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Incentive Mechanisms in Mega Project-Risk Management Considering Owner and Insurance Company as Principals

Jianbo Zhu[1]; Marcel Hertogh[2]; Jinwen Zhang[3]; Qianqian Shi[4]; and Zhaohan Sheng[5]

Abstract: In mega projects, the stakeholders may be exposed to significant on-site construction risk, especially the owners and insurance companies who take the most responsibility for the risk loss. It is difficult for insurance companies to diversify their risks by undertaking enough similar policies, and participating in on-site risk management has become an important method of active risk control. Based on the principal-agent relationship between the owner, insurance company, and contractor, this paper establishes incentive mechanisms for risk management considering the common agency and exclusive agency models. The results show that an insurance company's involvement in the common agency model creates external effects that can improve the utility of both the owner and the insurance company. The owner is then willing to provide a higher incentive coefficient, and the contractor's nonrisk and risk management efforts increase accordingly. From the owner's perspective, the influence of the participants' characteristics and external uncertainties on the incentive strategy are discussed. The results recommend that it is better for the owners and insurance companies to jointly establish a good cooperative relationship and build the incentive mechanism. The spillover effect has a positive effect on the cooperation between the two parties, while the impact of the uncertainty in risk management output on the cooperative relationship is negative. This paper contributes to the body of knowledge for understanding the on-site risk management considering stakeholders' participation and provides a practical mode for owners and insurance companies to implement active risk management in mega projects, thus achieving better risk governance of mega projects. **DOI: 10.1061/(ASCE)CO.1943-7862.0001915.**

Author keywords: Mega projects; Common agency; Risk management; Insurance.

Introduction

Mega projects often face great risks during the construction phase owing to their large scale, long construction period, and technical complexity (Hertogh and Westerveld 2010; Sheng 2018; Shi et al. 2020). Many construction techniques adopted in traditional small-scale construction projects have not been tested in a mega project context. For example, there were few precedents for large scale immersed pipe construction prior to the Hong Kong–Zhuhai–Macao Bridge project. Construction in the marine environment faces different issues from land-based construction and is affected by many risk factors, such as ocean currents, tides, and weather, as well as safety considerations for on-site construction vessels. This complex environment leads to a high degree of uncertainty in the construction process, posing a great risk to the mega project (Hu et al. 2015; Zhu et al. 2018). To mitigate the risk, owners and contractors often transfer a majority of project risk to an insurance company (Lu et al. 2010a). However, the transfer of risk does not always lead to risk reduction. For example, the Chinese government attaches great importance to safety production, but there are still a large number of opportunistic behaviors in construction projects, resulting in plenty of risk events. One example is the water inrush accident of the Foshan subway, and the sealing performance of the shield machine had declined during the construction process. However, the contractor failed to repair and replace the sealing device in time, which is one of the important causes of the accident. Another example is the collapse of the cooling tower in Fengcheng, Jiangxi Province, as the owner and the contractor did not demonstrate and evaluate the impact of the schedule adjustment on safety after greatly reducing the construction period, nor did they put forward corresponding organizational guarantees and safety guarantee measures, ultimately leading to serious accidents. Although the insurance company bears most of the compensation liability, the loss caused by the accident is still considerable. As financial enterprises, insurance companies usually lack risk management expertise and do not participate in on-site risk management. Furthermore, the number of mega projects is currently insufficient for insurance companies to achieve risk control by investigating a large number of insurance contracts for mega projects (El-adaway and Kandil 2009b). If the risk in a mega project is not appropriately managed, the insurance company often faces huge claims.

Improper risk management can also cause significant harm to the stakeholders' interests (Kim 2010). For construction projects, its ownership is generally more complicated (Ma et al. 2020), and the preferences of stakeholders are quite different (Meng et al. 2019). Risk events in construction projects are not uncommon,

[1]Postdoctor, School of Civil Engineering, Southeast Univ., Nanjing 211189, PR China. Email: zhujianbowss@163.com

[2]Professor, Faculty of Civil Engineering and Geosciences, Delft Univ. of Technology, Delft 2628 CN, Netherlands. Email: M.J.C.M.Hertogh@tudelft.nl

[3]Professor, School of Management and Engineering, Nanjing Univ., Nanjing 210093, China; Director, Engineering, Hong Kong–Zhuhai–Macao Bridge Authority, No. 368, Henglong Rd., Nanping Town, Xiangzhou District, Zhuhai 519060, China. Email: zjw@hzmbo.com

[4]Associate Professor, College of Economics and Management, Nanjing Univ. of Aeronautics and Astronautics, Nanjing 211106, PR China; Research Centre for Soft Energy Science, Nanjing Univ. of Aeronautics and Astronautics, Nanjing 211106, PR China (corresponding author). ORCID: https://orcid.org/0000-0002-8956-8203. Email: qqs1991@126.com

[5]Professor, School of Management and Engineering, Nanjing Univ., Nanjing 210093, PR China. Email: zhsheng@nju.edu.cn

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especially at construction sites. For example, as mentioned before, owing to the lack of effective risk control by the subcontractors, the cooling tower in Jiangxi Fengcheng collapsed on 24th November, 2016, causing 74 deaths and 2 injuries, resulting in significant losses to the owner, contractors, and insurance companies (Zhao et al. 2017). Mega project risk management has, therefore, been a central issue in the developing mega project management theories and practices. For example, over the past few years, a variety of emerging information and communication technologies, including building information modeling, video imaging, and sensors have been used for real-time risk monitoring and consequent risk analysis, as well as the establishment of risk mitigation strategies (Ding et al. 2016; Guo et al. 2018; Lyons and Skitmore 2004; Park et al. 2018; Valero et al. 2017). Another important issue in the field of project risk management is the problem of calculating insurance premiums, such as those covering workers' compensation insurance (Imriyas et al. 2007), and liquidated damages (Griffis and Christodoulou 2000). The application of multiple insurance types has been studied in depth (Bunni 2003; El-adaway and Kandil 2009a).

Mega project insurance is a significant and under-researched issue in mega project management. There are significant differences between mega project insurance and general project insurance, so independent research is required. First, the number of mega projects is scarce, so the main problem that comes with it is the lack of historical data. In addition, the occurrence probability of the risk events cannot be estimated; consequently, the insurance rate cannot be accurately calculated. According to the research of Raviv (1979), owing to the limited number of mega projects, it is difficult for insurance companies to apply an optimal insurance premium, which should be calculated based on at least 5,000 historical cases. Second, the owner of the mega project usually conducts overall insurance coverage for the needs of project insurance. Such a form of one project one insurance contract lacks continuity of time. Therefore, the insurance company cannot adjust the premium rate dynamically to constrain the risk management behavior of all parties involved in the current period. Third, mega projects often have high technical complexity, and one example is the Hong Kong–Zhuhai–Macao Bridge Island Tunnel Project, which required the construction of two artificial islands in the sea and a 5.6-km-long immersed tube tunnel. The technical methods are complex, the probability of occurrence of risk events is high, and the general risk management experience is difficult to apply. Finally, for an insurance company, it has only one goal, which is to reduce the probability of risk occurrence and thus fewer claims. For the owner and the contractor, risk management is only one of its multiple objectives, as quality, schedule, cost, and environmental protection also need to be controlled. Therefore, the objectives of insurance companies are different from those of other stakeholders. In summary, in view of the special nature of mega project insurance, insurance companies cannot conduct risk management through conventional means, while participating in onsite risk management has become a good strategy. Considering the different objectives with other stakeholders, how to participate in onsite risk management has become an important issue to be studied.

As Renn (2015) pointed out, as many stakeholders as possible should be involved in risk management. The involvement of insurance companies in the risk management of multiple stakeholders in mega projects stems from the inherent needs of insurance companies to understand and reduce risks. In addition, the participation of insurance companies may bring more risk management knowledge and capital on risk management, thus having a positive effect on risk management at the construction site. In the risk management of mega projects, the traditional perspective is to take the owner as the main stakeholder to supervise the risk management behavior of the contractor. In this case, it is an exclusive agent model with only one principal and one agent. This paper further forms the common agency model with two principals (insurance company and the owner) and one agent (contractor) under the consideration of the involvement of insurance company. Therefore, the main research question to be answered in this paper is:

1. Compared with the exclusive agency model, whether the resource investment of the owner and insurance company on the risk management of the contractor can improve their benefits under the common agency model.
2. Compared with the exclusive agency model, how does the owner's incentive coefficient change and what kind of strategy will the contractor adopt in the common agency model?

Risk management of mega projects is related to the vital interests of multiple stakeholders. The objective of this paper is to design and form a new risk management incentive contract through the participation of insurance company, so as to increase the risk management investment of the contractors, reduce the occurrence probability of risk events, and then achieve effective risk management of mega projects.

