardized eigenvalues are presented in **Table 3**.

Equilibrium Points under Loose Supervision are all Unstable (E_1, E_2, E_3, E_5). Under the continuous influence of disaster weather (where the value of D is large), the government's social governance benefit $W(D)$ increases significantly. According to the assumptions, the marginal social benefit of strict supervision ΔW is usually greater than the marginal supervision cost ΔCg. Consequently, the government's eigenvalue λ_3 is constantly positive at these points ($\lambda_3 > 0$), meaning the government has a strong incentive to switch from "Loose" to "Strict" supervision, making these points unstable. However, if extreme disaster duration causes regulatory costs to surge such that $\Delta Cg > \Delta W$ (i.e., $\lambda_3 < 0$), the government will be forced into loose supervision, and points like E_1 or E_5 could mathematically become stable. For the purpose of exploring the ideal safety equilibrium in this study, our subsequent simulations focus on the boundary where $\Delta W > \Delta Cg$ is maintained.

Table 3. System Equilibrium Points, Eigenvalues, and Stability Analysis.

Equilibrium Point	λ_1 (Construction Unit)	λ_2 (Third-Party Subject)	λ_3 (Government Dept)	Conclusion
$E_1(0,0,0)$	$-C_s(D)+R_c+S_g-[B-p_N(D)L_c(D)-q_{LN}(D)F_c]$	$-C_t+R_t+S_g-[M-p_N(D)L_t(D)-q_{LN}(D)F_t]$	$\Delta W-\Delta C_g+(q_{RN}(D)-q_{LN}(D))(F_c+F_t)$	Unstable Point
$E_2(1,0,0)$	$[B-p_N(D)L_c(D)-q_{LN}(D)F_c]-[-C_s(D)+R_c+S_g]$	$-C_t+R_t+S_g-[M-p_N(D)L_t(D)-q_{LN}(D)F_t]$	$\Delta W-\Delta C_g+(q_{RN}(D)-q_{LN}(D))F_t$	Unstable Point
$E_3(0,1,0)$	$-C_s(D)+R_c+S_g-[B-p_D(D)L_c(D)-q_{LD}(D)F_c]$	$[M-p_N(D)L_t(D)-q_{LN}(D)F_t]-[-C_t+R_t+S_g]$	$\Delta W-\Delta C_g+(q_{RD}(D)-q_{LD}(D))F_c$	Unstable Point
$E_4(0,0,1)$	$-C_s(D)+R_c+S_g-[B-p_N(D)L_c(D)-q_{RN}(D)F_c]$	$-C_t+R_t+S_g-[M-p_N(D)L_t(D)-q_{LN}(D)F_t]$	$-[\Delta W-\Delta C_g+(q_{RN}(D)-q_{LN}(D))(F_c+F_t)]$	Uncertain
$E_5(1,1,0)$	$[B-p_D(D)L_c(D)-q_{LD}(D)F_c]-[-C_s(D)+R_c+S_g]$	$[M-p_N(D)L_t(D)-q_{RN}(D)F_t]-[-C_t+R_t+S_g]$	$\Delta W-\Delta C_g$	Unstable Point
$E_6(1,0,1)$	$[B-p_N(D)L_c(D)-q_{RN}(D)F_c]-[-C_s(D)+R_c+S_g]$	$-C_t+R_t+S_g-[M-p_N(D)L_t(D)-q_{RN}(D)F_t]$	$-[\Delta W-\Delta C_g+(q_{RN}(D)-q_{LN}(D))F_t]$	Unstable Point
$E_7(0,1,1)$	$-C_s(D)+R_c+S_g-[B-p_D(D)L_c(D)-q_{RD}(D)F_c]$	$[M-p_N(D)L_t(D)-q_{RN}(D)F_t]-[-C_t+R_t+S_g]$	$-[\Delta W-\Delta C_g+(q_{RD}(D)-q_{LD}(D))F_c]$	Unstable Point
$E_8(1,1,1)$	$[B-p_D(D)L_c(D)-q_{RD}(D)F_c]-[-C_s(D)+R_c+S_g]$	$[M-p_N(D)L_t(D)-q_{RN}(D)F_t]-[-C_t+R_t+S_g]$	$-[\Delta W-\Delta C_g]$	ESS

Note: $\Delta W=(1-\theta)W(D), \Delta C_g=(1-\kappa)C_g$.

The Risk Point of Regulatory Failure (E_4): The equilibrium E_4(0,0,1) represents a worst-case scenario where strict government regulation coexists with widespread construction violations and third-party dereliction. Instead of labeling its stability as "uncertain," we can rigorously define its stability conditions. E_4 becomes an Evolutionarily Stable Strategy (ESS) if $\lambda_1 < 0$, $\lambda_2 < 0$, and $\lambda_3 < 0$. Based on **Table 3**, this requires the penalty intensities to fall below specific thresholds: $F_c < \frac{B-p_N(D)L_c(D)+C_s(D)-R_c-S_g}{q_{RN}(D)}$ and $F_t < \frac{M-p_N(D)L_t(D)+C_t-R_t-S_g}{q_{LN}(D)}$. If the static penalties (F_c,

F_t) fail to exceed these exact boundaries, the system becomes locked in this regulatory failure state. Managerially, this mathematical boundary reveals that under prolonged disasters, traditional static administrative penalties inevitably lose their deterrent effect, highlighting the institutional necessity for dynamic, duration-linked regulatory interventions rather than merely increasing fixed fines.

