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Optimal Incentive Contract with Asymmetric Cost Information

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Abstract: As a prevalent problem for construction projects, contractor cost details are unobserved or unknown to the owner. This paper considers a risk-averse owner (he) who engages a risk-neutral contractor (she) to complete a project when the contractor's overtime cost information is unknown to the owner. The owner designs a menu of incentive contracts for the contractor to choose/to negotiate with the contractor to maximize his profit. The incentive payment is determined by the saved time relative to the predetermined deadline. We provide optimal incentive contract menus under symmetric and asymmetric information settings, respectively. Moreover, by comparing the terms of optimal incentive contracts under both information settings, we find that even though the duration of a low-cost contractor will not change with the information setting. However, the owner has to pay more to induce the low-cost contractor to choose the appropriate contract under the asymmetric information setting. Meanwhile, the high-cost contractor receives less payment and completes the project later under the asymmetric information setting. In addition, we find the value of information increases with the level of risk aversion and the gap of costs, and is concave with respect to the probability of high-cost type or that of low-cost type. Finally, we use real data to verify our theoretical findings.
DOI: 10.1061/(ASCE)CO.1943-7862.0001832. *© 2020 American Society of Civil Engineers.*

Author keywords: Construction project; Asymmetric information; Incentive contract design.

Introduction

As a dominant feature of the construction industry, the contract has the potential to be a proactive planning device (Puddicombe 2009). Contract design problems have attracted growing attention in recent years from both scholars and practitioners (Qi 2018). Incentive provisions are used in construction contracts to reduce cost, to minimize project duration, and to maintain acceptable levels in the safety, productivity, technological progress, innovation, management efficiency, and quality of construction. Such contracts transfer some of the risk traditionally associated with the owner to the contractor in return for a reward if the contractor is able to achieve the target(s) set in the contract (Arditi and Yasamis 1998). In a typical construction project, because of the complicated environment and the influence of subjective human factors, there is huge difference in information acquisition between the owner and the contractor. To be specific, the owner may know the contractor's construction capacity in general terms but not in its specifics (Hosseinian and Carmichael 2013). The asymmetric information and potential profit may motivate the contractor to misreport her cost type to earn extra revenue. The informed party's (holding more/specific information) tendency to hide its real information for sake of its own interest while encroaching on the profit of the uninformed party and hurting the whole market is called adverse selection in the economics literature (Xiang et al. 2015). It will be critical to design proper contracts to solve the contract design problems.

Construction project management is a complex and systematic job, characterized by large scale, huge investment, long period, intensive knowledge, and technology. In the project implementation process, since the participants do not join in simultaneously and their experiences and interests vary greatly, asymmetric information is quite a common problem (Yang et al. 2016). The problem of asymmetric information arises naturally, referring to that before the contract is concluded. The party with more information obtains additional benefits by concealing or falsely reporting that information. In the field of economics, it is called the adverse selection problem. The classic example in economics' literature is the second-hand car market where both bad cars and good cars are sold in a market where the customer cannot identify whether the car is bad or good. Thus, the customers evaluate the cars by the expected valuation. The bad cars are sold at a better price and the good cars bear a higher price. Gradually, as good cars leave the market, the proportion of bad cars increases. This market is named the lemon market, which is an unhealthy development or even shrinking of the market (Akerlof 1970). The similar asymmetric information setting also exists in construction project management if either the owner or the contractor holds more information.

As the main participants of a project, the owner (he) and the contractor (she) will face the asymmetric information problem from the bidding stage. In view of the characteristics of the project, quality of construction largely depends on the contractor's capacity and the actions it will take. Therefore, it becomes the primary tasks for the owner to choose a suitable contractor and work out the proper incentive contracts to stimulate the contractor effectively. Specifically, the owner knows more about his construction needs and less about the information of the potential contractor, such as the

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Note. This manuscript was submitted on July 16, 2019; approved on November 18, 2019; published online on March 27, 2020. Discussion period open until August 27, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

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contractor's professional quality, technology, equipment, management level, and other construction ability information. The owner is the inferior party for this kind of information, while the contractor is the superior party. In pursuit of profit maximization, the owner hopes that the project will be finished with high quality and low cost. When the information about the contractor's cost is hidden, excessively depressed prices may disqualify the contractor of high cost, but handing over more profit to contractors will directly damage the owner's benefits. Hence, the remuneration payment for the contractor and the project time limit and quality should be set within a reasonable range.

We consider a principal–agent model for which the owner is treated as the principal who hopes to maximize the expected profit, while the contractor is treated as the agent. Normally the duration of a project is established based on similar projects or by past performance (Bubshait 2003). The contractor has private information about her overtime cost. Judging from the prior information, the owner knows that there are two types of contractors on the market, featured by the lower cost c_l and higher cost c_h respectively. The probabilities of these low-cost type and high-cost type of contractors are v and $(1-v)$, respectively. The objective is to provide a set of effective contracts to help the information-disadvantaged party (the owner) to engage an eligible contractor when the construction cost information of the contractor is unknown to the owner. And we use real data to elaborate the value of information with respect to: (1) the level of risk aversion, (2) the probability of lower-cost type of contractor v, and (3) the cost gap between the two types of contractors. The probability of contractor type and the cost gap can be viewed as the uncertainty that the owner may confront.

The structure of this paper is as follows. First, we briefly review related literature. Then we present the basic model, discuss the optimal contracts under symmetric information and asymmetry, and provide the optimal results, respectively. Finally, we carry out a numerical analysis by data from literature to verify our results.

Literature Review

This paper mainly involves research in two fields: asymmetric information literature and contract design in engineering project management. The first stream studies asymmetric information problems. Spence (1973) proposed the signaling model for the first time, in which signal means the observable actions taken by the party with more information to make the other party believe their reliability, such as the qualification level, list of completed projects and existing equipment, and other information provided by the contractor to the owner in project bidding. Li and He (2013) suggested that the opportunism and asymmetric information between the two parties in a contract alteration will lead to the phenomenon of hold up and contractor's underinvestment, causing construction delay, and reducing the utility of the owner. While asymmetric information exists in most markets, such as the insurance industry (Browne 1992; Cohen and Siegelman 2010; Shi et al. 2012), the wholesale used car market (Genesove 1993), the labor market (Bastani et al. 2015; Chen et al. 2018), new product development (Yang et al. 2014; Belleflamme and Peitz 2014), credit rationing (Banerji 1995; Hellmann and Stiglitz 2000), and supply chain management (Esmaeili and Zeephongsekul 2010; Lei et al. 2012; Xu et al. 2014; Wu et al. 2018), where many achievements have been made, the research in the field of engineering project management needs to be further explored. Our paper contributes to this stream of literature by introducing asymmetric information to extend the project management problem to be more practical. We consider the asymmetric information in terms of overtime cost which is an important and practical element in construction contracts.

Most of the papers in this stream use the principal–agent model. In real life, because of the presence of asymmetric information, the agent has information superiority and will hide her real information. The principal needs to design an incentive contract for agents to stimulate the agent to choose an action maximizing the principal's income. Salanie (2005) pointed out that in practice under the condition of asymmetric information, bargaining is a very complicated problem. The principal–agent model is a simplified method to distribute all the bargaining power to one side to simplify the problems. In the case of asymmetric information, the principal cannot observe the agent's behavior and can only observe relevant variables, which are jointly determined by the agent's actions and other exogenous random factors. Thus, where a principal cannot use a "forcing contract" to force the agent to choose the action the principal wishes, incentive and compliance constraints work. So, the principal's problem is to choose an incentive contract that satisfies the participation constraints and incentive compatibility constraints of the agent to maximize his expected utility. To be specific, the principal comes up with a take it or leave it contract and will require a yes or no answer; the agent has no right to propose another contract, only to choose the contract proposed by the principal. Xiang et al. (2015) believed that all models of asymmetric information can be discussed under the framework of principal–agent. In recent years, some researchers have applied the principal–agent theory to project management problems. Wang and Liu (2015) integrated the fairness preference theory with the principal–agent model and worked out the optimal incentives when principals (governments) employ agents (investors) who have fairness preferences. In economics literature, there is a handful of papers on the principal–agent problems. Müller and Turner (2005) study the impact of the principal–agent relationship and contract type on communication between the project owner and manager. Liu et al. (2016) constructed principal–agent models in the presence of opportunistic tendencies in private investors based on the contractual relationship between the government and private investors in public-private partnerships (PPP) projects to analyze the incentive mechanism for inhibiting investors' opportunistic tendencies in PPP projects. Different from previous studies, we complement this stream of literature by considering the contractor's construction overtime cost as asymmetric information and analyzing how to design an incentive contract and the effect of asymmetric information on the proposed contract.