This paper considers insurance companies' participation in mega project risk management. In mega projects, the owner and the contractor have established a task-based contractual relationship. The owner and the insurance company have signed an insurance policy, and both of which are strong contractual relationships based on the contract, while there is no such contract between the contractor and the insurance company. The owner's task is the contractor's primary responsibility, and the insurance company's task forms a part thereof. In such contractual relationships, the owner and insurance company need to develop rational incentive strategies to maximize their respective interests, while the contractor must expend the optimal effort under the established incentive mechanism to maximize profits. This paper is organized as follows. First, a review of construction insurance, the principal-agent relationship, common agency theory, and incentive theory are presented. Next, based on principal-agent theory, common agency and exclusive agency models are established and solved, followed by a discussion of the results and a comparison of the two models. Thereafter, a numerical simulation is presented to illustrate the implications. Finally, conclusions are drawn based on the results.

Literature Review

Insurance in the Construction Industry

The construction industry is highly risky, and project insurance is one of the important risk management methods. Generally, the operation of insurance companies needs to be based on "the law of large numbers," which ensures that the actual result is close to the expected value, thereby reducing the operating risk of insurance companies. However, the investment of a single project is usually considerable, while the number of projects is limited in the construction industry. Therefore, the number of homogeneous project risks is not sufficient to allow insurance companies to do risk control. As a result, how insurance companies manage risk has become an important topic. First, based on the case of Singapore's general insurance industry, Imriyas et al. (2006) proposed a framework for calculating the optimal premiums by establishing a fuzzy expert support system conceptual model. Cheng et al. (2011) used the evolutionary support vector machine inference model (ESIM) to create a loss prediction model to improve the risk assessment methodology and provide support for the contractor in decision making concerning the insurance deductible. Imriyas (2009) proposed a method to adjust the premium rate through a real-time monitoring system of on-site safety management combined with an expert system and increase the premium to penalize contractors who lack input in safety management. In addition to signing an insurance contract with an insurance company, the risk-retention group (RRG) is another insurance method. Risk sharing can effectively promote the group members to engage in proactive risk management and knowledge sharing in order to pay extra premiums (Adkisson 2006). El-Adaway (2013) proposed the approach of application for the RRGs under IPD contracts.

Compared with general construction project insurance, participating in mega project insurance brings greater operational challenges to insurance companies. Regarding mega project insurance, the first question is who should buy the insurance, that is, whether it should be led by the owner or the contractor. Schexnayder et al. (2004) found that compared to contractor controlled insurance programs (CCIPs), owner-controlled insurance programs (OCIPs) are more likely to be used in mega projects. This may increase the administrative burden on the owners, but the owner is still satisfied with the cost savings and safety effects of the project by using an OCIP. Lu et al. (2010b) and Ndekugri et al. (2013) demonstrated that OCIP can improve project performance based on the case of Taiwan high-speed railway and the data from the construction industry in the United Kingdom, respectively. According to our survey of some Chinese construction projects, the insurance companies involved in mega projects were extremely concerned about on-site risks. For example, the insurance company of Hong Kong–Zhuhai–Macao Bridge conducted an on-site risk survey and warned risk and implemented risk management system training. In addition to the insurance policy, the Taihu Lake Tunnel Project has also signed a supplementary agreement that requires insurance companies to provide risk training services and risk management services and to establish disaster prevention and loss prevention funds. Apparently, insurance companies have shown great interest in participating in proactive risk management in mega projects, while the related research on how insurance companies participate is still lacking.

Incentive Mechanism

In the construction industry, the relationships among the parties involved in the project are temporary, and the incentive mechanism plays an important role in regulating the parties' behaviors in such a relationship. After analyzing 113 capital projects, Suprapto et al. (2016) pointed out that incentive contracts significantly improved project performance. Many researchers have found that incentives play an important role in motivating the participants to invest more effort in projects (On Cheung et al. 2018; Love et al. 2010; Rose and Manley 2010a, b). Incentives have become an important tool in project management (Bower et al. 2002) and have been applied to many aspects, such as adjusting the efficiency of highway construction and encouraging knowledge sharing (Meng and Gallagher 2012; El-Gafy and Abdelhamid 2015). In the practice of project management, there are widespread conflicts among multiple management objectives in terms of optimization (Ozcan-Deniz et al. 2011), such as quality, cost, schedule adherence, and environmental protection. Considering multiple task incentives, Holmstrom and Milgrom (1991) first established an incentive model based on principal-agent theory, which has been extended by many scholars. Multitask incentive models have also been used extensively in project management, such as models based on cost and duration established by Hosseinian and Carmichael (2012).

Principal-Agent Theory

Incentives are often implemented in projects through contract design, while principal-agent theory is the mainstream theory of contract design and has become an important and widely used analytical tool for contracting (Eisenhardt 1989). Turner and Müller (2003) extended the principal-agent theory to the field of project management, pointing out that in essence a project is a temporary organization based on task delegation. Then, the principal-agent theory has been regarded as an important tool for analyzing project governance (Müller and Turner 2005; Turner and Müller 2004) to address the interest distribution and opportunistic behavior in project cooperation and resolve the risk-sharing concern by establishing a pain-gain sharing model (Chang 2013). The principal-agent theory effectively explains the relationships among the stakeholders in the project, and it has also been widely used in recent research on public-private partnership (PPP) projects (Rwelamila et al. 2014), including discussing how the first P (the public) is organized and composed, to set appropriate risk-sharing ratios to facilitate negotiations between the government and investors (Parker et al. 2018), and so forth. The core idea of the principal-agent theory is that the principal can share the efforts of the agent so that the agent may pay more efforts (Chang 2013). In risk management, the principal can share part of the risk management benefits to the agent through the design of the contract, which can promote the agent to exert more efforts in risk management. In general, only one principal and one agent are considered. In this paper, an insurance company is also considered as a principal, thus forming a model with two principals and one agent, which is called the common agency theory in the principal-agent theory.

For the situations where there are multiple principals, Bernheim and Whinston (1985, 1986) first defined the principal-agent relationship comprising more than one principal as a common agency. This multi principal relationship is widely found in the retail, insurance, tourism, and government sectors. Regarding common agency, scholars have studied the problem of information asymmetry, adverse selection, mechanism design (Gal-Or 1991; Biglaiser and Mezzetti 1993; Martimort and Stole 2009; Stole 1991), and extension to dynamic models (Bergemann and Välimäki 2003). The common agency theory can well describe the principal-agent relationship between the government and state-owned enterprises and is used by scholars to study bureaucratic accountability (Gailmard 2012) and state-owned enterprise reform (Siqueira et al. 2009).

Problem Descriptions and Research Methodology

Mega projects face a high degree of complexity, its risks far exceed that of the general projects, and stakeholders are highly concerned about risk management in mega projects. In addition to increasing supervision, the owner can promote the contractor's risk management behavior by signing an incentive contract. However, in addition to risk management, the owner's multitask management for the contractor also includes quality, schedule, and similar considerations. The essence of risk management gains is the reduction in expected losses compared to tasks with explicit returns. A portion of these expected losses have been priced in the form of mega project insurance, and the owner paid premiums to the insurance company to transfer the risk. The owner needs to consider two main aspects when designing incentive contracts; one is to expand the funding sources of incentive fees, and the other is to balance risk management with other goals. The insurance company only cares about risk management, so its incentive goal is not consistent with the owner. Therefore, in the context of considering both the owner and the insurance company as principals, how to design the incentive contract and how the contractor responds to the incentive contract become important issues that need to be studied. To study the

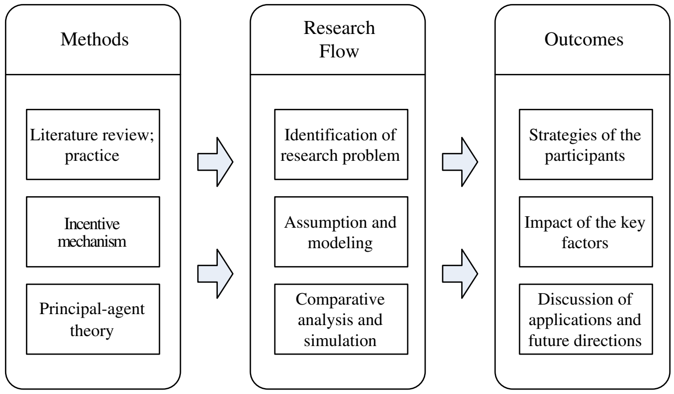

Fig. 1. Schematic of research steps.

design of the incentive mechanism, this research was conducted in three steps, as shown in Fig. 1.

From the perspective of an insurance company, it is not a good idea to participate in on-site risk management, and it deviates from the main business and is easy to become a financial black hole for management expenses. For general project insurance, insurance companies are more willing to operate based on accurate calculations of large amounts of data and dynamic adjustments of premium rate over multiple periods. However, the risk events in mega projects often lead to huge economic losses, which have led to insurance companies facing huge claims. Participation in the on-site risk management of mega projects has become a forced choice for insurance companies.