The Ideal Evolutionary Stable Strategy (E_8): $E_8(1, 1, 1)$ is the target state pursued in this study. The conditions for it to be judged as an "Evolutionary Stable Strategy (ESS)" are as follows:

For the Government: It must satisfy $\Delta W > \Delta Cg$. In the context of disasters such as typhoons and rainstorms, public safety is of the highest priority, so this condition is naturally met. For the Construction Unit: It must satisfy $\lambda_1 < 0$. By extracting λ_1 from **Table 3** and setting $\lambda_1 = 0$, we can formally derive the critical disaster duration threshold (D^*). The equilibrium condition requires: $[B - p_D(D)L_c(D) - q_{RD}(D)F_c] - [-C_s(D) + R_c + S_g] < 0$. Rearranging this inequality to isolate the compliance cost yields: $C_s(D) < p_D(D)L_c(D) + q_{RD}(D)F_c - B + R_c + S_g$. By substituting the exponential cost function $C_s(D) = C_{base}e^{\alpha D}$ (defined in Assumption 2) into this inequality and solving for D, we obtain the explicit mathematical boundary: $D < \frac{1}{\alpha}\ln(\frac{p_D(D)L_c(D)+q_{RD}(D)F_c-B+R_c+S_g}{C_{base}})$. Let the right side of this equation be defined as D^*. This formal derivation mathematically proves that the system can only maintain the ideal safety equilibrium (E_8) when the actual disaster duration D remains strictly below D^*. Once $D > D^*$, the exponential accumulation of compliance costs mathematically breaches the regulatory defense line, making the net benefit of violation exceed that of compliance. This indicates that the government's static fine F_c and the accident risk deterrence $L_c(D)$ are eventually overwhelmed by the surging suspension cost, rendering regulatory failure unavoidable.

For the Third-Party Subject: It must satisfy $\lambda_2 < 0$. By extracting the eigenvalue from **Table 3** and setting it strictly less than zero, we establish the explicit algebraic condition: $C_t < R_t + S_g - M + p_N(D)L_t(D) + q_{RN}(D)F_t$. Mathematically, this implies that the third party's cost of diligence (Ct) must be strictly bounded by the sum of its compliance benefits ($R_t + S_g$) and the expected regulatory/liability penalties ($p_N(D)L_t(D) + q_{RN}(D)F_t$), minus the collusion rent (M).

Other Intermediate States (E_6, E_7) and Free-Rider Dynamics: The intermediate states show a dynamic manifestation of the classic free-rider problem from principal-agent literature. When the construction unit strictly complies, the immediate on-site accident risk drops. The third party is then economically incentivized to free-ride on the construction unit's safety investments to save its own diligence cost (C_t). This shows that the ideal equilibrium (E_8) is fragile and prone to reverting to E_6 unless regulatory pressure targets third-party dereliction directly. Increasing the penalty (Ft) for unilateral dereliction forces the third party back toward diligence, destabilizing these intermediate points.

5. Results and Simulation Analysis

5.1. Evolutionary Stable Strategy

Based on the Jacobian matrix analysis, the ideal Evolutionary Stable Strategy (ESS) of the system points to$E_8(1, 1, 1)$, representing the strategy combination of "Construction Unit Compliant Suspension, Third-party Diligent Performance, and Government Strict Supervision." In the context of the Guangdong–Hong Kong–Macao Greater Bay Area, characterized by high building density and the strong destructive power of typhoons, the baseline parameters for the numerical simulation are conceptually inspired by the region's typical regulatory framework and disaster characteristics. These parameters are relative utility weights designed to verify the mathematical stability of the replicator dynamics, rather than calibrated monetary values derived from GBA statistical yearbooks. While theoretical, this equilibrium point represents the Pareto optimal state that maximizes social public safety benefits. For this stable condition to be maintained, the main constraint would be that it was the case where violation would mean a negative net benefit on the part of construction units and a positive value on the part of the third party would also occur for the third party's diligence, which is $\lambda < 1$. This means that the sum of the penalties imposed by the government regulatory departments Fc and Ft, together with the likelihood that the catastrophe $Lc(D)$ may generate, must erect such a formidable barrier of "cost" so as to offset a compliance cost $Cs(D)$ that rises exponentially as the duration of the suspension D prolongs. For the numerical simulations, the baseline parameters are calibrated based on the general practice of GBA construction projects. To address the dynamic probability variables defined in Assumption 3, we establish their baseline initial values (at $D = 0$) as follows: $q_{RD}^{min} = 0.8, q_{RN}^{min} = 0.6, q_{LD}^{min} = 0.5, q_{LN}^{min} = 0.3$. The initial accident probabilities are $p_{D}^{min} = 0.2, p_{N}^{min} = 0.7$. To ensure full reproducibility of the dynamic simulations across varying disaster durations, the upper limits for the bounded exponential functions are set as $q_{ij}^{max} = min(q_{ij}^{min} + 0.15, 1.0)$ and $p_{k}^{max} = min(p_{k}^{min} + 0.2, 1.0)$, with growth coefficients $\beta = 0.1$ and $\gamma = 0.1$. The remaining economic parameters are set as follows: $B = 100$, $Rc = 20$, $Sg = 15$, $Fc = 80$, $Ft = 40$, $Ct = 25$, $M = 50$, $W = 150$, and $Cg = 30$. Note that these values denote relative utility units rather than exact monetary amounts, which are used to test the evolutionary trends under the E_8 state. We selected these baseline values to strictly satisfy the mathematical inequalities derived in Section 4.3 for the E_8 equilibrium (e.g., ensuring initial penalties outweigh baseline compliance costs). This establishes a theoretically valid regulatory starting point before the disaster duration (D) begins to extend. In these numerical simulations, the x-axis represents the abstract evolutionary time (t), which denotes the iterative process of strategy adjustment among the boundedly rational agents. The simulation is set to terminate, and convergence is achieved, when the population proportion of a strategy reaches either 0.01 or 0.99. The global convergence trajectories using these initial settings are illustrated in **Figure 2**.