The second stream of literature related to our work is the contract design in project management. There are many related research studies on the contractor selection problem. Ioannou and Leu (1993) compared the low-bid and average-bid methods used for competitive bidding in the US construction industry and revealed that the average-bid method and its variations have the potential to improve contracting practices both for the owner and the contractor. Hatush and Skitmore (1997) described a systematic multicriteria decision-analysis technique for contractor selection and bid evaluation based on utility theory. After selecting the contractor, project management focuses on the study of adjusting project activities to achieve a balance between duration, cost, and quality. Ahmed et al. (2016) study bidding as a method of contractor selection. They show that although multistage bidding incurs more losses but more likely avoids the winner's curse that appears in single-stage bidding. Abotaleb and El-Adaway (2017) use a multistage decision approach to determine the optimal bid value to maximize the probability of winning a construction project. Apart from the aforementioned papers, we focus on the information asymmetry feature in the contract design process by considering only one contractor and simplifying the biding process between the owner and the contractor. El-Adaway et al. (2016) states that time management is one of the most important factors in the construction projects. Zhang et al. (2015) concluded that incentive contracts play an important role in reducing moral hazard in the research on the project supervision system based on the principal–agent model. Xiang et al. (2015) studied the asymmetric information among owners, contractors, and supervisors by means of questionnaires, and distinguished the primary and secondary order of asymmetric information phenomena. Kerkhove and Vanhoucke (2016) analyzed a large amount of relevant literature and showed that the most traditional tradeoff problem in project management exists between project cost and project duration. Yang et al. (2016) studied the impact of uncertain project duration and contractor's private information about risk sensitivity on the incentive contract mechanism and the project manager's profit. They proved that when the project duration is uncertain, the project manager is more willing to obtain the contractor's risk-sensitivity information, which is consistent with our findings. Qi (2018) designed two incentive contracts, a duration-based contract and a deadline-based contract, and he explored whether owners benefit more from knowing the contractor's construction capabilities when the deadline-based incentive contract is used. Instead of considering construction capabilities or duration uncertainty, our paper is distinct from the aforementioned work in that we consider the contractor's construction overtime cost as asymmetric information based on a deadline-based incentive contract.

Model

We consider a deadline-based incentive contract design problem involving two players: a risk-averse owner (he) and a risk-neutral contractor (she), which is also applied in Hosseinian and Carmichael (2013). The overtime cost of the contractor is unknown to the owner. First, the owner provides a menu of contracts to the contractor. Then, the contractor either selects one or rejects them at all. The owner can identify the overtime cost information based on the decision of the contractor.

It is known to all that the duration of a construction project is a crucial factor in project management. The earlier the project is completed, the sooner owner can operate the project and the more income can be generated. Further, based on the principle of risk sharing, risks that can be estimated accurately and controlled should be managed by the party who has more effective control of them. Risks that cannot be estimated should be assumed by the party with the ability to handle them or can obtain insurance for them. In the field of engineering project management, the owners are often the ones who take on risks that cannot be accurately assessed (Li and He 2013). Therefore, we assume that the owner is risk averse. In the literature of information economics, the utility function of risk aversion is assumed to be a concave function. In our paper, the utility of the owner increases with the reduced project duration, and the rate of utility increase decreases with the saving in project time. In other word, the owner's utility function $R(\Delta T)$ satisfies this condition: $\{[d^2R(\Delta T)]/(d\Delta T^2)\} \leq 0$. As stated in previous research (Kwon et al. 2010; Hosseinian and Carmichael 2013), the owner of the exponential utility function is as follows:

$$R(\Delta T) = 1 - e^{-r\Delta T} \tag{1}$$

where ΔT = savings in construction time related to the predetermined deadline D, T = actual construction period, and $\Delta T = D - T$. Fig. 1 shows the utility function among different risk aversion levels r. Clearly the owner expects a larger ΔT. The

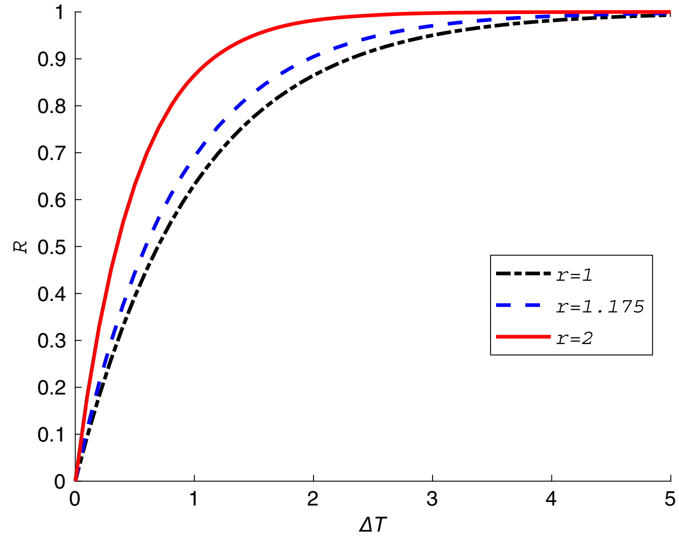

Fig. 1. Utility function curve.

exponential utility function represents the constant absolute risk aversion (CARA). The parameter $r > 0$ denotes the absolute risk aversion coefficient (ARA), which means that the owner's risk aversion is a fixed value, and the larger the r value is, the higher the degree of owners' risk aversion will be. This form is more convincing than the quadratic utility function, which represents increasing risk-aversion coefficients. Therefore, exponential utility function has been widely used in economics, especially in the theory of portfolio selection (Bodnar et al. 2015).

We assume that the owner is facing a risk neutral contractor and he will provide the contractor with a linear incentive payment based on the predetermined deadline of the project $W = \alpha + \beta\Delta T$, which has been widely used in previous studies (Yang et al. 2016; Qi 2018). The parameter α denotes the fixed remuneration paid to the contractor, which is determined in the contract and seemingly has no direct correlation with the duration of the project. The slope parameter $\beta > 0$ represents the bonus item, that is, the more time the contractor saves by completing the project early (saved time), the more reward she will get. Given the deadline, D, of the project, the owner designs the construction period T (we use ΔT in the derivation process which has no influence on the actual contract design process) and the fixed payment α to the contractor, leaving the bonus item constant. Therefore, the gain of the owner is the net profit after deducting the payment to the contractor:

$$\pi = G + \theta R(\Delta T) - (\alpha + \beta\Delta T) = \theta R(\Delta T) - \beta\Delta T - \alpha \tag{2}$$

where G = basic revenue for the owner if project is finished on time. It has no impact on the optimization process, so we omit it to keep the narrative clearer and more concise. The parameter θ is the coefficient that converts utility into income. To ignore the trivial cases and exhibit a valuable reward for the owner, we focus on the cases where θ is relatively large, $r\theta > c_i$.

Assume that for every unit of time savings, the contractor needs to pay an extra construction cost, c. Then the actual profit of the contractor would be

$$U = (\alpha + \beta\Delta T) - c\Delta T = \alpha + (\beta - c)\Delta T \tag{3}$$

The owner will design and provide the incentive contracts $(\alpha_1, \Delta T_1)$ or $(\alpha_2, \Delta T_2)$ to the contractor, and the contractor decides whether to accept them. We assume that there are two types of

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contractors in the market, characterized by different construction costs, c_l or c_h respectively ($c_l \leq c_h$). The owner knows the prior probability of them to be v and $(1-v)$. So, the net income of the contractor is $U_1 = \alpha + (\beta - c_l)\Delta T$ and $U_2 = \alpha + (\beta - c_h)\Delta T$. To ensure that the contractor selects the contract commensurate with her actual construction cost, we use the incentive compatibility constrain

$$\alpha_1 + (\beta - c_l)\Delta T_1 \geq \alpha_2 + (\beta - c_l)\Delta T_2 \tag{4}$$

$$\alpha_2 + (\beta - c_h)\Delta T_2 \geq \alpha_1 + (\beta - c_h)\Delta T_1 \tag{5}$$

We denote the inequalities Eqs. (4) and (5) as IC1 and IC2, respectively. To ensure that the contractor is willing to participate in the contract, individual rational constraints are expressed as follows:

$$\alpha_1 + (\beta - c_l)\Delta T_1 \geq 0 \tag{6}$$

$$\alpha_2 + (\beta - c_h)\Delta T_2 \geq 0 \tag{7}$$

We denote the inequalities Eqs. (6) and (7) as IR1 and IR2, respectively.