In the model, this paper is based, in part, on a multitask common agency model by principal-agent theory and assumes that the contractor's effort is divided into two forms of risk management and nonrisk management. Meanwhile, most of the assumptions used in this paper are based on the investigation and interview of mega projects under construction in the eastern and southern provinces of China. In particular, two forms of the principal-agent model are considered in this paper. The first type is to consider the owner as the only principal to design a multitask incentive mechanism for the contractor, and the insurance company does not participate in the incentive contract, that is, the exclusive agency model, as shown in Fig. 2(a). The second type is to consider both the owner and the insurance company as the principal to design a multitask incentive mechanism for the contractor, that is, the common agency model, as shown in Fig. 2(b). The implementation of the incentive mechanism can be seen in a timeline as shown in Fig. 3, in which the events in the solid line boxes belong to the exclusive agency model, and the common agency model includes the events both in the solid line and dotted line boxes. First, the owner chooses whether to allow the insurance agency to participate in the incentive mechanism design, and then the owner (and insurance company) provides an incentive contract through the choice of incentive coefficient. The contractor then chooses to accept or not accept the contract. If the contractor accepts the contract, the contractor chooses the level of effort of risk and nonrisk management based on the principle of maximizing its own interests. Then, after being disturbed by

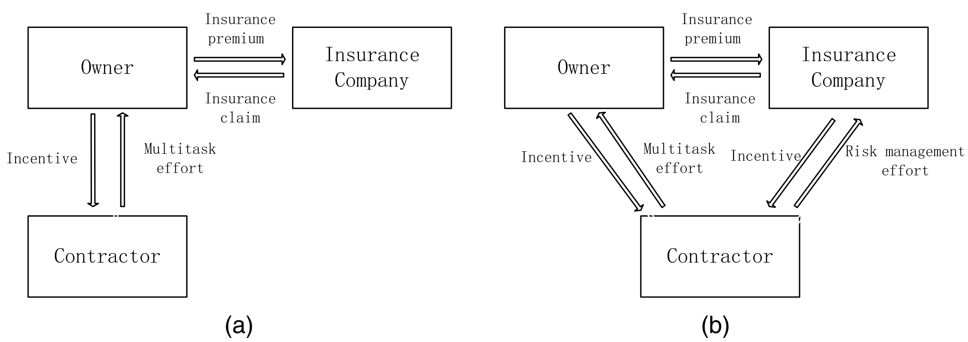

Fig. 2. Principal-agent relationship between the stakeholders in two modes.

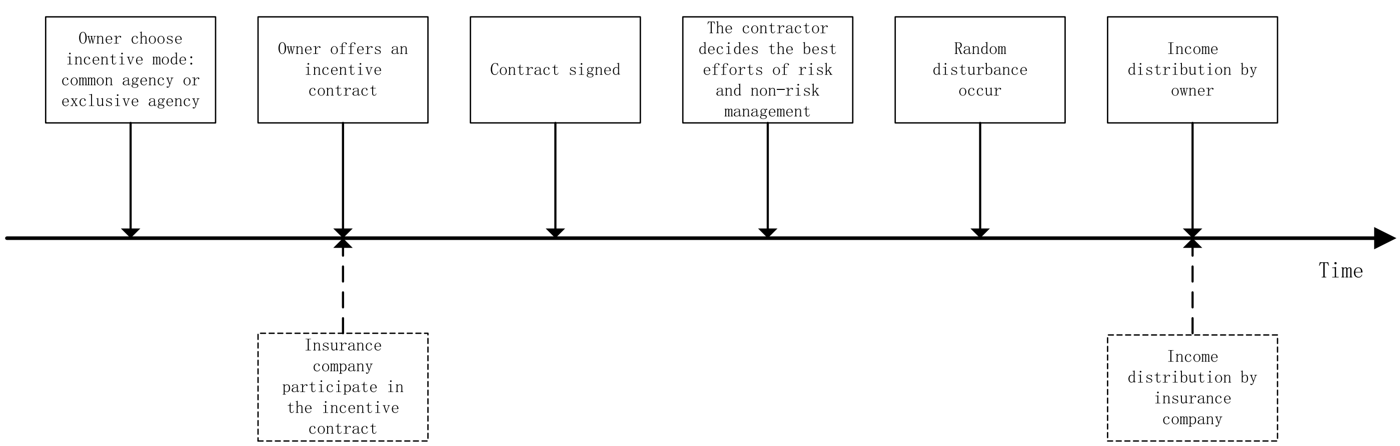

Fig. 3. Contracting process of the incentive mechanism.

random events, the final benefit of the project was determined. Finally, the owner and the insurance company distribute the profits according to the contract. Based on the principal-agent model and decision-making timeline, first, we solve the incentive strategies of insurance institutions and owners under the two models of the common agency model and exclusive agency model, as well as the multitask resource input strategy of a contractor. Next, we compare and analyze the strategic changes of the owner, insurance company, and contractor under the two models and then analyze the utility changes of the owners. Finally, the results of the above analysis were verified by numerical simulation.

Model for Incentive Mechanism

Common Agency Model with Insurance Company's Involvement

In this section, a common agency model is developed to investigate the impact of an insurance company's involvement in project performance goals, including the incentive coefficient, utility of the principals, and contractors' effort. The objective of establishing an incentive model for owners, insurance companies, and contractors is to allow the owners and insurance companies to maximize their own benefits by setting an incentive coefficient and sharing the revenue with the contractors. The contractor is responsible for ensuring many benefits for the owner, including schedule adherence, quality, safety, and environmental protection, as well as to the insurance company, in terms of reduced risk claims through risk elimination.

This paper divides utility into two categories: risk management and nonrisk management. The former type of utility arises from the reduction of the direct economic losses caused by risk events, while the latter is the quantification of the benefits generated by achieving the project's construction goals. This section discusses a common agency model among the owner, insurance company, and contractor.

The former insurance contract is signed by the owner and the insurance company, and it specifies the deductible rate, which is the risk-retention ratio for the owner. The owner, contractor, and insurance company have no other direct insurance relationship. The contractor is directly employed by the owner and must undertake tasks assigned by both the owner and the insurance company. The principal-agent relationship between the owner and contractor is primary, and the relationship between the insurance company and contractor is secondary. The owner-assigned tasks represent all the tasks that the contractor must undertake, including both risk and nonrisk management aspects, while the tasks assigned by the insurance company tasks concern risk management issues.

The utility of the contractor's efforts on behalf of the owner is W_o, which consists of two parts: risk management output and nonrisk management output. The total management output is determined by the contractor's risk management effort (s) and nonrisk management effort (q). The risk management efforts reduce the number of safety incidents, producing economic benefits and potential additional social benefits to the owners, namely, reputation. Therefore, the contractor's total output to the owner is expressed as follows:

$$W_o = \beta_q q + \beta_{s1} s + \alpha\beta_{s2} s + \varepsilon_1 \tag{1}$$

where β_q = economic utility coefficient of the nonrisk management output; β_{s1} = reputation utility coefficient of the risk management output; and β_{s2} = economic utility coefficient of the risk management output. Furthermore, α =owner's risk-retention ratio determined in the insurance contract, where $\alpha \in [0, 1]$; and ε_1 = random variable with a mean of 0 and a variance of σ_1^2, that is $\varepsilon_1 \sim N(0, \sigma_1^2)$.

Furthermore, the total output that the contractor produces for the insurance company is

$$W_i = (1-\alpha)\beta_{s2} s + \varepsilon_2 \tag{2}$$

As the insurance company can only reduce the compensation for the risk management efforts, its income is determined by β_{s2}, which is also affected by uncertainty. Furthermore, ε_2 is a variable with a mean of 0 and a variance of σ_2^2, that is $\varepsilon_2 \sim N(0, \sigma_2^2)$.

The owner and the insurance company independently sign an incentive contract with the contractor. By observing the contractor's output, they each develop a beneficial incentive strategy. The contract between the owner and contractor comprises two parts: the first part is the fixed fee (v_o), and the second part is the incentive fee by which the revenue is shared with the contractor to encourage further investment efforts. The contract between the insurance company and contractor is similar, and we assume that there is no negative incentive. Therefore, the incentive contract between the owner and contractor can be expressed as

$$w_o = v_o + \gamma W_o \tag{3}$$

where v_o = fixed fee of the contract between the owner and contractor; and γ = incentive coefficient determined by the owner, where $\gamma > 0$.

Similarly, the incentive contract between the insurance company and the contractor can be expressed as

$$w_i = v_i + \lambda W_i \tag{4}$$

where v_i = fixed fee part of the contract between the insurance company and the contractor; and λ = incentive coefficient determined by the insurance company, where $\lambda > 0$. It should be noted that the contract between the owner and contractor ensures that the contractor is willing to accept the incentive contract. The insurance company does not need to pay an additional fixed fee to ensure that the contractor is involved; hence, $v_i = 0$.