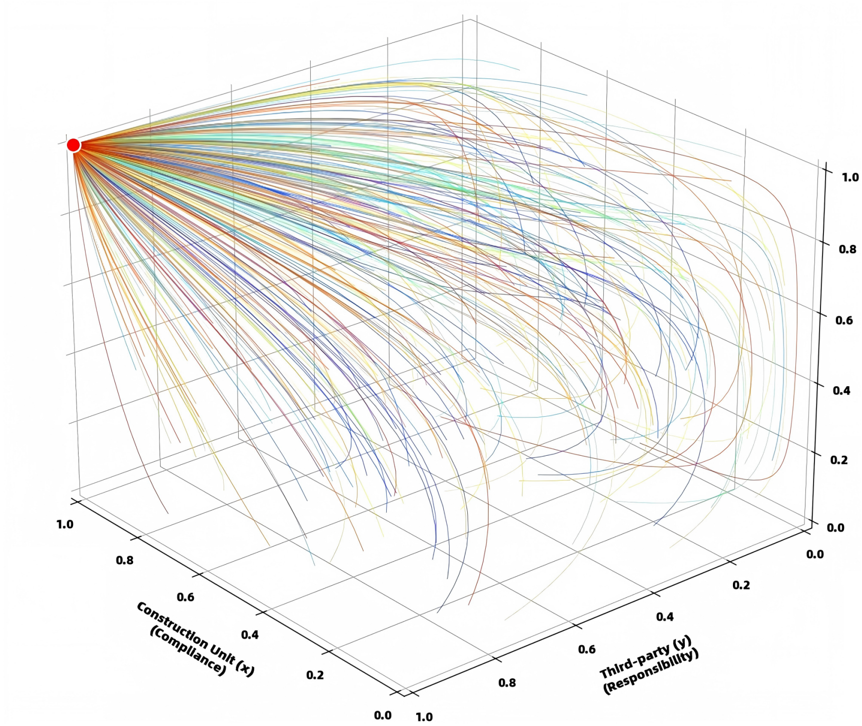

Figure 2. Global convergence trajectories of tripartite strategies evolving towards $E_8(1,1,1)$ under persistent disaster impact (Simulation runs n = 150).

But despite that sturdiness, it still had some serious "temporary fragility". This model has one important discovery: the steadiness in an evolving setup is no fixed point, but is constantly driven around by a disaster continuity mark D. As disaster duration D goes on, the cumulative effect of compliance costs, denoted as $Cs(D)$, produces an immense centrifugal power trying to push the construction unit out of the following rules and into breaking them. When the D value passes a certain crucial level, causing the total cost of conformity to surpass the total cost of violations, the inequality switches directions. The system will soon break away from its perfect E_8 status and tumble down to the $E_4(0,0,1)$ "regulation collapse" situation. Here, in this situation, even though the government does keep up strict oversight, it just feels there isn' t really anything left, because they' d lose everything else if forced to close off, which makes more third parties care less about it, given the increased amount in keeping it under control.

To determine whether systemic collapse could be delayed or prevented, numerical simulations were conducted rather than merely confirming the existence of an equilibrium point. Focuses on simulation of intervention effects on the three evolutionary trajectories via intensity differentials between regulatory instruments like time-varying punishment/precision aid with respect to varying levels of disaster continuity *D*. To find out what sort of boundary would make the system land on E_8's stable area with various parameters, this kind of research will be helpful to know about the suspension supervision policy in the GBA to face long-term extreme weather.

5.2. Sensitivity Analysis

The sensitivity analysis in this paper follows a one-factor-at-a-time design, in which individual parameters are varied separately in order to illustrate their directional effects on the evolutionary trajectories of the system. This approach is useful for identifying the influence of specific parameters under the current model setting, although it does not fully capture the interaction effects that may arise when multiple parameters change simultaneously in a nonlinear evolutionary game.

In this part, we look at what makes the system move from being not quite right towards the really good state called $E_8(1,1,1)$ then see if the system is okay with having more disasters happen over time by using computers to check things out on a list that has important parts of it. Pay attention to every single one of these subjects' choices in strategies based on their trajectory deviations throughout various points in time where we' ve changed some very minor aspects of our setup. Try to find out those sensitive factors about suspending supervision of construction projects within the Greater Bay Area.

This section conducts a sensitivity analysis to identify the key factors driving the system toward the ideal equilibrium $E_8(1,1,1)$and to evaluate the system's robustness under prolonged disaster conditions. By systematically varying critical parameters, we observe the trajectory deviations in the strategic choices of the three subjects. This analysis aims to uncover the sensitive variables influencing suspension supervision in the GBA.

5.2.1. Sensitivity Analysis of Variables Related to Construction Units

- **Sensitivity Analysis of Compliant Suspension Cost (*Cs*)**

It should be noted that while $C_s(D) = C_{base} \times e^{\alpha D}$ is a continuous function, the evolutionary time (*t*) on the x-axis represents a micro-behavioral timescale. To align them, we decouple these scales by treating *D* as a discrete scenario parameter. The different constant values of *Cs* in the simulation simply represent specific snapshots of the disaster at different duration stages (e.g., early-stage versus late-stage disaster impact). As shown in **Figure 3**, when simulating scenarios with longer disaster durations (i.e., higher discrete levels of *Cs*), the construction unit's convergence to "Compliant suspension" significantly slows down. Importantly, the exact location of this threshold *Cs** is not a fixed, unique number; it is highly dependent on the regulatory parameter mix and shifts rightward (increasing system robustness) when offset by higher fines (*Fc*) or subsidies (*Sg*). However, once *Cs* exceeds the theoretical threshold *Cs**, the system experiences a sudden regime shift rather than a gradual decline. The evolutionary trajectory abruptly reverses, dragging the third party into dereliction. This bifurcation indicates a highly non-linear dynamic: compliance remains deceptively stable until the financial buffer is completely exhausted, at which point the entire regulatory structure collapses instantly.