The owner's incentive contract design problem can be formulated

$$\begin{aligned}\max_{\alpha_1,\Delta T_1,\alpha_2,\Delta T_2}\Pi = G + v[\theta R(\Delta T_1) - \beta\Delta T_1 - \alpha_1] \\ + (1-v)[\theta R(\Delta T_2) - \beta\Delta T_2 - \alpha_2]\end{aligned} \tag{8}$$

As shown in Fig. 2, we are going to discuss two models: a symmetric information case and an asymmetric information case. In the symmetric information case, the owner knows the exact overtime cost information of the contractor, thus he only needs to ensure the individual rational constraints hold. While, in the asymmetric information case, the owner lacks the overtime cost information, thus the optimal contract menu should be designed when both the incentive compatibility constraints and individual constraints hold simultaneously.

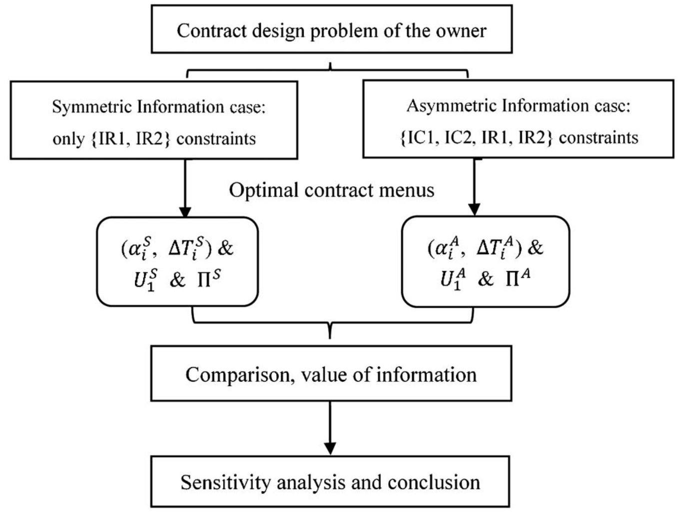

Fig. 2. Structure of the paper.

Optimal Incentive Contracts and Analysis

In this section, we elaborate on the principal–agent model based on the deadline-based incentive contract. We obtain the optimal incentive contracts under symmetric information and asymmetric information, respectively. Fig. 2 references the structure of this paper.

Optimal Incentive Contract under Symmetric Information

Before analyzing the contract design under the asymmetric information case, we discuss the optimal incentive contract under the symmetric case, for which the owner knows the contractor's exact cost information. We refer to this case as Case A. In the symmetric information case, the contract design for one type of contractor does not affect the contract selection for another type of contractor, so the incentive compatibility constraint can be ignored. The model can be expressed as

$$\begin{aligned}&\max_{\alpha_1,\Delta T_1,\alpha_2,\Delta T_2}\Pi = G + v[\theta R(\Delta T_1) - \beta\Delta T_1 - \alpha_1] + (1-v)[\theta R(\Delta T_2) - \beta\Delta T_2 - \alpha_2],\\ &s.t.\\ &\alpha_1 + (\beta - c_l)\Delta T_1 \geq 0, \quad (IR1)\\ &\alpha_2 + (\beta - c_h)\Delta T_2 \geq 0. \quad (IR2)\end{aligned} \tag{9}$$

Proposition 1: Under the symmetric information case, the optimal incentive contract is given by

$$\begin{cases}\alpha_i^S = \dfrac{(c_i - \beta)}{r}\ln\left(\dfrac{\theta r}{c_i}\right)\\ \Delta T_i^S = \dfrac{1}{r}\ln\left(\dfrac{\theta r}{c_i}\right)\end{cases}; \ i = l, h \tag{10}$$

Proof: Under the symmetric information setting, the contractor cost, c_i, is accurately learned by the owner, whose goal is to find a suitable α_i and ΔT_i to maximize their profit, Π

$$\begin{aligned}\Pi = G + v[\theta R(\Delta T_1) - \beta\Delta T_1 - \alpha_1]\\ + (1-v)[\theta R(\Delta T_2) - \beta\Delta T_2 - \alpha_2]\end{aligned}$$

Subject to

$$U = (\alpha_i + \beta\Delta T_i) - c_i\Delta T_i = \alpha_i + (\beta - c_i)\Delta T_i \geq 0$$

In order to ensure that the contractor is willing to participate in the project, the individual rationality constraint must bind

$$\alpha_i + \beta\Delta T_i = c_i\Delta T_i$$

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By substituting it into Eq. (2), we can obtain

$$\pi_i = G + \theta R(\Delta T_i) - c_i \Delta T_i$$

Since the second-order derivative of Π with respect to ΔT_i

$$\frac{d^2\pi_i}{d\Delta T_i^2} = -r^2 \theta e^{-r\Delta T_i} < 0$$

So π_i is strictly concave in ΔT_i. The optimal shortened construction duration ΔT_i^* satisfies the first-order condition as follows:

$$r\theta e^{-r\Delta T_i} - c_i = 0$$

Which yields

$$\Delta T_i^S = \frac{1}{r} \ln\left(\frac{\theta r}{c_i}\right)$$

To ensure that $\Delta T_i^S \geq 0$ and $\theta r \geq c_i$, and according to the above results, we can obtain

$$\alpha_i^S = \frac{(c_i - \beta)}{r} \ln\left(\frac{\theta r}{c_i}\right)$$

Proposition 1 provides us with closed form of the optimal incentive contract $(\alpha_1^S, \Delta T_1^S)$ and $(\alpha_2^S, \Delta T_2^S)$. We proved that the individual rational constraint is binding at optimality. In addition, the owner's income profit margin is $[(d\pi_i)/(d\Delta T)] = \theta r e^{-r\Delta T} \leq \theta r$. We need to satisfy $\theta r \geq c_h \geq c_l$, which also results in $\Delta T \geq 0$. This condition will ensure that the advance of the project is necessary only if it can create value above the potential cost, otherwise it will waste resources. It also can be seen that when the bonus item perfectly meets the contractor's construction cost, the owner does not need to pay additional compensation to the contractor. When the project is completed before the predetermined date, to ensure the contractor participates, her income should be able to cover the construction cost at least. So, if the bonus item is less than the contractor's cost, the owner should pay the contractor a certain fixed compensation ($\alpha_i^S \geq 0$). Accordingly, if the reward is greater than the contractor's construction cost, the owner can deduct some payment ($\alpha_i^S < 0$).

Proposition 2: Under symmetric information case, the optimal profit of the contractor is

$$U_i = 0, i = l, h \tag{11}$$

The corresponding optimal expected payoff of the owner is

$$\Pi^S = G + \theta - \frac{c_l v + (1-v)c_h}{r}(1 + \ln \theta r) + \frac{1}{r}(c_l v \ln c_l + (1-v)c_h \ln c_h) \tag{12}$$

Proposition 2 points out that when the owner knows the construction cost information of the contractor accurately, both types of contractors have no reserve profit. It is worth noting that the final profits for the owner and the contractor have no relation to the bonus item β.