The contractor's cost (c) consists of two parts: the nonrisk management effort (q), with a cost coefficient of k_q, and the risk management effort (s), with a cost coefficient of k_s. To reflect the effect of diminishing marginal utility in the actual construction process and to simplify the calculation, we assume that the impact of the effort on cost is quadratic (Liu et al. 2016). Therefore, the cost function can be expressed as follows:

$$c = \frac{1}{2}k_q q^2 + \frac{1}{2}k_s s^2 \tag{5}$$

The utilities of the owner and the insurance company are based on the output of the contractor's performance and the incentive they have offered. It is assumed that the owner and the insurance company are risk-neutral (Van Ackere 1993). Therefore, the utility of the owner is $E_o = -v_o + (1-\gamma)W_o$, and the utility of the insurance company is $E_i = (1-\lambda)W_i$. The contractor's revenue originates from the incentive fees from the owner and the insurance company minus the cost. Here, we assume that the contractor is risk averse as an agent (Eisenhardt 1989). Therefore, the expected utility obtained by the contractor from the owner can be expressed as

$$U_o = v_o + \gamma(\beta_q q + \beta_{s1} s + \alpha\beta_{s2} s) - \frac{1}{2}\rho\gamma^2\sigma_1^2 - \frac{1}{2}k_q q^2 \tag{6}$$

The expected utility obtained by the contractor from the insurance company can be expressed as

$$U_i = \lambda(1-\alpha)\beta_{s2}s - \frac{1}{2}\rho\lambda^2\sigma_2^2 - \frac{1}{2}k_s s^2 \quad (7)$$

In this case, the owner and the insurance company are both principals, and the contractor is the agent. The design of the incentive mechanism is equivalent to solving the following principal-agent model:

$$\max_{v_o,\gamma} E_o = -v_o + (1-\gamma)W_o \quad (8)$$

$$\max_{v_i,\lambda} E_i = -v_i + (1-\lambda)W_i \quad (9)$$

$$s.t.\ E(U_o) \geq \omega \quad (10)$$

$$\max_{q,s} E(U_o + U_i) \quad (11)$$

In the aforementioned principal-agent model, the owner (as the main principal) must ensure that the contractor has sufficient interest to participate. This can be achieved by ensuring that the contractor's utility can be greater than or equal to its retained utility. The contractor obtains the expected utility from the owner and should meet the participation constraint $E(U_o) \geq \omega$. Thereafter, the contractor needs to consider the benefit and cost of risk management and nonrisk management efforts to maximize its utility and make decisions. That is, the contractor's decision making is subject to the incentive compatibility constraint $\max_{q,s} E(U_o + U_i)$. On this basis, the owner and insurance company calculate the incentive strategy set for the contractor by maximizing their respective utilities, thus completing the design of the incentive mechanism. Bringing the parameters into the principal-agent model, we can obtain

$$\max_{v_o,\gamma} E_o = -v_o + (1-\gamma)(\beta_q q + \beta_{s1}s + \alpha\beta_{s2}s) \quad (12)$$

$$\max_{\lambda} E_i = (1-\lambda)(1-\alpha)\beta_{s2}s \quad (13)$$

$$s.t.\ v_o + \gamma(\beta_q q + \beta_{s1}s + \alpha\beta_{s2}s) - \frac{1}{2}\rho\gamma^2\sigma_1^2 - \frac{1}{2}k_q q^2 \geq \omega \quad (14)$$

$$\max_{q,s} E(U_{oi}) = v_o + \gamma(\beta_q q + \beta_{s1}s + \alpha\beta_{s2}s) - \frac{1}{2}\rho\gamma^2\sigma_1^2 + \lambda(1-\alpha)\beta_{s2}s - \frac{1}{2}\rho\lambda^2\sigma_2^2 - \frac{1}{2}k_q q^2 - \frac{1}{2}k_s s^2 \quad (15)$$

By solving the principal-agent model, we can obtain

The optimal incentive coefficients of the owner and insurance company are, respectively

$$\gamma = \frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho\sigma_1^2 + k_s\beta_q^2} \quad (16)$$

$$\lambda = \frac{1}{2} - \frac{(\beta_{s1} + \alpha\beta_{s2})}{2(1-\alpha)\beta_{s2}} \times \frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho\sigma_1^2 + k_s\beta_q^2} \quad (17)$$

The optimal efforts of the contractor's nonrisk management and risk management are as follows:

$$q = \frac{\beta_q}{k_q}\frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho\sigma_1^2 + k_s\beta_q^2} \quad (18)$$

$$s = \frac{(1-\alpha)\beta_{s2}}{2k_s} + \frac{(\beta_{s1} + \alpha\beta_{s2})}{2} \times \frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s^2 k_q \rho\sigma_1^2 + k_s^2\beta_q^2} \quad (19)$$

Exclusive Agency Model without the Insurance Company's Involvement

This section considers a single principal. Only the owner and contractor sign an incentive contract, and the insurance company is not allowed to participate in the incentive mechanism. This model is useful for a comparative study to investigate the changes in the owner's strategy and contractor's performance with and without the insurance company's involvement. Similar to the model in the section "Problem Descriptions and Research Methodology," the contract still comprises a fixed fee plus incentive fee. The principal-agent model is further simplified into a multitask incentive model considering risk and nonrisk management as follows:

$$\max_{\gamma} E_o = -v_o + (1-\gamma)(\beta_q q + \beta_{s1}s + \alpha\beta_{s2}s) \quad (20)$$

$$s.t.\ v_o + \gamma(\beta_q q + \beta_{s1}s + \alpha\beta_{s2}s) - \frac{1}{2}\rho\gamma^2\sigma_1^2 - \frac{1}{2}k_q q^2 - \frac{1}{2}k_s s^2 \geq \omega \quad (21)$$

$$\max_{q,s} E(U_o) = v_o + \gamma(\beta_q q + \beta_{s1}s + \alpha\beta_{s2}s) - \frac{1}{2}\rho\gamma^2\sigma_1^2 - \frac{1}{2}k_q q^2 - \frac{1}{2}k_s s^2 \quad (22)$$

By solving the model, we can obtain the following:

The incentive coefficient of the owner is

$$\gamma_1 = \frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho\sigma_1^2 + k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2} \quad (23)$$

The optimal efforts of the contractor's nonrisk and risk management are respectively

$$q_1 = \frac{\beta_q}{k_q}\frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho\sigma_1^2 + k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2} \quad (24)$$

$$s_1 = \frac{(\beta_{s1} + \alpha\beta_{s2})}{k_s}\frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho\sigma_1^2 + k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2} \quad (25)$$

Analysis and Discussion

In this section, we model the common agency and the exclusive agency separately and solve for the optimal strategies of the owner, insurance company, and contractor in the two situations. The insurance company's participation in the incentive mechanism realized its purpose of active risk management, changed the passive situation where the risk management output was determined only by the owner's incentive strategy, and had a significant impact on the strategies of both the owner and contractor. Therefore, it is meaningful to conduct a comparative analysis of the differences between the common agency and exclusive agency models and discuss the results.

Analysis of Owner's Optimal Incentive Coefficient

As the main principal, the owner is a key participant in the incentive mechanism under the two principal-agent modes. In the common agency model, the owner adopts the optimal incentive coefficient (γ) for the contractor, and for a simple deformation, we can obtain

$$\gamma = 1 + \frac{k_q(\beta_{s1} + \alpha\beta_{s2})^2 - k_s k_q \rho \sigma_1^2}{k_s k_q \rho \sigma_1^2 + k_s \beta_q^2}$$

The owner's optimal incentive coefficient is affected by the contractor's cost coefficient, risk and nonrisk management output coefficients, risk-retention ratio, and uncertainty. The impacts of the risk management output coefficient and risk-retention ratio on the incentive coefficient are positive, while the uncertainty and the impact of the nonrisk management output coefficient on the incentive coefficient are negative.

In contrast, under the exclusive agent model, the owner's optimal incentive strategy for the contractor is γ_1 [Eq. (23)]. To compare the changes of the incentive coefficient in two cases, we can divide the owner's incentive coefficient in the common agency model by the incentive coefficient in the exclusive agency model and obtain

$$\frac{\gamma}{\gamma_1} = 1 + \frac{k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho \sigma_1^2 + k_s \beta_q^2}$$

The results show that the owner's optimal incentive coefficient in the common agency model is greater than that in the exclusive agency model. By comparing the incentive coefficient changes in the owner's two models, under the common agency model, we find that there is a good synergy between the owner and insurance company and that the owner is willing to share more revenue with the contractor to achieve the risk and nonrisk management project goals. Compared with the two incentive strategies, the increase in both the contractor's output ability in risk management and the owner's reputation output coefficient increases the difference between them. The increase in the uncertainty and the contractor's output ability in nonrisk management narrows the difference.