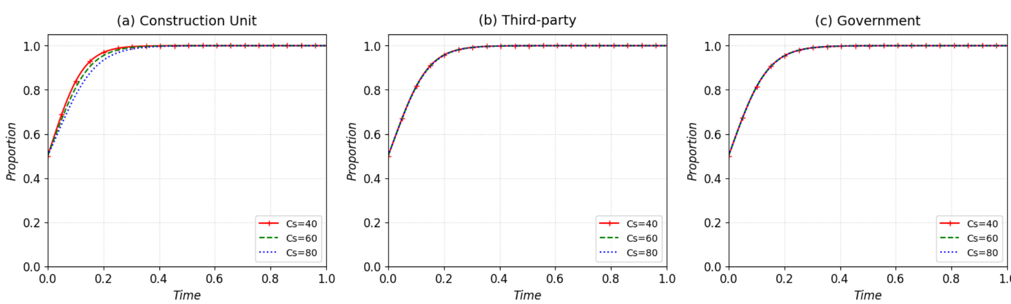

Figure 3. Impact of safety production input cost (*Cs*) on the evolutionary strategies of tripartite subjects.

In practice, this fixed expense accumulation—such as daily equipment rentals and idle labor costs—grows continuously due to persistent rain or typhoons, eventually eroding the initial resistance against uncertainty. When the deterministic loss of suspension outweighs the expected penalty for violation, strong speculative behaviors emerge. This demonstrates that relying solely on administrative suspension orders is unsustainable over extended periods. Therefore, the government needs to implement "suspension compensation" mechanisms or "construction period extensions" linked to the D value during prolonged disasters. It is essential to offset the marginal increment in Cs to prevent the compliance baseline from being breached under heavy financial pressure.

While the initial increase in compliance due to higher penalties (Fc) is intuitive, the simulation reveals a critical non-linear saturation effect. As illustrated in **Figure 4**, increasing the penalty Fc accelerates the construction unit's convergence toward compliant suspension. However, the simulation demonstrates a clear saturation effect rather than a linear improvement. When Fc is relatively low, incremental increases significantly enhance compliance probability. Yet, as Fc reaches higher levels, its regulatory leverage weakens, exhibiting an asymptotic convergence limit. This indicates that static fines merely establish a baseline cost for violations. While this asymptotic convergence is a mathematical property of replicator dynamics, it reflects a specific behavioral reality in construction: risk-taking under financial distress. When the cumulative compliance cost $Cs(D)$ threatens a firm's solvency, the deterrent effect of static fines saturates. A construction unit facing guaranteed losses from prolonged suspension will rationally gamble on the probabilistic risk of violation. This demonstrates that relying on static penalties is structurally flawed under persistent disasters. Therefore, dynamic penalty mechanisms where Fc scales with disaster duration (D) are necessary.

- **Sensitivity Analysis of Expected Accident Loss (Lc)**

Lc represents the awareness of danger by a building's construction units. Simulation results show (**Figure 5**) that, with a bigger Lc value, it takes less time for the construction unit to get into the compliant state. Lc contains both direct compensations and implicit ones, like loss of reputation. In the Greater Bay Area, which is affected a lot by typhoons, there is an accident of scaffold collapse that causes destruction and is very dangerous. An Lc number that is big means the company feels strongly about the danger from problems. It seems like the government should improve the "visualisation" aspect of alert info regarding natural catastrophes. Simulate the outcome of an incident so that it improves a construction unit sense of risk at no extra cost to regulation enforcement.

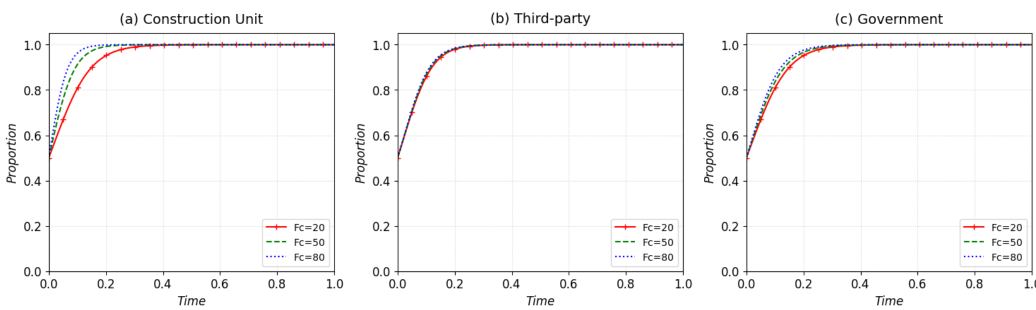

Figure 4. Impact of penalty intensity (Fc) on the evolutionary strategies of tripartite subjects.