Optimal Incentive Contract under Asymmetric Information

Under asymmetric cost information, the contractor's cost type is her private information, and we use Case A for easy reference. In this case, it is easy to see that the contractor with lower cost has the motivation to choose the contract for the higher cost contractor, as she can benefit from the contract designed for the higher cost one. Hence, the owner faces adverse selection and only knows the prior probabilities of these two contractors, namely v and $(1-v)$, and he will design and offer a menu of incentive contracts to maximize his expected profit. This part is a typical solution process of asymmetric information in the discrete case by applying the information revelation principle. As there are many optimization variables involved, it is difficult to guarantee which constraints are certainly effective; we will explain this problem in the next section. The incentive contracts design model of the owner can be established as

$$\begin{aligned}
&\max_{\alpha_1,\Delta T_1,\alpha_2,\Delta T_2} \Pi = G + v[\theta R(\Delta T_1) - \beta\Delta T_1 - \alpha_1] + (1-v)[\theta R(\Delta T_2) - \beta \Delta T_2 - \alpha_2]\\
&\text{s.t.}\\
&\alpha_1 + (\beta - c_l)\Delta T_1 \geq \alpha_2 + (\beta - c_l)\Delta T_2, \quad (IC_1)\\
&\alpha_2 + (\beta - c_h)\Delta T_2 \geq \alpha_1 + (\beta - c_h)\Delta T_1, \quad (IC_2)\\
&\alpha_1 + (\beta - c_l)\Delta T_1 \geq 0, \quad (IR_1)\\
&\alpha_2 + (\beta - c_h)\Delta T_2 \geq 0. \quad (IR_2)
\end{aligned} \tag{13}$$

Lemma 1: Under asymmetric information case, we will have that at the optimum

1. (IR_2) is active, so $\alpha_2 = (c_h - \beta)\Delta T_2$
2. (IC_1) is active, whence $\alpha_1 - \alpha_2 = (\beta - c_l)(\Delta T_2 - \Delta T_1)$
3. $\Delta T_1 \geq \Delta T_2$
4. (IC_2) and (IR_1) can be neglected
5. lower cost contractor chooses the efficient shortened construction period

$$\Delta T_1 = \Delta T_1^*$$

Proof: We use (IC_1) to prove property (1):

$$\alpha_1 + (\beta - c_l)\Delta T_1 \geq \alpha_2 + (\beta - c_l)\Delta T_2 \geq \alpha_2 + (\beta - c_h)\Delta T_2$$

since $\Delta T_2 \geq 0$ and $c_l < c_h$. If (IR_2) was inactive, so would be (IR_1), and we could decrease α_1 and α_2 by the same amount. This would increase the owner's profit without an effect on incentive compatibility. So, we have $\alpha_2 = (c_h - \beta)\Delta T_2$.

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Property (2) is proved by assuming that (IC_1) is inactive. Then

$$\alpha_1 + (\beta - c_l)\Delta T_1 > \alpha_2 + (\beta - c_l)\Delta T_2 \geq \alpha_2 + (\beta - c_h)\Delta T_2 = 0$$

We can therefore diminish α_1 without breaking incentive compatibility or the individual rationality constraint (IR_1). This obviously increases the owner's profit, and therefore the original mechanism cannot be optimal. Thus, we have $\alpha_1 + (\beta - c_l)\Delta T_1 = \alpha_2 + (\beta - c_l)\Delta T_2$.

To prove property (3), let us add (IC_1) and (IC_2)

$$(\beta - c_h)(\Delta T_2 - \Delta T_1) \geq \alpha_1 - \alpha_2 \geq (\beta - c_l)(\Delta T_2 - \Delta T_1)$$

The bonus term β cancel out, and we get

$$\Delta T_1 \geq \Delta T_2$$

since $c_h > c_l$.

By property (4), the (IC_2) can be neglected, since (IC_1) is active, and $\alpha_1 - \alpha_2 = (\beta - c_l)(\Delta T_2 - \Delta T_1) \leq (\beta - c_h)(\Delta T_2 - \Delta T_1)$. The proof of property (1) shows that (IR_2) is active, so (IR_1) can be neglected.

Finally, by property (4), we can prove that $\{[dR(\Delta T_1)]/(d\Delta T_1)\} = c_l/\theta$.

If $\{[dR(\Delta T_1)]/(d\Delta T_1)\} > c_l$, for instance, let ε be a small positive number, and consider the new mechanism $(\alpha_1' = \alpha_1 - (\beta - c_l)\varepsilon, \Delta T_1' = \Delta T_1 + \varepsilon)$, $(\alpha_2, \Delta T_2)$. It is easily seen that

$$\begin{aligned} &\alpha_1' + (\beta - c_l)\Delta T_1' = \alpha_1 + (\beta - c_l)\Delta T_1 \geq 0 \quad \text{and} \\ &\alpha_1' + (\beta - c_h)\Delta T_1' = \alpha_1 + (\beta - c_h)\Delta T_1 + \varepsilon(c_l - c_h) \end{aligned}$$

So, the new mechanism satisfies all four constraints. Moreover

$$\begin{aligned} &\frac{\theta R(\Delta T_1') - \beta\Delta T_1' - \alpha_1' - [\theta R(\Delta T_1) - \beta\Delta T_1 - \alpha_1]}{\varepsilon} \\ &\quad \cong \theta\frac{dR(\Delta T_1)}{d\Delta T_1} - \beta + (\beta - c_l) \end{aligned}$$

$$\begin{aligned} \Rightarrow &R(\Delta T_1') - \beta\Delta T_1' - \alpha_1' \\ &= R(\Delta T_1) - \beta\Delta T_1 - \alpha_1 + \varepsilon\left(\theta\frac{dR(\Delta T_1)}{d\Delta T_1} - c_l\right) \end{aligned}$$

This tells us that the new mechanism yields higher profits than the original one, which is inconsistent. In the case that $\{[dR(\Delta T_1)]/(d\Delta T_1)\} < (c_l/\theta)$, we can prove in the same way that it is impossible by changing the sign of ε.

Lemma 1 indicates that the contractor with higher unit construction cost cannot obtain reservation profit $(U_2 = 0)$, and if she chooses a contract designed for another type of contractor, the profit she can obtain is not positive. Contractors with lower construction costs can obtain reservation profit $(U_1 \geq 0)$ in both of the types of contracts. From the owner's perspective, he wishes that the lower cost contractor can shorten construction time, thus he may get a more efficient construction period contract from the contractor.

Proposition 3: Under asymmetric information case

if $0 \leq v \leq [(r\theta - c_h)/(r\theta - c_l)]$, the optimal incentive contract is given as

$$\begin{aligned} \alpha_1^A &= \frac{c_h - c_1}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l} + \frac{c_1 - \beta}{r}\ln\frac{r\theta}{c_l} \\ \Delta T_1^A &= \frac{1}{r}\ln\frac{r\theta}{c_l}, \\ \alpha_2^A &= \frac{c_h - \beta}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l}, \\ \Delta T_2^A &= \frac{1}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l}. \end{aligned} \tag{14}$$

$$\text{if } \frac{r\theta - c_h}{r\theta - c_l} < v \leq 1$$

$$\begin{aligned} \alpha_1^A &= \frac{c_l - \beta}{r}\ln\frac{r\theta}{c_l}, \\ \Delta T_1^A &= \frac{1}{r}\ln\frac{r\theta}{c_l}, \\ \alpha_2^A &= 0, \\ \Delta T_2^A &= 0. \end{aligned} \tag{15}$$

Proof: We have already learned from Lemma 1 that

$$\begin{aligned} &\alpha_2 = (c_h - \beta)\Delta T_2, \\ &\alpha_1 = (c_h - c_l)\Delta T_2 + (c_l - \beta)\Delta T_1, \\ &\frac{dR(\Delta T_1)}{d\Delta T_1} = \frac{c_l}{\theta} \end{aligned}$$

Substitute them into the owner's profit function and maximize it

$$\begin{aligned} \max_{\Delta T_2}\Pi = G &+ v[\theta R(\Delta T_1) - \beta\Delta T_1 - \alpha_1] \\ &+ (1 - v)[\theta R(\Delta T_2) - \beta\Delta T_2 - \alpha_2] \end{aligned}$$

It is equivalent to solving $\max_{\Delta T_2}(1-v)(\theta R(\Delta T_2) - c_h\Delta T_2) + v(c_l - c_h)\Delta T_2$

When $v \neq 1$, the derivative with respect to ΔT_2 is

$$\frac{dR(\Delta T_2)}{d\Delta T_2} = \frac{c_h}{\theta} + \frac{v(c_h - c_l)}{(1-v)\theta} > \frac{c_h}{\theta}$$

which indicates that the contract reached between the owner and the contractor with higher cost is sub-efficient. Further, we can get

$$\begin{aligned} &\Delta T_1^A = \frac{1}{r}\ln\frac{r\theta}{c_l}, \quad \Delta T_2^A = \frac{1}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l}, \\ &\alpha_1^A = \frac{c_h - c_l}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l} + \frac{c_l - \beta}{r}\ln\frac{r\theta}{c_l}, \\ &\alpha_2^A = \frac{c_h - \beta}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l} \end{aligned}$$