Analysis of Contractor's Risk Management Effort

In the common agency model, because of the insurance company's incentive strategy for the contractor's risk management, the incentive mechanism generates additional financial support, and this portion of the funds is not available under the exclusive agency model. The contractor, under the incentive of the owner or insurance company, adjusts its efforts to maximize its profits. Comparing the degree of contractor risk management efforts under the common agency and exclusive agency models, we can derive some important conclusions

$$\frac{s}{s_1} = 1 + \frac{\lambda(1-\alpha)\beta_{s2}}{\gamma(\beta_{s1} + \alpha\beta_{s2})}$$

Under the common agency model, the contractor can simultaneously obtain the incentive fees from the owner and insurance company, and its risk management efforts will be greater. The insurance company's incentive coefficient and the risk transferred by the insurance contract magnifies the difference in effort. Furthermore, the owner's incentive coefficient, risk management reputation, and self-retention risk narrow the difference in effort.

Analysis of the Contractor's Nonrisk Management Effort

Compared with the exclusive agency model, the insurance company participates in the incentive mechanism in the common agency model. The insurance company stimulates the contractor to invest more effort in risk management by sharing the benefits of risk management with the contractor. The contractor's nonrisk management efforts do not directly improve the insurance company's utility, and the incentive strategy of the insurance company applies only to the risk management efforts. However, does the insurance company's incentive strategy for risk management efforts indirectly affect the contractor's nonrisk management efforts? Based on the presented considerations, we compare the contractor's nonrisk management efforts in these two models and obtain

$$\frac{q}{q_1} = 1 + \frac{k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho \sigma_1^2 + k_s \beta_q^2}$$

Obviously, in the common agency model, the owner has adopted a more positive incentive strategy that makes the contractor profitable and increases the investment in nonrisk management efforts. This suggests that the insurance company's participation has produced spillover effects. Although it does not directly stimulate nonrisk management efforts, it increases the owner's incentive coefficient, making the contractor invest more effort into nonrisk management.

The differences in the contractor's nonrisk management efforts between the two models will be amplified by the cost coefficient of nonrisk management effort, reputation coefficient, economic output coefficient of risk management, and owner's risk-retention ratio. The output coefficient of nonrisk management, cost coefficient of risk management, risk aversion coefficient of the contractor, and uncertainty narrow the difference.

Analysis of the Owner's Utility

Both the owner and insurance company benefit from the contractor's risk management efforts. In the exclusive agency model, only the owner pays the incentive fee, and the insurance company does not participate in the incentive contract but can also benefit from the reduction of risk events. Under the common agency model, both the owner and insurance company pay the incentive fee while achieving their own goals. By inputting the relevant solution results into the owner's utility function, we can obtain the following:

In the common agency model, the owner's utility is

$$E(U_o) = -\omega + \frac{1}{2}\frac{\beta_q^2}{k_q}\frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho \sigma_1^2 + k_s \beta_q^2} + \frac{1}{2}\frac{(1-\alpha)\beta_{s2}(\beta_{s1} + \alpha\beta_{s2})}{k_s} \quad (26)$$

In the exclusive agency model, the owner's utility is

$$E(U_o) = -\omega + \frac{1}{2}\frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_s k_q \rho \sigma_1^2 + k_s \beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2} \times \left(\frac{k_s\beta_q^2 + k_q(\beta_{s1} + \alpha\beta_{s2})^2}{k_q k_s}\right) \quad (27)$$

By comparing the difference between the owner's utility in the two models, we find that the owner's utility in the common agency model is greater than that in the exclusive agency model. In the common agency model, the insurance company can participate in the incentive mechanism for the contractor's risk management, which has a good external effect on the owner's utility. As the owner and the insurance company have signed the insurance contract, the distribution of the risk loss is confirmed in the insurance contract. The insurance company's participation in the incentive mechanism can strengthen the project's risk management in the common agency model, while an exclusive agent model clearly misses an important stakeholder. The owner reduces the loss of

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the self-retention risk while increasing the risk reputation gain, thereby improving the owner's utility.

Numerical Examples

The previous section established the common agency and exclusive agency models and discussed the participants' strategies and utilities. To better understand the impact of various parameters on the strategies and utilities, this section uses numerical examples to demonstrate the application of these two models. In this section, the perception coefficient of nonrisk management and the economic coefficient of risk management are selected as two important parameters that need to be examined in terms of their impact on the owner and insurance company's optimal incentive strategies and utilities and the contractors' optimal effort in risk and nonrisk management. We have interviewed the stakeholders of the mega projects that are under construction in eastern China, including the owner, project managers of the construction units, and the insurance company. Besides, a semistructured questionnaire was also conducted. Then, the following parameters and assumptions are set based on these survey results as well as the actual insurance contract. Furthermore, we assume that the contractor's risk aversion coefficient is $\rho = 0.7$, the owner's reputation perception coefficient of risk management is $\beta_{s1} = 0.28$, and the risk self-retention ratio of the owner is $\alpha = 0.15$. The cost coefficient of nonrisk management is $k_q = 0.63$, the cost coefficient of risk management is $k_s = 0.42$, and the contractor's retention utility is $\omega = 0.02$. It is difficult to accurately estimate the variance in the contractor's income, which is affected by random factors. To simplify the calculation, we assume that the variance between the contractor's utility and the owner's is $\sigma_1^2 = 0.81$. The results of the numerical simulation, based on the presented parameter settings, are presented in Figs. 4–7.

Optimal Incentive Strategies Change with the Perception Coefficients

Fig. 4 shows how the optimal incentive strategies of the owner and the insurance company change with the nonrisk management perception coefficient (β_q) and the perception economic coefficient of risk management (β_{s2}) in the common agency model. Different from the reputation effect that is only related to the owner, the perception economic coefficient of risk management effort represents the contractor's ability to reduce the risk loss; the distribution of the risk loss between the owner and the insurance company is

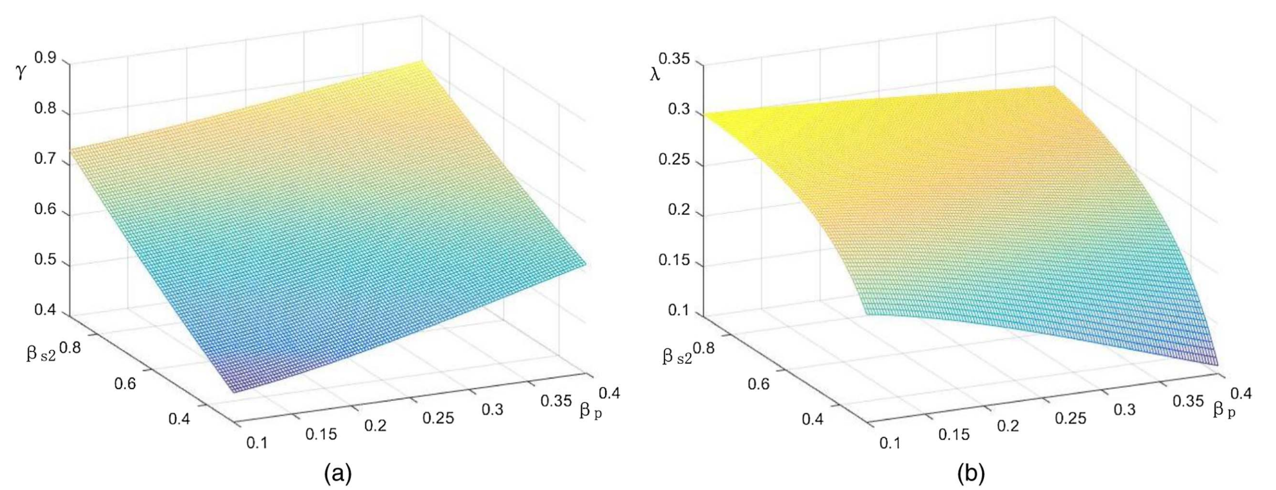

Fig. 4. Optimal incentive strategies for owner and insurance company.

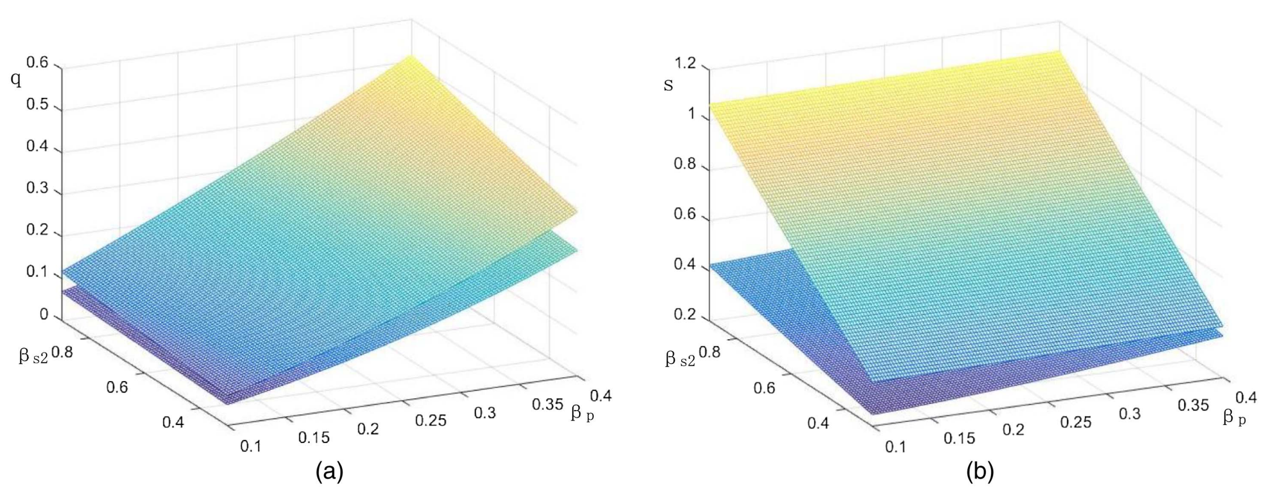

Fig. 5. Optimal strategies of the nonrisk and risk management effort for contractors.