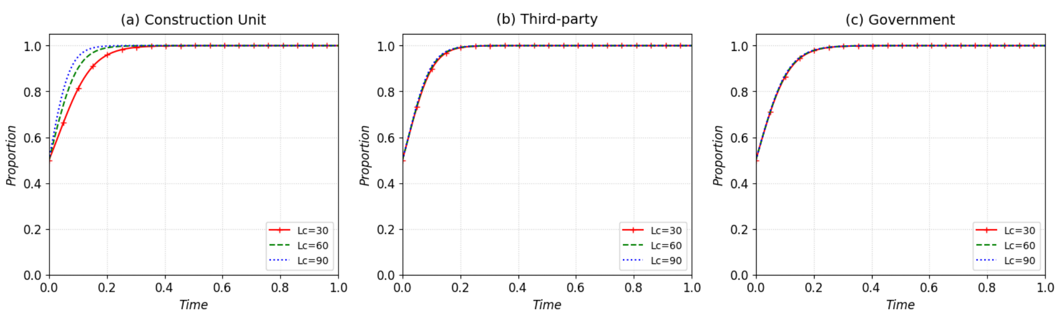

Figure 5. Impact of expected accident loss (Lc) on the evolutionary strategies of tripartite subjects.

- **Testing Alternative Functional Specifications**

It is necessary to consider whether the regime shift from compliance to violation is merely an artifact of the exponential cost assumption ($C_s(D) = C_{base} \times e^{\alpha D}$). If we test an alternative linear specification, such as $C_s(D) = C_{base} + \alpha D$, the mathematical outcome remains fundamentally the same. As long as the compliance cost accumulates over time ($\frac{\partial C_s}{\partial D} > 0$) and the static penalty (F_c) remains fixed, the cost will eventually intersect and exceed the penalty threshold. The exponential function does not create the regulatory failure; it only dictates how quickly the threshold is reached. We selected the exponential form because it better captures the cascading financial impacts of prolonged construction delays, but the transition to the "violation and dereliction" state (E_4) is a systemic property of using static penalties in a dynamic environment, rather than a functional artifact.

5.2.2. Sensitivity Analysis of Variables Related to the Third-Party Subject

Sensitivity analysis for collusion rent-seeking (M). **Figure 6** shows how the third party changes with M. Small M means a hard-working third party, and large M leads to fast changes in strategy and ends at "dereliction/collusion".

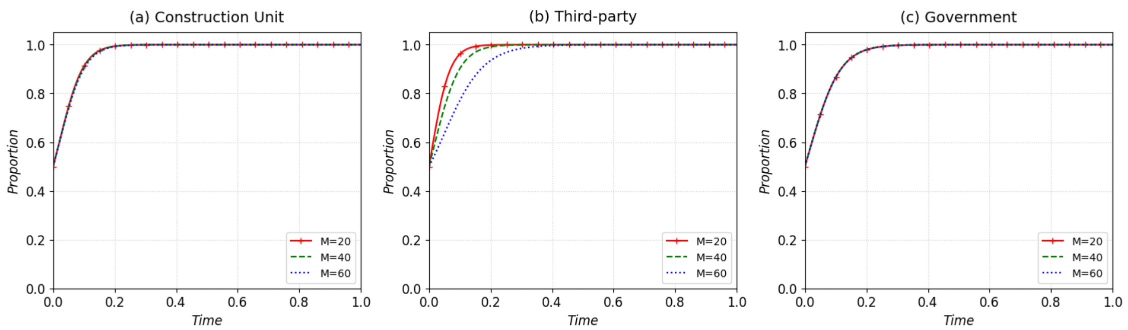

Figure 6. Impact of collusion rent (M) on the evolutionary strategies of tripartite subjects.

During the duration of the disaster, construction organizations are motivated to pass along the gains to another player in order to hide violations and dodge large monetary penalties Fc. If M is high enough to cover the penalty due to dereliction and reputational loss (Ft), it turns out the third-party subjects—as someone behaving economically rationally—would opt into the position as the compromise point and the breach point in the line of regulations. That is, the chain of illegal benefit flow from the construction unit to the third-party subjects has been cut off. Like setting up "government escrow for supervisory fee payments" or making a "blacklist system with lifetime bans," we want to lower the expected value of M.

Sensitivity Analysis of Diligent Performance Cost (Ct): As shown in **Figure 7**, an increase in Ct significantly reduces the probability of the third party adopting the diligent strategy. During severe weather conditions, on-site investigations become physically difficult and hazardous, implicitly raising Ct without corresponding compensation. Consequently, third-party subjects are more likely to default to dereliction. To mitigate this, regulatory bodies should accelerate the deployment of digital monitoring tools (e.g., UAVs and IoT sensors) to structurally lower the human inspection cost Ct. Alternatively, implementing targeted performance subsidies during extreme weather events is essential to incentivize continued diligence.

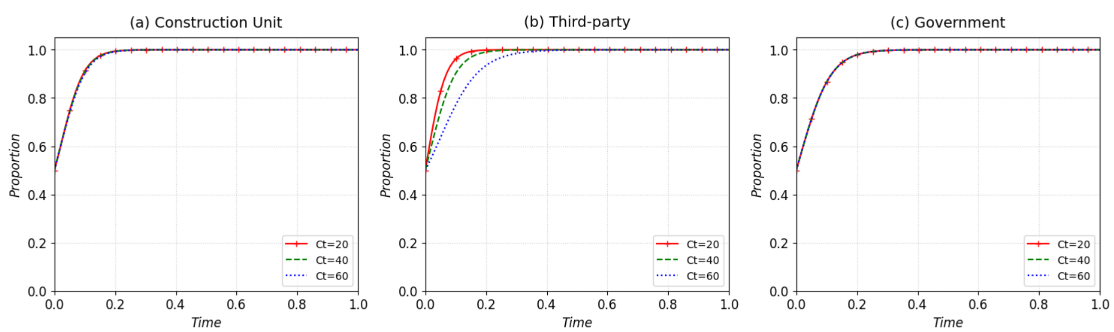

Figure 7. Impact of diligence cost (Ct) on the evolutionary strategies of tripartite subjects.