To ensure $\Delta T_1^A \geq 0$, we will get $c_l \leq r\theta$; and to ensure $\Delta T_2^A \geq 0$, we have $c_h \leq r\theta(1-v) + vc_l$, that is $v \in \{0, [(r\theta - c_h)/(r\theta - c_l]\}$. It is easy to determine that

$$\forall v \in \left(\frac{r\theta - c_h}{r\theta - c_l}, 1\right], \quad \Delta T_2^A = 0, \quad \alpha_2^A = 0, \quad \alpha_1^A = \frac{c_l - \beta}{r}\ln\frac{r\theta}{c_l}$$

Proposition 3 provides us with closed solution of the optimal incentive contract $(\alpha_1^A, \Delta T_1^A)$, $(\alpha_2^A, \Delta T_2^A)$ under asymmetric construction cost information. First, it is interesting to note that bonus term β only influences fixed payment α and has nothing to do with ΔT. In line with common sense, α_i^A decreases monotonously with β because the higher the reward for each unit of shortened time, the less the corresponding fixed payment. Second, ΔT_1^A and ΔT_2^A are increasing in θ. Namely, if the owner can get more profit from a unit of utility because of shortened construction duration, he will certainly hope that the contractor can shorten the construction duration more significantly through contract design. In addition, we find that when v value is high enough, which means the owner may quite possibly encounter a contractor with lower cost, the contract he will design for the lower-cost contractor is the same as the one achieves under symmetric information. But at the price of reaching an efficient contract with the lower cost contractor, he will give up the higher cost contractor with zero saving in time expectation.

Corollary 1: Under asymmetric information case, the optimal incentive contracts satisfy

(a) $\Delta T_1^A \geq \Delta T_2^A$,

(b) if $\beta \geq c_l$, then $\alpha_2^A \geq \alpha_1^A$; Otherwise, if $\beta < c_l$, then $\alpha_2^A < \alpha_1^A$.

Proof: We have already proved (a) $\Delta T_1 \geq \Delta T_2$ in lemma 1.

If $v \in \{[0, [(r\theta - c_h)/(r\theta - c_l)]]\}$, we use $\Delta = \alpha_1^A - \alpha_2^A = [(\beta - c_l)/r] \ln\{[c_l(1-v)]/(c_h - vc_l)\}$. It is easy to prove that $\ln\{[c_l(1-v)]/(c_h - vc_l)\} < 0$, since $c_l > c_h$. Then when $\beta \geq c_l$, $\Delta \leq 0$, which means $\alpha_2^A \geq \alpha_1^A$; when $\beta < c_l$, $\Delta > 0$, indicating $\alpha_2^A < \alpha_1^A$. If

$$v \in \left(\frac{r\theta - c_h}{r\theta - c_l}, 1\right], \quad \alpha_1^A = \frac{c_l - \beta}{r} \ln\frac{r\theta}{c_l}, \quad \alpha_2^A = 0$$

obviously $\alpha_2^A < \alpha_1^A$.

Corollary 1 reveals that the owner expects that the lower construction-cost contractor could shorten the construction period more, which is consistent with common sense. Because the total compensation (the owner's cost) paid to stimulate the contractor may be relatively low, the owner may be able to obtain more benefit from completing a project ahead of schedule, which gives him stronger motivation to complete the project as soon as possible. For the contractor with higher construction cost, the cost of motivating them to complete the project ahead of schedule may be higher than the utility (benefit), so the owners have no incentive to require them to complete the project within the same construction period as the contractor with lower construction cost.

In addition, in the designated incentive contract, if the bonus item β is more than the construction cost c_l, the fixed payment to the lower cost contractor will be less than the other type of contractor. On the contrary, if β is less than c_l, the fixed remuneration α_1^A paid to the lower cost contractor is higher than the fixed remuneration α_2^A available to the other type of contractor. The difference between α_2^A and α_1^A decreases with bonus item β monotonously, which means the closer β is to c_l, the closer α_1^A and α_2^A are.

Proposition 4: Under asymmetric information case, the optimal profits for the two types of contractors are given by

$$U_1^A = \begin{cases} \dfrac{c_h - c_l}{r} \ln\dfrac{r\theta(1-v)}{c_h - c_l v}, & \text{if } 0 \leq v \leq \dfrac{r\theta - c_h}{r\theta - c_l}, \\ 0, & \text{if } \dfrac{r\theta - c_h}{r\theta - c_l} < v \leq 1. \end{cases} \tag{16}$$

$$U_2^A = 0 \tag{17}$$

The corresponding expected payoff for the owner is

$$\Pi^A = \begin{cases} G + \theta - \dfrac{c_h}{r} - \dfrac{vc_l}{r}\ln\dfrac{r\theta}{c_l} - \dfrac{c_h - vc_l}{r}\ln\dfrac{r\theta(1-v)}{c_h - vc_l}, & 0 \leq v \leq \dfrac{r\theta - c_h}{r\theta - c_l}; \\ G + v\left(\theta - \dfrac{c_l}{r} - \dfrac{c_l}{r}\ln\dfrac{r\theta}{c_l}\right), & \dfrac{r\theta - c_h}{r\theta - c_l} < v \leq 1 \end{cases} \tag{18}$$

Proof: Substitute the results in Proposition 3 into the owner's utility function $R(\Delta T) = 1 - e^{-r\Delta T}$, then for $0 \leq v \leq [(r\theta - c_h)/(r\theta - c_l)]$, $R(\Delta T_1) = 1 - (c_l/r\theta)$; $R(\Delta T_2) = 1 - \{(c_h - vc_l)/[r\theta(1-v)]\}$. Put these results and the results of Proposition 3 into the owner's profit function

$$\Pi^{\mathrm{A}} = G + v[\theta R(\Delta T_1) - \beta\Delta T_1 - \alpha_1] + (1-v)[\theta R(\Delta T_2) - \beta\Delta T_2 - \alpha_2]$$

$$= G + \theta - \frac{c_h}{r} - \frac{vc_l}{r}\ln\frac{r\theta}{c_1} - \frac{c_h - vc_l}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l}$$

If $[(r\theta - c_h)/(r\theta - c_l)] < v \leq 1$, $R(\Delta T_2) = 0$. Similarly, we have

$$\Pi^{\mathrm{A}} = G + v\left(\theta - \frac{c_l}{r} - \frac{c_l}{r}\ln\frac{r\theta}{c_l}\right)$$

In the same way, we can get the contractor's income. It is also noted that in the case of asymmetric information, the final profit for both the owner and the contractor have nothing to do with the bonus item β. Under the condition of information asymmetry, contractors with lower unit construction cost can get extra profit. That's why the owner has to give the contractor a piece of pie in the form of informational rent to induce him to report his cost type information truthfully. The results are shown in Table 1.

Value of Cost Information

In this subsection, we analyze the influence of asymmetric information on the owner's decision by comparing the optimal contract design results under the two situations of symmetric information and information asymmetry, including the parameters in the contract, the benefits available to the contractor, and the owner's benefits. It is intuitive that asymmetric information is disadvantageous for owners, and will mislead the owners' decisions. This section will give a more convincing analysis by mathematical deduction.

Information Value for Contractor

By comparing the optimal solutions of symmetric information and asymmetric information settings, we conclude the difference in Proposition 5.

Proposition 5: By comparing the optimal incentive contract under symmetric information case with that under asymmetric information case, we can obtain that

If $0 \leq v \leq [(r\theta - c_h)/(r\theta - c_l)]$, $\alpha_1^S \leq \alpha_1^A$, $\Delta T_1^S = \Delta T_1^A$, $U_1^A \geq U_1^S$; $\alpha_2^S \geq \alpha_2^A$, $\Delta T_2^S \geq \Delta T_2^A$, $U_2^A = U_2^S = 0$

If $[(r\theta - c_h)/(r\theta - c_l)] < v \leq 1$, $\alpha_1^S = \alpha_1^A$, $\Delta T_1^S = \Delta T_1^A$, $U_1^A = U_1^S = 0$; $\alpha_2^S \geq \alpha_2^A$, $\Delta T_2^S \geq \Delta T_2^A$, $U_2^A = U_2^S = 0$

Proof: The results follow directly from Propositions 1–4.