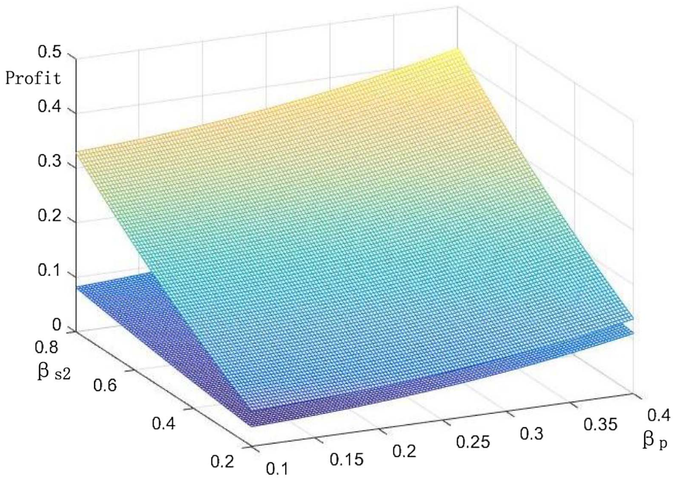

Fig. 6. Owner's utility in the two modes.

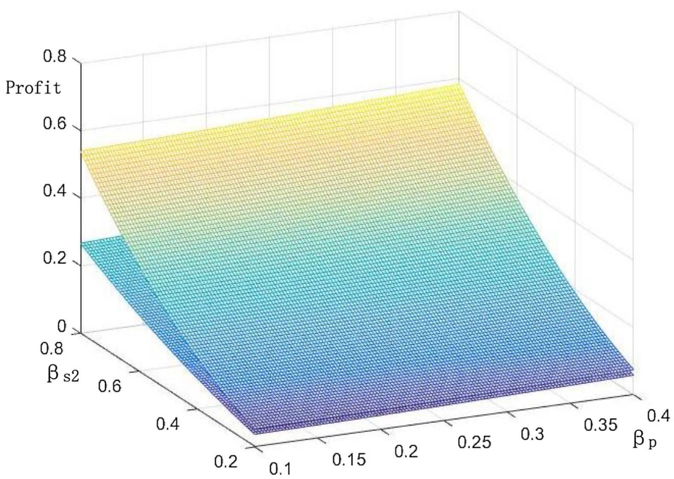

Fig. 7. Insurance company's utility in the two modes.

determined by the risk self-retention ratio. The perception economic coefficient of risk management is crucial in terms of its influence on the principal's strategy and utility. The perception coefficient of nonrisk management is not directly related to the utility of the insurance company, but by observing its impact on the results, we can better understand the external effects of the insurance company's participation in the incentive mechanism.

For the owner, as shown in Fig. 4(a), when β_{s2} is fixed, the optimal incentive strategy (γ) of the owner increases as β_q increases. When β_q is fixed, the optimal incentive strategy (γ) of the owner increases as β_{s2} increases. This shows that the economic perception coefficient of risk and nonrisk management effort both increase the effectiveness of the owner's incentive strategy and that the owner's increased share of the utility can effectively encourage the contractor to invest more effort. For insurance companies, as shown in Fig. 4(b), when β_{s2} is fixed, the insurance company's optimal incentive strategy (λ) decreases as β_q increases. When β_q is fixed, the insurance company's optimal incentive strategy (λ) increases as β_{s2} increases. Therefore, the insurance company's incentive strategy is the same as the owner's response to the perception economic coefficient of risk management, but it is opposite in terms of nonrisk management.

In other words, the increases in the perception economic coefficient of risk and nonrisk management cause an increase in the effectiveness of the insurance company's incentive strategy. Therefore, as these two coefficients increase, the owner is also willing to increase the incentive coefficient to encourage the contractor to invest more effort. For the insurance company, the increase of the output coefficient in risk management also encourages it to provide a higher incentive coefficient, which is consistent with the owner. However, an increase in the output coefficient of nonrisk management negatively impacts its incentive coefficient. This is mainly because the increase in the output coefficient in nonrisk management prompts the owner to increase the incentive coefficient, thus giving the insurance company a free-rider effect. There is no need for the insurance company to increase the incentive coefficient, and providing a lower incentive coefficient can increase its profit.

Optimal Efforts Change with the Perception Coefficients

Fig. 5 shows the changes in the efforts in nonrisk management and risk management as the parameters change in the common agency model and the exclusive agency model. An obvious conclusion can be obtained, and this has been discussed in the section "Analysis of Contractor's Risk and Nonrisk Management Effort." In the common agency model, the contractor's nonrisk and risk management efforts are greater than in the exclusive agent model.

As shown in Fig. 5(a), when β_{s2} is fixed, the contractor's nonrisk and risk management efforts increase as β_q increases. When β_q is fixed, the contractor's nonrisk and risk management efforts increase as β_{s2} increases. The influence of the changes in β_{s2} and β_q on the contractor's nonrisk and risk management efforts is relatively similar, as shown in Fig. 5(b), but they have different levels of influence. Obviously, β_q is the output coefficient of nonrisk management efforts, which directly impact the changes in nonrisk management effort, and β_{s2} is the economic output of the risk management effort, which greatly impacts the changes in the risk management efforts. In addition, the figure shows that the contractor's risk management efforts change significantly with the change in β_{s2}, while the influence of β_q on the change in the contractor's nonrisk management effort is not significant. Under the parameter settings in this paper, the insurance company, as the beneficiary of 85% of the economic output of risk management, participates in the incentive contract in the common agency model, which becomes a powerful supplement to the incentive contract. The difference in the contractor's nonrisk management effort level between the two models is relatively small as the β_q increases because these differences mainly come from the spillover effects of the insurance company's participation in the incentive contract, and the effect is limited.

Profits Change with the Perception Coefficients

As the strategies of both the owner and insurance company possess certain externalities for each other, the utility surfaces of the owner and the insurance company under the common agency model have remained above that of the exclusive agency, as depicted in Figs. 6 and 7. In Fig. 6, the owner's utilities in the two models are relatively close when the value of β_{s2} is small. As β_{s2} increases, a gap appears, and the superiority of the common agency model is gradually reflected, which is consistent with the change in utility of the insurance company in Fig. 7. As shown in Fig. 6, when β_{s2} is fixed, the owner's utility increases as β_q increases. When β_q is fixed, the owner's utility increases as β_{s2} increases. Therefore, combined with the conclusions displayed in Fig. 4, the increase in the utility perception coefficient of risk and nonrisk efforts can increase the effectiveness of the incentive mechanisms, making the contractors more willing to work hard, to increase the owners' utility.

The insurance company's utilities presented in Fig. 7 are similar to those of the owner with changes in parameters β_{s2} and β_q. The results show that the changes in the insurance company's utility are more sensitive to β_{s2} because the insurance company's commitment to economic losses is greater than the commitment proportion of the owners. In contrast, the insurance companies are not sensitive to β_q. This is because the main beneficiary of β_q is the owner, and the insurance company can enjoy the free-rider effect produced by the increase of β_q, but this effect is relatively weak.

Through the simulation of the owner's and insurance company's strategies and utilities, the results show that both the perception economic coefficients of risk and nonrisk management outputs have a significant impact on their strategies. In both models, a higher perception economic coefficient of risk management can improve the effectiveness of the owner's strategy to the contractor so that the owner can increase the incentive coefficient to improve their own utility. This is consistent with the impact of the nonrisk management output coefficient. For the insurance company, the effect of the perception economic coefficient of risk management on its incentive strategy is the same as that of the owner, while the effect of the coefficient of nonrisk management is just the opposite because of the free ride effect. We also find that in the common agency model, the contractor's nonrisk and risk management efforts are both greater than that in the exclusive agency model. In the common agency model, the insurance company is allowed to participate in the incentive contract so that it can use the incentive mechanism reasonably and share the benefits with the contractor, thus generating good synergy with the owner's incentive mechanism and improving its own utility. Therefore, the utilities of the owner and insurance company under the common agency model are larger than that of the exclusive agency model, which can be observed in Figs. 6 and 7.