5.2.3. Sensitivity Analysis of Variables Related to Government Regulatory Departments

Sensitivity Analysis of Regulatory Cost (*Cg*): According to **Figure 8**, *Cg* is an important part of those negative factors that hold governments accountable and prevent them from becoming overly authoritarian; when we see *Cg* start rising (that goes back up), there is clearly visible movement towards 'relaxing' or loosening up their supervisory role over what they' re looking at; so there will probably be some kind of reduction from strict control mode into a more lenient one for how they watch things.

In major disaster weather situations, the government faces many practical problems, including insufficient police and traffic obstruction, so achieving thorough coverage is quite expensive. If *Cg* is too high, then worries over fiscal and human resources would push the government to lessen the rate at which it supervises, causing the system to drift towards an E_4 state of regulatory failure.

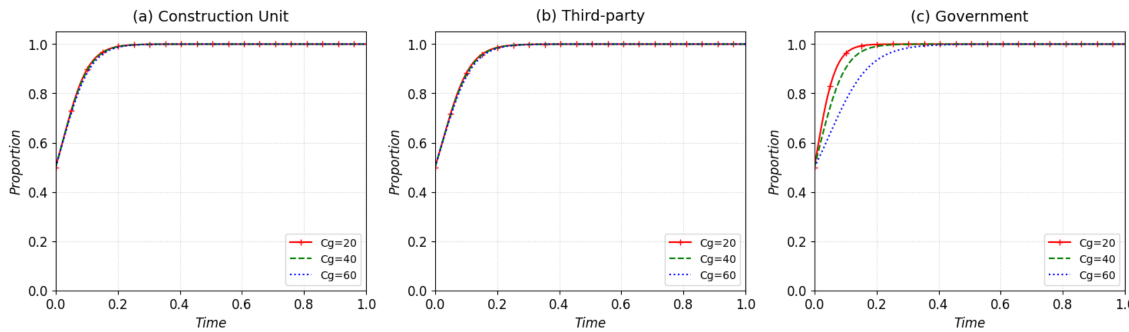

Figure 8. Impact of government regulation cost (*Cg*) on the evolutionary strategies of tripartite subjects.

So the best approach with *Cg* would be to reduce it so we can maintain more permanent supervision. In the Greater Bay Area, we need to actively promote a "Smart Construction Site" supervision platform, use Internet of Things sensors for the current status supervision of construction sites, deep foundations, etc. This will be able to do off-site, cheap, all-around exact supervision.

Sensitivity analysis on social governance benefits (*W*): *W* is the government's degree of importance about public safety. Simulation results in **Figure 9**: When *W* has bigger value, there will be stronger willingness by the government to select strong supervision. And it's transmitted also through the game, so they both just go towards it being okay with it or just being hard work much quicker.

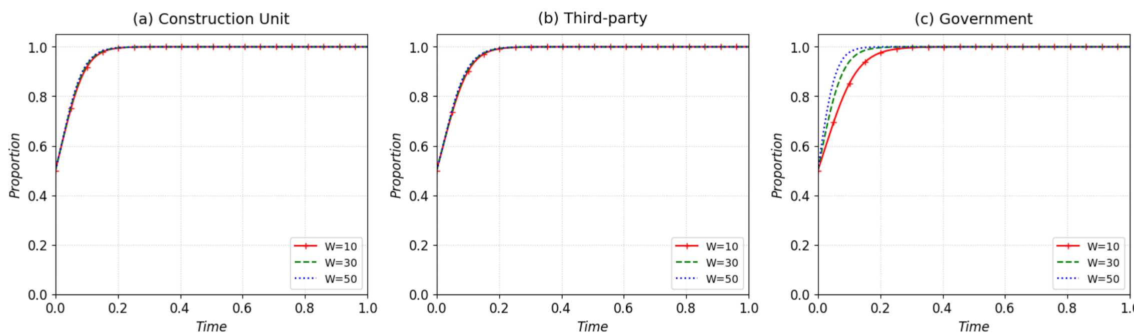

Figure 9. Impact of social governance benefit (*W*) on the evolutionary strategies of tripartite subjects.

Stronger *D* (Disaster Continuity) leads to more potential casualties, resulting in greater social governance benefits *W* for successful avoidance. Thus, the motive of a government would also make that investment, no matter how much it costs during those extreme periods. Higher levels should include whether disaster prevention was done, or how well, in an evaluation of local governments. Use increased emphasis on *W*, which is caused by administrative inducements, so low-level supervisory organizations keep up with the idea of putting people and their lives over money and stuff.

Stronger disaster continuity (*D*) leads to higher potential casualties, resulting in greater social governance benefits *W* for successful risk avoidance. Consequently, the government is highly motivated to invest in strict supervision during extreme weather, regardless of the regulatory costs. Administratively, incorporating disaster prevention performance into local government evaluations effectively increases the weight of W, ensuring that grassroots regulatory bodies prioritize public safety over financial constraints.

As money is not unlimited, this implies that the suggestion would go toward targeting subsidies as opposed to giving them to everyone. Subsidies are best aimed at those projects with extremely large expenditure for compliance purposes (such as very tough foundation holes in the most dangerous phase) and can also be linked with putting up monitoring equipments, to obtain better efficiency with fewer resources. As shown in **Figure 10**, changes in incentive subsidy influence the evolutionary strategies of the tripartite subjects, further supporting the need for targeted subsidy allocation.