Proposition 5 shows the difference between the optimal incentive contracts and profits under symmetric and asymmetric information

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cases. If v is small, the owner anticipates the contractor as a high cost type with high probability. Then, the fixed payment α_2^A is set comparatively high. To avoid the low-cost type contractor pretending to be a high-cost type and choose a high type contract, the owner has to improve the corresponding fixed payment α_1^A. High α_1^A can lead the low type contractor to choose a low-type incentive contract. On the other hand, as v is large, the owner knows that the contractor is less likely a high-cost type. Then, the remuneration α_2^A decreases. It implies the attraction of high type incentive contract reduces as well. Thus, α_1^A decreases correspondingly. If α_1^A reduces to α_1^S, the low-cost contractor loses the incentive to pretend to be a high-cost contractor. Obviously, by hiding or reporting false information, the party possessing more information can break the balance of the market and get extra revenue or other forms (e.g., in this article can be a longer project period). So, there should be some incentive (that can also be called informational rent) for the party with more information to report their information truthfully. Finally, we arrive at the fact that reducing their costs is an effective way for contractors to obtain additional profits.

Owner's Information Value

Coupling Propositions 2 and 4, we find that the owner can earn the entire profit under the symmetric information case as he is able to possess the entire contractor's profit. However, he is unable to achieve this in the presence of asymmetric cost-type information, and will surrender part of the profits to the contractor. Thus, the owner is willing to pay an informational rent to acquire information about the contractor's cost type. The maximum amount he is willing to pay is the information value of cost type, or the difference between his profit under symmetric cost type information and asymmetric cost type information. The expression for the value of the cost type information is given by

$$\mathrm{VOI} = \Pi^{\mathrm{S}} - \Pi^{\mathrm{A}} \tag{19}$$

where Π^{S} and Π^{A} are given in Propositions 2 and 4, respectively.

Proposition 6: The value of the contractor's cost type information is as follows:

(a) VOI =

$$\begin{cases} \frac{1}{r}\left((c_h - c_l v)\ln\left(\frac{1-v}{c_h - c_l v}\right) + (1-v)c_h\ln(c_h) + v(c_h - c_l)(1+\ln(r\theta))\right), & 0 \le v \le \frac{r\theta - c_h}{r\theta - c_l} \\ \frac{1}{r}\left((1-v)\left(\theta r - c_h \ln\left(\frac{r\theta}{c_h}\right) - c_h\right)\right), & \frac{r\theta - c_h}{r\theta - c_l} < v \le 1 \end{cases} \tag{20}$$

(b) VOI is continuous at $v = [(r\theta - c_h)/(r\theta - c_l)]$, and when $\theta \ge \max\{\theta_1, \theta_2\}$, $\mathrm{VOI} \ge 0$,

(c) VOI is concave in v, $\forall v \in [0,1]$

$$\theta_1 = \mathrm{e}^{\frac{(c_h v - c_l v)(\ln(r)+1) + (1-c_h v)\ln(c_h) - (c_h - c_l v)\ln(\frac{c_h - c_l v}{1-v})}{(c_l - c_h)v}}, \qquad \theta_2 = \frac{c_h}{r}$$

Proof:

(a) The VOI expression follows directly from Propositions 2 and 4 and Eq. (19).

(b) At boundary point $v = [(r\theta - c_h)/(r\theta - c_l)]$, we can prove that

$$\lim_{v \to \frac{r\theta - c_h}{r\theta - c_l}^+} \mathrm{VOI} = \lim_{v \to \frac{r\theta - c_h}{r\theta - c_l}^-} \mathrm{VOI} = \frac{(1-v)}{r}\left(r\theta - c_h \ln\left(\frac{r\theta}{c_h}\right) - c_h\right), \qquad \left.\frac{d\mathrm{VOI}}{dv}\right|_{v \to \frac{r\theta - c_h}{r\theta - c_l}^+} = \left.\frac{d\mathrm{VOI}}{dv}\right|_{v \to \frac{r\theta - c_h}{r\theta - c_l}^-} = \frac{c_h \ln(\frac{r\theta}{c_h}) - r\theta + c_h}{r}$$

When

$$0 \le v \le \frac{r\theta - c_h}{r\theta - c_l}, \qquad \frac{d\mathrm{VOI}}{d\theta} = \frac{v(c_h - c_l)}{r\theta} \ge 0$$

That is, VOI is increasing monotonically with θ. Let $\mathrm{VOI} = 0$, we have

$$\theta = \theta_1 = \mathrm{e}^{\frac{(c_h v - c_l v)(\ln(r)+1) + (1-c_h v)\ln(c_h) - (c_h - c_l v)\ln(\frac{c_h - c_l v}{1-v})}{(c_l - c_h)v}}$$

When $[(r\theta - c_h)/(r\theta - c_l)] < v \le 1$

$$\frac{d\mathrm{VOI}}{d\theta} = \frac{(1-v)(r\theta - c_h)}{r\theta} \ge 0$$

VOI is increasing monotonically with θ as well. Let $\mathrm{VOI} = 0$, we have $\theta = \theta_2 = (c_h/r)$.

(c) If $0 \le v \le [(r\theta - c_h)/(r\theta - c_l)]$

$$\frac{d\mathrm{VOI}}{dv} = \frac{1}{r(1-v)}\left((c_h - c_l)(1-v)\ln(\theta r) - c_l(1-v)\ln\left(\frac{1-v}{c_h - c_l v}\right) - (1-v)c_h\ln(c_h) - v(c_h - c_l)\right),$$

$$\frac{d\mathrm{VOI}^2}{d^2 v} = \frac{(c_l - c_h)^2}{(c_l v - c_h)r(1-v)^2} \le 0$$

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VOI is concave in v. When $[(r\theta - c_h)/(r\theta - c_l)] < v \le 1$, we already know from (b), if $\theta \ge \theta_2$

$$\mathrm{VOI} = \frac{1}{r}\left((1-v)\left(\theta r - c_h \ln\left(\frac{r\theta}{c_h}\right) - c_h\right)\right) \ge 0$$

And because $(1-v) \ge 0$,

$$\left(\theta r - c_h \ln\left(\frac{r\theta}{c_h}\right) - c_h\right) \ge 0,$$

$$\frac{d\mathrm{VOI}}{dv} = -\frac{\theta r - c_h \ln(\frac{r\theta}{c_h}) - c_h}{r} \le 0$$

VOI is increasing monotonically with v. Hence, $\forall v \in [0,1]$, VOI is concave in v.

Proposition 6 denotes that if $\theta \ge \max\{\theta_1, \theta_2\}$, which means the owner can benefit enough profit on unit utility from a shortened construction period, the value of information about the contractor's cost type is always positive for him. Also the property can be explained as the owner cannot get more benefit from contract design under asymmetric information, accounting for the informational rent the owner is willing to pay to get the real information.

What's more, VOI is concave in v. The intuition behind this finding is as follows. An extremely small or big v (i.e., $v = 0$ or $v = 1$) represents that a certain type of contractor accounts for more in the market, so the owner is more likely to meet that kind of contractor. But if v value is not an extreme number (i.e., $v = 0.5$), the owner has difficult in telling the cost type of the contractor, making the value of the information much more helpful. This conclusion verifies that the greater the risk faced by the owner, the higher the information value will be: when a certain type of contractor takes up a larger proportion in the market, the lower the probability that the owner will encounter another type. Therefore, the lower the "not corresponding" risk faced by the corresponding contract, the lower the value of the information of the contractor cost type to the owner. When the cost type information of the contractor is difficult to determine, the greater the risk of the contract not corresponding to the contractor type provided by the owner, the greater the loss it may cause, and correspondingly, the greater the value of the contractor information to the owner.

Numerical Analysis

In this section, we complement our analytical results for the comparative study with the numerical studies to investigate the impacts of parameter settings on the optimal incentive contract, the owner's expected profit, and the magnitude of the information value of the contractor's cost type.