Conclusion

Stakeholders in mega projects often face significant risk exposure, and risk transfer contracts with insurance companies have become the preferred choice for many projects. However, as the number of mega projects is limited, the insurance companies cannot calculate the risk premium through a statistical analysis. Attempting to participate in mega project risk management has become a viable choice for insurance companies. This paper considered the owners and insurance companies as principals and establishes a common agency model and an exclusive agency model, respectively, and analyzes the strategies of the owner, insurance company, and contractor in the two models. The research results show that compared with the exclusive agency model, both the owner and the insurance company have achieved an increase in utility under the common agency model. This indicates that the incentive strategies of the insurance company for risk management have produced good external effects for the owner. The construction practice in China shows that the insurance companies have been trying to take various ways to participate in on-site risk management after signing the insurance contract, including risk investigation, management guidance, and knowledge sharing. The incentive contract based on the common agency model proposed in this paper is a more feasible way, which also expands the source of risk management investment funds. This study further investigates that the participation of an insurance company encourages the owner to increase the incentive coefficient instead of having a negative effect on the owner's investment and that it also avoids the free-riding effect. Meanwhile, although the insurance company only provided incentives for risk management, the levels of both risk and nonrisk management efforts of the contractors have been improved due to a significant spillover effect.

Specifically, many parameters have a great impact on incentive coefficients and utility. The impact of the risk management effort output coefficient and the owner's self-retaining risk ratio on the ratio of the incentive coefficient is positive, while the uncertainty and nonrisk effort output coefficient's impact is negative. Under the common agency model, the contractor's level of nonrisk and risk management efforts increases. The nonrisk management effort is affected only by the owner, and the influence of the coefficient is therefore consistent with the owner's incentive coefficient. By comparing the differences in the risk management efforts between the two models, the incentive coefficient of the insurance company and the total risk transferred to the insurance company magnify the difference in the risk management efforts. The owner's incentive coefficient, risk management reputation, and self-retention risk narrow the difference in the level of risk management effort. The results of the study were verified by numerical simulations. The results show that the increases in the perception coefficient of nonrisk and risk management efforts both increase the effectiveness of the owner's incentive. These two factors have a positive impact on the owner's incentive coefficient, whereas the perception coefficient of risk management has a positive impact, and the perception coefficient of nonrisk management negatively impacts the insurance company's incentive coefficient. In the common agency model, the contractor's nonrisk and risk management efforts are both greater than those in the exclusive agency model. Both the owner's and the insurance company's utilities in the common agency model are significantly larger than those in the exclusive agency model, and the economic perception coefficients of risk and nonrisk management both have positive effects on the utilities of the owner and insurance company.

Based on the presented analysis, three recommendations are as follows. First, if the insurance company has a strong willingness to participate in risk management, the owner should encourage the insurance company to act as a principal in the design of the incentive mechanism. The participation of more stakeholders has a positive effect on the performance of risk management. Second, although insurance companies only incentivize the output of risk management, it has produced a positive spillover effect, which can promote contractors to increase their efforts in nonrisk management. The final recommendation is that the uncertainty of risk management output narrows the difference between the two models in this research, and the incentive mechanism cannot achieve good results. Thus, the incentive mechanism is more likely to succeed in preventing cyclical risks, such as the prevention of typhoon risk losses in large bridge construction.

The paper contributes to the body of knowledge for understanding the incentive mechanism in the mega project risk management considering the participation of an insurance company. By constructing an incentive model that treats owner and insurance company both as principals, this model enables both parties to design incentive mechanisms for contractors, and this has changed the situation in which insurance companies lack the means to intervene in on-site risk management. This research is beneficial to the stakeholders of mega projects to better understand how to participate in the risk management by incentive mechanism, thus achieving a better risk governance of mega projects.

Mega project insurance is a very meaningful topic, the insurance market for mega projects that can operate stably and effectively is of great significance for the long-term implementation of this type of mega project. This paper proposed a multitask incentive mechanism for insurance companies to participate in major projects, thus providing some new insights into improving projects' governance structures. It should be noted that the incentive model designed in this paper is suitable for mega construction projects, and their huge potential risk loss may attract insurance companies to participate in on-site risk management because insurance companies cannot reduce risks through statistical methods. It is suitable for projects where there is considerable room for improvement in on-site risk management. Instead, it is not suitable for satellites or large scientific installations because these projects' risk management has a ceiling effect, and insurance companies' participation in risk management cannot achieve good results. In addition, it is suitable for projects where the owner predominates and does not apply to some projects where the contractor predominates. In addition, this research considered only one method by which the owner and insurance company devise risk transfer contracts. In practice, there may be other forms of contract design, such as the setting of deductibles or the risk payment of gradients, that lead to complex scenarios. Furthermore, interference in the contractor's multitasking results in reduced efficiency. These situations have made the design of the incentive mechanism challenging and worthy of further research.

Data Availability Statement

All data generated or analyzed during the study are included in the published paper. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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References

Adkisson, J. 2006. *Captive insurance companies: An introduction to captives, closely-held insurances, and risk retention group*. Bloomington, IN: iUniverse.

Bergemann, D., and J. Välimäki. 2003. "Dynamic common agency." *J. Econ. Theory* 111 (1): 23–48. https://doi.org/10.1016/S0022-0531(03)00079-6.

Bernheim, B. D., and M. D. Whinston. 1985. "Common marketing agency as a device for facilitating collusion." *RAND J. Econ.* 16 (2): 269–281. https://doi.org/10.2307/2555414.

Bernheim, B. D., and M. D. Whinston. 1986. "Common agency." *Econometrica* 54 (4): 923–942. https://doi.org/10.2307/1912844.

Biglaiser, G., and C. Mezzetti. 1993. "Principals competing for an agent in the presence of adverse selection and moral hazard." *J. Econ. Theory* 61 (2): 302–330. https://doi.org/10.1006/jeth.1993.1071.

Bower, D., G. Ashby, K. Gerald, and W. Smyk. 2002. "Incentive mechanisms for project success." *J. Manage. Eng.* 18 (1): 37–43. https://doi.org/10.1061/(ASCE)0742-597X(2002)18:1(37).

Bunni, N. G. 2003. *Risk and insurance in construction*. London: Routledge.

Chang, C. Y. 2013. "Principal-agent model of risk allocation in construction contracts and its critique." *J. Constr. Eng. Manage.* 140 (1): 04013032. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000779.

Cheng, M. Y., H. S. Peng, Y. W. Wu, and Y. H. Liao. 2011. "Decision making for contractor insurance deductible using the evolutionary support vector machines inference model." *Expert Syst. Appl.* 38 (6): 6547–6555. https://doi.org/10.1016/j.eswa.2010.11.084.

Ding, L. Y., B. T. Zhong, S. Wu, and H. B. Luo. 2016. "Construction risk knowledge management in BIM using ontology and semantic web technology." *Saf. Sci.* 87 (Aug): 202–213. https://doi.org/10.1016/j.ssci.2016.04.008.

Eisenhardt, K. M. 1989. "Agency theory: An assessment and review." *Acad. Manage. Rev.* 14 (1): 57–74. https://doi.org/10.5465/amr.1989.4279003.

El-Adaway, I. H. 2013. "Promoting the sustainability of relational contracting through addressing third party insurance obstacles." *J. Manage. Eng.* 29 (3): 216–223. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000140.

El-Adaway, I. H., and A. A. Kandil. 2009a. "Contractors' claims insurance: A risk retention approach." *J. Constr. Eng. Manage.* 135 (9): 819–825. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000033.

El-Adaway, I. H., and A. A. Kandil. 2009b. "Construction risks: Single versus portfolio insurance." *J. Manage. Eng.* 26 (1): 2–8. https://doi.org/10.1061/(ASCE)0742-597X(2010)26:1(2).

El-Gafy, M., and T. Abdelhamid. 2015. "Impact of I/D contracts used for expediting Michigan's road construction." *J. Constr. Eng. Manage.* 141 (7): 05015005. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000977.

Gailmard, S. 2012. "Accountability and principal-agent models." In *Oxford handbook of public accountability*, edited by M. Bovens, R. E. Goodin, and T. Schillemans. Oxford, UK: Oxford University Press.

Gal-Or, E. 1991. "A common agency with incomplete information." *RAND J. Econ.* 22 (2): 274–286. https://doi.org/10.2307/2601023.

Griffis, F. H., and S. Christodoulou. 2000. "Construction risk analysis tool for determining liquidated damages insurance premiums: Case study." *J. Constr. Eng. Manage.* 126 (6): 407–413. https://doi.org/10.1061/(ASCE)0733-9364(2000)126:6(407).

Guo, S., C. Xiong, and P. Gong. 2018. "A real-time control approach based on intelligent video surveillance for violations by construction workers." *J. Civ. Eng. Manage.* 24 (1): 67–78. https://doi.org/10.3846/jcem.2018.301.

Hertogh, M. J. C. M., and E. Westerveld. 2010. *Playing with complexity, management and organisation of large infrastructure projects*. Rotterdam, Netherlands: Erasmus Univ.