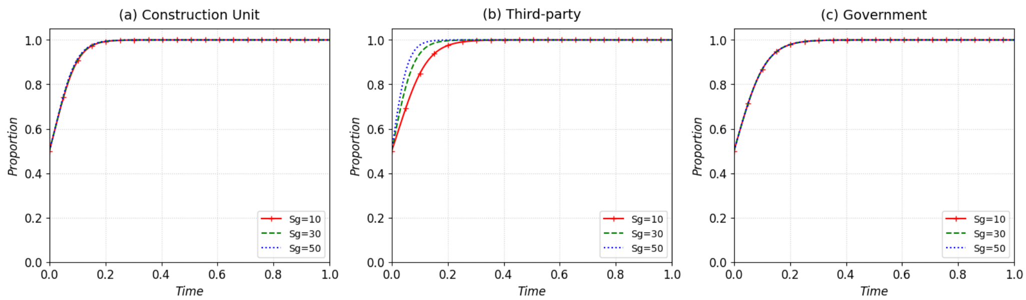

Figure 10. Impact of incentive subsidy (Sg) on the evolutionary strategies of tripartite subjects.

6. Discussion

The three-party evolutionary game model constructed in this study highlights a theoretical vulnerability: under the simulated long-duration disaster scenarios inspired by the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) context, the stability of the construction safety supervision system possesses "temporal vulnerability".

Simulations showed us that "Compliance–Diligence–Strict supervision" (E_8) had no firm, unchanging static point; rather, it was a shifting line that was affected by disaster time (D). As typhoon or rainstorm retention time increases, the idle equipment cost and the construction unit's delay cost (Cs) accumulate exponentially. Once this rigid expenditure crosses the critical threshold (Cs*), the enterprise's risk preference undergoes a structural shift. At this point, if the third-party regulatory defense line is also compromised by rent-seeking benefits (M), the system experiences a regime transition, shifting from a high-level safety equilibrium into a locked-in state of "regulatory failure" (E_4). Within the boundaries of our mathematical assumptions, this theoretically illustrates that a potential driver for safety risks in regions like the GBA is not merely a lack of safety awareness, but rather the compounding economic pressure of disaster duration. The model's shift toward noncompliance stems from the asymmetric growth rates of compliance costs (Cs) and expected accident losses (Lc). While prolonged disasters increase both variables, expected accident losses are probabilistic and inherently bounded by the project's total value. In contrast, compliance costs—driven by deterministic, cascading contract defaults and idle labor—compound exponentially. This deterministic financial drain eventually overtakes the probabilistic deterrence of accident risks, inverting the cost-benefit structure. We acknowledge that this regime transition is fundamentally driven by the exponential cost assumption, and thus these dynamics should be interpreted as theoretical propositions regarding the vulnerabilities of static regulatory systems, rather than empirically validated facts.

While the directional trends of the variables are intuitive, the model's primary utility is identifying the exact algebraic boundaries where traditional regulatory logic fails. For instance, the saddle point E_6 is a dynamic manifestation of the free-rider problem from principal-agent theory: the third party free-rides on the contractor's strict compliance to save diligence costs. Additionally, the model formally captures the "desperation effect" of high penalties through the threshold condition $C_s^* = R_c + S_g - B + p_D(D)L_c(D) + q_{RD}(D)F_c$. This equation demonstrates that the critical threshold is not a static point, but a moving boundary determined by specific parameter combinations. While increasing the static fine (Fc), government subsidies (Sg), or expected accident losses (Lc) mathematically raises this compliance boundary—thereby expanding the system's tolerance for disaster duration—the exponential accumulation of compliance costs *Cs*(*D*) during a prolonged disaster eventually outpaces it. Once $C_s(D) > C_s^*$, the system collapses into regulatory failure (E_4). This mathematical proof shows that under extreme financial distress, maximizing static penalties forces a structural shift toward collective violation rather than compliance.

The sensitivity analysis points to a theoretical trade-off. Since the numerical thresholds are uncalibrated, they cannot dictate actual monetary fines. Their value is strictly in mechanism design. The boundary *Cs* indicates that static tools become structurally vulnerable during prolonged disasters. To maintain mathematical equilibrium, the regulatory architecture needs flexibility. For instance, increasing fines (*Fc*) promotes compliance but shows diminishing returns as compliance costs (*Cs*) approach a firm's survival threshold. Subsidies (*Sg*) are costly and have weaker leverage, meaning they are better used as targeted rather than universal tools. Digital monitoring (UAVs, IoT) provides a conceptual alternative by lowering both regulatory (*Cg*) and diligence (*Ct*) costs. For regions like the GBA, maintaining equilibrium theoretically points to: (1) dynamic fines scaling with disaster duration *D*; (2) targeted subsidies for extreme compliance costs; and (3) digital monitoring deployment. However, the cost-effectiveness of these approaches requires future empirical testing.

Looking at the construction governance practice in the GBA beyond isolated game data, it is necessary to face the intrinsic tension between "high-pressure supervision" and "enterprise survival" under extreme weather conditions. Most existing regulatory logics are designed based on "instantaneous shocks," defaulting to the assumption that stopping work to avoid risk is a low-cost, short-duration action. They fail to consider the "cost-compliance inversion" phenomenon caused by the lengthening of disaster chains in the context of climate change. Construction units at the very end of the supply chain, when faced with weather like Typhoon "Saola", which might last 1–2 days or a period of heavy continuous rainfall, are not simply engaging in "risk aversion"; rather, it's an act of "survival". In cases of high costs associated with following rules, if we rely only on orders given by government regulatory departments and moral preaching by people, then it seems that it would have no result. It can even generate hidden speculation activities instead. Furthermore, the model also finds that there is a decreasing value of governments' desire to regulate as the regulation cost *Cg* increases. The word is clear: with the actual world's real human resources restriction, one must admit it has been almost impossible to achieve any real sustained and extended "on-site" inspection, with such "manpower-intensive" inspection. There is "regulation fatigue," which gives space for rule-breakers to continue working.