The data comes from two related studies (Al-Kaisy and Nassar 2009; Hosseinian and Carmichael 2013). In Hosseinian and Carmichael's research, 60 practitioners were interviewed (2013). The practitioners were senior construction personnel familiar with contracts management, divided equally between contractors

Table 1. Optimal solutions of incentive contracts and profits

Optimization		Case S	Case A
α_1	$v \in \left[0, \frac{r\theta - c_h}{r\theta - c_l}\right]$	$\frac{(c_l - \beta)}{r}\ln\left(\frac{\theta r}{c_l}\right)$	$\frac{c_h - c_l}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l} + \frac{c_l - \beta}{r}\ln\frac{r\theta}{c_l}$
	$v \in \left(\frac{r\theta - c_h}{r\theta - c_l}, 1\right]$		$\frac{c_l - \beta}{r}\ln\frac{r\theta}{c_l}$
ΔT_1	$v \in \left[0, \frac{r\theta - c_h}{r\theta - c_l}\right]$	$\frac{1}{r}\ln\left(\frac{\theta r}{c_l}\right)$	$\frac{1}{r}\ln\left(\frac{\theta r}{c_l}\right)$
	$v \in \left(\frac{r\theta - c_h}{r\theta - c_l}, 1\right]$		$\frac{1}{r}\ln\left(\frac{\theta r}{c_l}\right)$
α_2	$v \in \left[0, \frac{r\theta - c_h}{r\theta - c_l}\right]$	$\frac{(c_h - \beta)}{r}\ln\left(\frac{\theta r}{c_h}\right)$	$\frac{c_h - \beta}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l}$
	$v \in \left(\frac{r\theta - c_h}{r\theta - c_l}, 1\right]$		0
ΔT_2	$v \in \left[0, \frac{r\theta - c_h}{r\theta - c_l}\right]$	$\frac{1}{r}\ln\left(\frac{\theta r}{c_h}\right)$	$\frac{1}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l}$
	$v \in \left(\frac{r\theta - c_h}{r\theta - c_l}, 1\right]$		0
U_1	$v \in \left[0, \frac{r\theta - c_h}{r\theta - c_l}\right]$	0	$\frac{c_h - c_l}{r}\ln\frac{r\theta(1-v)}{c_h - c_l v}$
	$\in \left(\frac{r\theta - c_h}{r\theta - c_l}, 1\right]$	0	0
U_2		0	0
Π	$v \in \left[0, \frac{r\theta - c_h}{r\theta - c_l}\right]$	$G + \theta - \frac{c_l v + (1-v)c_h}{r}(1 + \ln\theta r)$	$G + \theta - \frac{c_h}{r} - \frac{vc_l}{r}\ln\frac{r\theta}{c_l} - \frac{c_h - vc_l}{r}\ln\frac{r\theta(1-v)}{c_h - vc_l}$
	$v \in \left(\frac{r\theta - c_h}{r\theta - c_l}, 1\right]$	$+\frac{1}{r}(c_l v \ln c_l + (1-v)c_h \ln c_h)$	$G + v\left(\theta - \frac{c_l}{r} - \frac{c_l}{r}\ln\frac{r\theta}{c_l}\right)$

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Table 2. Owners' experience (years) in the construction industry

Experience (years)	Owner (%)
<5	0
5–10	10
11–15	27
16–20	13
21–25	17
26–30	17
31–35	10
>35	7

Table 3. Owner involvement in projects

Number of projects	Owner
<5	10
5–15	10
16–25	13
26–35	20
36–45	23
46–55	20
>55	3

Table 4. Owners' levels of risk aversion

Owner's corresponding number	1–2	3–5	6–13	14–18	19–20	21–26	27	28	29–30
Level of risk aversion (r)	0.33	0.4	0.5	0.67	0.8	1	1.25	1.43	2

Note: we derive the mean of r from this table as our default value.

and owners. The owner organizations were generally government departments. Seventeen percent of them had more than 31 years of experience in the construction industry, 34% of them had experience between 21 and 30 years, and 40% of them between 11 and 20 years, as shown in Table 2. Sixty-six percent of them were engaged in more than 26 projects, as shown in Table 3. The results of their study show that the average risk aversion level of the 30 interviewers is 1.175, and we use this value as our default r value. The specific levels of risk aversion are shown in Table 4.

Al-Kaisy and Nassar (2009) employed a hypothetical example of a highway maintenance project. This case has a great fit with our model. A highway agency is contemplating the use of nighttime construction in a project that would require the closure of the rightmost lane of a three-lane directional freeway mainline. The length of closure is 3.218 km and the expected duration of work is five days. They attempted to compare the daytime construction efficiency with nighttime construction efficiency, while the construction cost of these two types can also be viewed as two cost type contractors' real construction cost in our study (supposing different working time results in different cost). Average traffic volumes on weekdays as observed recently at the construction site are collected, thus we can get an estimate of users' delay costs during the project. Using historical data from similar projects, the estimated construction cost for this project is $586,000 using daytime work shift with an estimated increase in construction cost of 15.8% ($678,588) for nighttime work shift. These data are summarized in Table 5. We break down the total cost to every hour and view 10% of the users' delay cost (which can be viewed as social cost and if it is saved, a proportion of such cost can serve as a bonus for the contractors.) under daytime shift as the bonus for the contractor. Then we can derive our default value for later analysis as shown in Table 6.

Table 5. Parameter values used for numerical studies

Number of projects	Daytime shift	Nighttime shift
Users' delay cost	$2,089,033	$186,396
Construction cost	$586,000	$678,588
Working time	10 h × 5 days	9 h × 5 days

Table 6. Parameter values used for numerical studies

Parameter	G	c_l	c_h	θ	β	r	v
Value	1,000	11,720	15,080	20,000	4,178	1.175	0.5

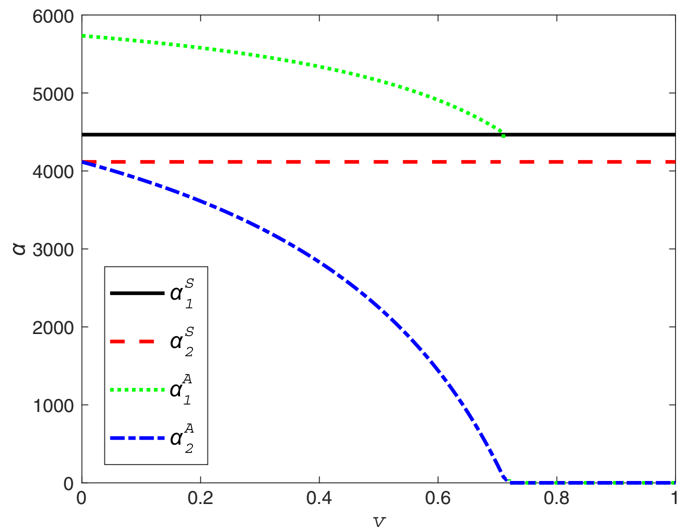

Fig. 3. Impact of v on α.

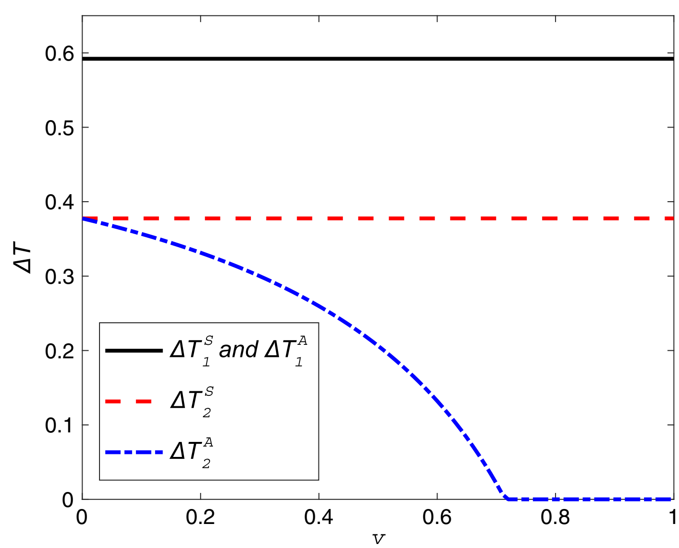

Fig. 4. Impact of v on ΔT.