Holmstrom, B., and P. Milgrom. 1991. "Multitask principal-agent analyses: Incentive contracts, asset ownership, and job design." *J. Law Econ. Organ.* 7: 24. https://doi.org/10.1093/jleo/7.special_issue.24.

Hosseinian, S. M., and D. G. Carmichael. 2012. "Optimal incentive contract with risk-neutral contractor." *J. Constr. Eng. Manage.* 139 (8): 899–909. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000663.

Hu, Z. N., Y. L. Xie, and J. Wang. 2015. "Challenges and strategies involved in designing and constructing a 6 km immersed tunnel: A case study of the Hong Kong–Zhuhai–Macao Bridge." *Tunnelling Underground Space Technol.* 50 (Aug): 171–177. https://doi.org/10.1016/j.tust.2015.07.011.

Imriyas, K. 2009. "An expert system for strategic control of accidents and insurers' risks in building construction projects." *Expert Syst. Appl.* 36 (2): 4021–4034. https://doi.org/10.1016/j.eswa.2008.02.029.

Imriyas, K., L. S. Pheng, T. A. Lin, and C. S. Lean. 2006. "A fuzzy expert system for computing workers' compensation insurance premiums in construction: A conceptual framework." *Archit. Sci. Rev.* 49 (3): 270–284. https://doi.org/10.3763/asre.2006.4937.

Imriyas, K., L. S. Pheng, and E. A. L. Teo. 2007. "A framework for computing workers' compensation insurance premiums in construction." *Constr. Manage. Econ.* 25 (6): 563–584. https://doi.org/10.1080/01446190601110116.

Kim, S. G. 2010. "Risk performance indexes and measurement systems for mega construction projects." *J. Civ. Eng. Manage.* 16 (4): 586–594. https://doi.org/10.3846/jcem.2010.65.

Liu, J., R. Gao, C. Y. Cheah, and J. Luo. 2016. "Incentive mechanism for inhibiting investors' opportunistic behavior in PPP projects." *Int. J. Project Manage.* 34 (7): 1102–1111. https://doi.org/10.1016/j.ijproman.2016.05.013.

Love, P. E., P. R. Davis, R. Chevis, and D. J. Edwards. 2010. "Risk/reward compensation model for civil engineering infrastructure alliance projects." *J. Constr. Eng. Manage.* 137 (2): 127–136. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000263.

Lu, I. F., S. J. Guo, and Y. J. Pan. 2010a. "Construction project management and insurance program for Taiwan high speed rail project." *Leadership Manage. Eng.* 11 (1): 45–56. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000088.

Lu, I. F., S. J. Guo, and Y. J. Pan. 2010b. "Owner-controlled insurance program and construction project management for Taiwan high speed rail project." *J. Manage. Eng.* 26 (4): 164–175. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000034.

Lyons, T., and M. Skitmore. 2004. "Project risk management in the Queensland engineering construction industry: A survey." *Int. J. Project Manage.* 22 (1): 51–61. https://doi.org/10.1016/S0263-7863(03)00005-X.

Ma, H. Y., S. X. Zeng, H. Lin, and R. C. Zeng. 2020. "The impact of public sector on sustainability of public-private partnership (PPP) projects." *J. Constr. Eng. Manage.* 146 (2): 04019104. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001750.

Martimort, D., and L. Stole. 2009. "Market participation in delegated and intrinsic common-agency games." *RAND J. Econ.* 40 (1): 78–102. https://doi.org/10.1111/j.1756-2171.2008.00056.x.

Meng, Q., Z. Li, J. Du, H. Liu, and X. Ding. 2019. "Negotiation for time optimization in construction projects with competitive and social welfare preferences." *Complexity* 2019: 13. https://doi.org/10.1155/2019/3269025.

Meng, X., and B. Gallagher. 2012. "The impact of incentive mechanisms on project performance." *Int. J. Project Manage.* 30 (3): 352–362. https://doi.org/10.1016/j.ijproman.2011.08.006.

Müller, R., and J. R. Turner. 2005. "The impact of principal–agent relationship and contract type on communication between project owner and manager." *Int. J. Project Manage.* 23 (5): 398–403. https://doi.org/10.1016/j.ijproman.2005.03.001.

Ndekugri, I., H. Daeche, and D. Zhou. 2013. "The project insurance option in infrastructure procurement." *Eng. Constr. Archit. Manage.* 20 (3): 267–289. https://doi.org/10.1108/09699981311324005.

On Cheung, S., L. Zhu, and K. Wai Lee. 2018. "Incentivization and interdependency in construction contracting." *J. Manage. Eng.* 34 (3): 04018010. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000601.

Ozcan-Deniz, G., Y. Zhu, and V. Ceron. 2011. "Time, cost, and environmental impact analysis on construction operation optimization using genetic algorithms." *J. Manage. Eng.* 28 (3): 265–272. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000098.

Park, J., Y. Cho, and A. Khodabandelu. 2018. "Sensor-based safety performance assessment of individual construction workers." *Sensors* 18 (11): 3897. https://doi.org/10.3390/s18113897.

Parker, D. W., U. Dressel, D. Chevers, and L. Zeppetella. 2018. "Agency theory perspective on public-private-partnerships: International development project." *Int. J. Productivity Perform. Manage.* 67 (2): 239–259. https://doi.org/10.1108/IJPPM-09-2016-0191.

Raviv, A. 1979. "The design of an optimal insurance policy." *Am. Econ. Rev.* 69 (1): 84–96.

Renn, O. 2015. "Stakeholder and public involvement in risk governance." *Int. J. Disaster Risk Sci.* 6 (1): 8–20. https://doi.org/10.1007/s13753-015-0037-6.

Rose, T. M., and K. Manley. 2010a. "Client recommendations for financial incentives on construction projects." *Eng. Constr. Archit. Manage.* 17 (3): 252–267. https://doi.org/10.1108/09699981011038051.

Rose, T. M., and K. Manley. 2010b. "Financial incentives and advanced construction procurement systems." *Project Manage. J.* 41 (1): 40–50. https://doi.org/10.1002/pmj.20145.

Rwelamila, P. D., P. Fewings, and C. Henjewele. 2014. "Addressing the missing link in PPP projects: What constitutes the public?" *J. Manage. Eng.* 31 (5): 04014085. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000330.

Schexnayder, C. J., S. L. Weber, and S. A. David. 2004. "Transportation agency use of owner-controlled insurance programs." *J. Constr. Eng. Manage.* 130 (4): 517–524. https://doi.org/10.1061/(ASCE)0733-9364(2004)130:4(517).

Sheng, Z. 2018. *Fundamental theories of mega infrastructure construction management*. New York: Springer.

Shi, Q., M. Hertogh, M. Bosch-Rekveldt, J. Zhu, and Z. Sheng. 2020. "Exploring decision-making complexity in major infrastructure projects: A case study from China." *China Manage. J.* https://doi.org/10.1177/8756972820919205.

Siqueira, K., T. Sandler, and J. Cauley. 2009. "Common agency and state-owned enterprise reform." *China Econ. Rev.* 20 (2): 208–217. https://doi.org/10.1016/j.chieco.2009.02.001.

Stole, L. A. 1991. *Mechanism design under common agency.* Cambridge, MA: Program in Law and Economics, Harvard Law School.

Suprapto, M., H. L. Bakker, H. G. Mooi, and M. J. Hertogh. 2016. "How do contract types and incentives matter to project performance?" *Int. J. Project Manage.* 34 (6): 1071–1087. https://doi.org/10.1016/j.ijproman.2015.08.003.

Turner, J. R., and R. Müller. 2003. "On the nature of the project as a temporary organization." *Int. J. Project Manage.* 21 (1): 1–8. https://doi.org/10.1016/S0263-7863(02)00020-0.

Turner, J. R., and R. Müller. 2004. "Communication and co-operation on projects between the project owner as principal and the project manager as agent." *Eur. Manage. J.* 22 (3): 327–336. https://doi.org/10.1016/j.emj.2004.04.010.

Valero, E., A. Sivanathan, F. Bosché, and M. Abdel-Wahab. 2017. "Analysis of construction trade worker body motions using a wearable and wireless motion sensor network." *Autom. Constr.* 83 (Nov): 48–55. https://doi.org/10.1016/j.autcon.2017.08.001.

Van Ackere, A. 1993. "The principal/agent paradigm: Its relevance to various functional fields." *Eur. J. Oper. Res.* 70 (1): 83–103. https://doi.org/10.1016/0377-2217(93)90234-E.

Zhao, X. H., W. C. Cheng, J. S. Shen, and A. Arulrajah. 2017. "Platform collapse incident of a power plant in Jiangxi, China." *Nat. Hazard.* 87 (2): 1259–1265. https://doi.org/10.1007/s11069-017-2800-z.

Zhu, Y., J. Zhang, and X. Gao. 2018. "Construction management and technical innovation of the main project of Hong Kong–Zhuhai–Macao Bridge." *Front. Eng. Manage.* 5 (1): 128–132.