Compared with existing studies, the findings of this research offer new insights into construction safety governance. Previous evolutionary game models in construction safety primarily focused on routine supervision and static penalty mechanisms [2,10], concluding that simply increasing fines can effectively deter violations. However, our results demonstrate that under persistent disaster conditions, the marginal utility of fines diminishes significantly when compliance costs (*Cs*) grow exponentially. This finding aligns with the perspective of Gong et al. [23] regarding the necessity of dynamic penalties, but our study further advances this by explicitly linking the dynamic adjustment to an external environmental variable (disaster duration *D*). Furthermore, while Chen and Tang [30] highlighted the risk of third-party collusion driven by economic rent, our simulation reveals that extreme weather exacerbates this risk by implicitly raising the physical cost of diligence (*Ct*). This indicates that during prolonged disasters, targeted performance subsidies are more effective than universal rewards in maintaining the third-party regulatory defense line.

When mapping these mathematical boundaries to governance concepts, the model underscores the need for dynamic regulation. Specific tools mentioned here—like catastrophe insurance or IoT monitoring—are not endogenously modeled or empirically tested. They are simply exploratory examples showing how policymakers might achieve the parameter constraints (such as lowering *Cs*, *Cg*, or *Ct*) needed for equilibrium. A duration-linked penalty, for example, conceptually keeps the expected cost of violation above the compliance threshold, closing the arbitrage gap as a disaster prolongs.

7. Conclusion

This paper puts forward the use of the disaster endurance index (*D*) in the regulatory game model that this paper finds the boundary for theory under the static regulation environment. Based on these data, we can determine how good it is at maintaining $E_8(1,1,1)$ if we only care about dynamic penalties and L's are strictly worse than total compliance costs. But for D growing bigger, $Cs(D)$ follows an exponential increase which crosses over the cost barrier, thus resulting in the system collapsing into a regulatory failure $E_4(0,0,1)$. Furthermore, the analysis demonstrates that while increasing the static penalty Fc initially promotes compliance, it exhibits a clear saturation effect, meaning it cannot indefinitely offset the exponentially growing compliance costs under prolonged disasters. Additionally, excessive third-party collusive rent M immediately leads to supervisory failure. These findings are theoretical propositions, not empirically proven facts. They show that the compliance boundary is highly sensitive to time-accumulated costs. As a result, the model provides a rationale for exploring adaptive punishment-compensation structures to prevent regulatory failure, though any practical application depends on future empirical validation.

8. Research Limitations and Future Work

The primary limitation of this study is the absence of empirical data calibration. The current model is established based on theoretical deduction and relative parameter simulation. Specifically, it lacks empirical calibration using GBA-specific data, such as actual typhoon frequencies, real fine amounts, or exact compliance cost estimates. Because the disaster index D and the economic parameters are not yet anchored to specific meteorological records or financial data from the GBA, the identified critical thresholds represent structural mathematical conditions rather than actionable policy figures. Consequently, the findings should be interpreted strictly as a theoretical framework for mechanism design—demonstrating that regulatory variables must structurally scale with disaster duration—rather than an empirical tool for policy calibration. Furthermore, the model has not fully considered the heterogeneous characteristics of projects of different scales or the irrational psychological fluctuations of frontline crews. Methodologically, while the exponential cost function illustrates the worst-case scenario of supply chain cascading failures, future studies must test alternative functional forms (e.g., quadratic or piecewise) and employ bifurcation analysis to fully map the system's topological robustness under parameter uncertainty. Methodologically, the exponential cost function serves as a theoretical proxy for cascading supply chain failures. Future studies should test alternative functional forms (e.g., polynomial or piecewise) and use bifurcation analysis to map the system's robustness under functional uncertainty. Additionally, our numerical simulation relies primarily on a one-at-a-time (OAT) sensitivity approach, which restricts the full visualization of complex parameter interactions. Subsequent research could apply global sensitivity analysis (such as Sobol indices or 3D phase diagrams) to quantify how simultaneous variations—like the joint adjustment of fines, subsidies, and detection probabilities—shape the equilibrium. Finally, calibrating these theoretical thresholds with real-world case data from the GBA remains a necessary step to provide grounded decision support.

Future research should introduce real-world case data to calibrate the model thresholds. Furthermore, future research should endogenously model specific technological or financial interventions to evaluate their direct impact on the payoff structures. The goal is to explore precise governance methods under the uncertainties of extreme climate at a more micro-level, thereby providing empirically grounded decision support for regional resilience construction.

Author Contributions

Conceptualization, H.G. and X.W.; methodology, H.G. and J.L.; software, H.G.; validation, J.L. and X.F.; formal analysis, H.G. and J.L.; investigation, H.G. and J.L.; resources, X.W. and X.F.; data curation, H.G. and J.L.; writing—original draft preparation, H.G. and J.L.; writing—review and editing, X.W. and X.F.; visualization, H.G.; supervision, X.W. and X.F.; project administration, X.W. and X.F. H.G. and J.L. have contributed equally to this work and share first authorship. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. As stated in the methodology, this study relies on theoretical modeling and numerical simulation. It does not involve human or animal subjects, nor does it rely on empirical questionnaire surveys or interviews that require ethical approval.

Informed Consent Statement

Not applicable. This study does not involve human subjects.

Data Availability Statement

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding authors. The simulation parameters and mathematical models are fully described within the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this manuscript, the authors used AI solely for language refinement. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

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