First, we analyze the effect of the ratio of the lower cost v contract in the market, as summarized in Figs. 3–6. In Figs. 3 and 4, in the case of symmetric information, v has no influence on the optimal contract. In the asymmetric information case, α_1^A, α_2^A, ΔT_2^A decrease as v increases, and the requirement of ΔT for the lower

J. Constr. Eng. Manage., 2020, 146(6): 04020054

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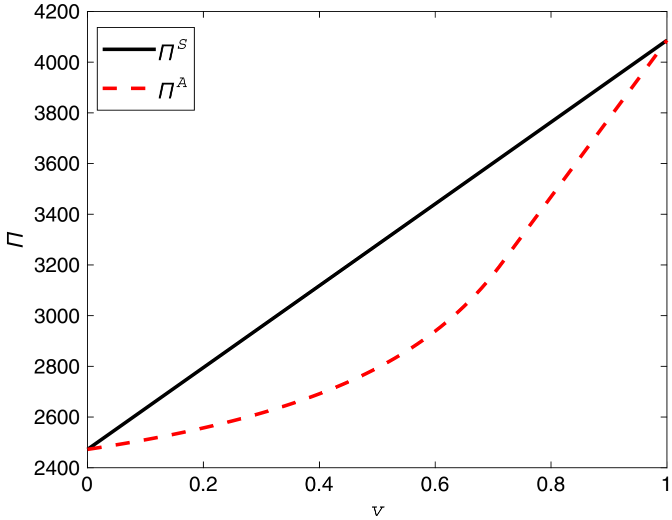

Fig. 5. Impact of v on Π.

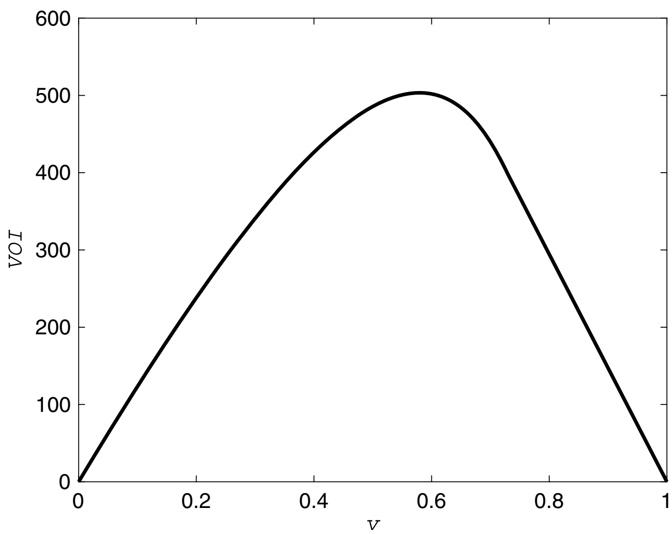

Fig. 6. Impact of v on VOI.

cost contractor is consistent with that in symmetric information case, which has been proved in Proposition 5. Under information asymmetry, α is decreasing in v, that is when the lower cost contractor is relatively high in the market share, the fixed payment for the contractor will be low. It is intuitive that the more likely it is that the owner will face a lower cost contractor, the less fixed payment he is willing to pay.

In Fig. 5, we consider the impact of v on the owner's expected income. As shown in Fig. 5, the owner's expected profits in both information structures are increasing in v. This is an expected result because lower construction cost is beneficial and can results in more earnings for the owner.

Combining Figs. 5 and 6, we find that, the owner's income under the condition of asymmetric information is always less than that under the condition of symmetric information. The owner wants to know the exact cost type of the contractor, so he is willing to pay a certain amount of information rent. The maximum value the owner is willing to pay is VOI. Further, Fig. 6 illustrates that although VOI is piecewise function for $\forall v \in [0,1]$, it is concave in v in general, corresponding to Proposition 6. When v deviates from

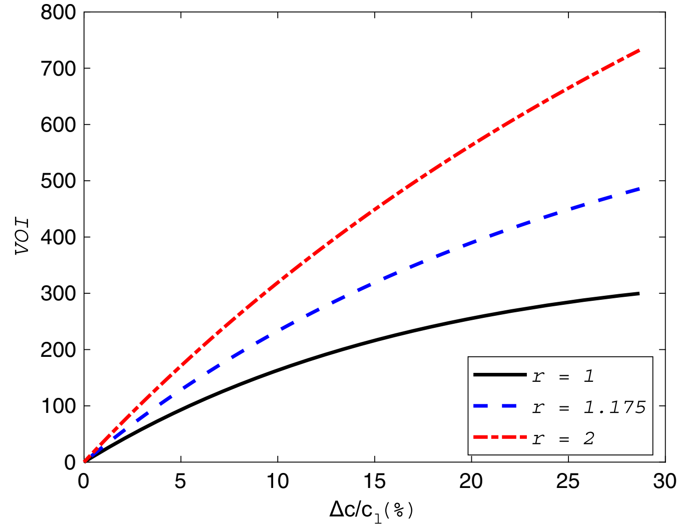

Fig. 7. Impact of cost gap on VOI.

the extreme value 0 or 1, the owner is more difficult to determine the risk type of the contractor, hence the greater the risk it faces, resulting in higher information value.

Finally, in Fig. 7, we observe that when the lower cost type contractors are not enough in the market $\{0 \leq v \leq [(r\theta - c_h)/(r\theta - c_l)]\}$, as the value of the cost c_l moves toward the higher cost c_h, that as the difference between the two kinds of cost decreases, the value of the cost type information decreases. This is expected. The decreases in the difference between the costs imply that the owner faces decreasing potential loss in the contract design. Therefore, the less information rent the owner is willing to pay the contractor. And the higher r value, which means the higher risk aversion the level of the owner the higher the information value as well.

Conclusion and Future Research

In this paper, we consider a contract design problem of the owner when he has asymmetric cost information of the contractor. In particular, a risk-averse owner with exponential utility function provides a contract to a risk-neutral contractor whose extra construction overtime cost is unknown to the owner. The owner designs a deadline-based incentive contract menu to encourage the contractor to reveal his private information actively and shorten the construction period. It is difficult to directly observe or trust the cost information from the contractor because the contractor has the incentive to report a high overtime cost. Thus, we use a principle-agent model to model the interaction between the owner and the contractor who has hidden cost information. We obtain the explicit form of the optimal incentive contract. We show that the owner's profit under symmetric information is always higher than that under asymmetric information because the owner should commit information rent to the contractor.

Moreover, we find that: (1) for low-cost contractors, the project duration will not change with the cases of symmetric information and asymmetry. However, in the case of symmetric information, the contractor can get extra rewards as the owner will pay more for the information rent. (2) For a high-cost contractor, they cannot get extra profit no matter what the situation is, even though they are allowed to complete the project later under asymmetric information setting. (3) Besides, for the owner, the value of information is positively related to the level of risk aversion. Also, the value of information is concave and unimodal in the probability of the cost type. If the owner is not sure about the cost type, i.e., the probabilities of high-cost type and low-cost type are half and half, the value of information reaches maximum. In other words, the owner has to pay more if the uncertainty of the contractor type is higher.

In summary, the contributions of this paper are as follows:

- It enriches the literature of construction project management by studying the incentive contract design problem between a risk-averse owner and a risk-neutral contractor who holds more cost information than the owner.
- Under an asymmetric information setting, we prove the owner has to pay more fixed payment as information rent to let a low-cost contractor choose the appropriate contract truthfully. Meanwhile, the high-cost contractor receives less payment and completes later under asymmetric information setting.
- We use real data to show the value of information is concave and unimodal in terms of the uncertainty of cost information and increases in the level of risk aversion and the cost gap of the two types of contractors.
- Finally, several future research directions deserve attention: (1) in this paper, we only consider one owner and one contractor. However, in reality, there are more complicated situations when one owner contracts with multiple contractors. Or, the contractor has parallel and serial tasks. The tasks are correlated with each other. On the one hand, the owner has to design more complicated contract menus with more complex payment plans to inspire the contractor. On the other hand, the competition between the contractors who have the private information may change their strategies. (2) In practice, the cost of contractor is not a certain constant during the whole project duration, which may be influenced by many other factors, including the change of environment, construction seasons, which could extend our static model to a dynamic environment. Furthermore, the tight requirement for the construction period, the higher the cost the contractor may have to pay. In other words, the cost is a nonlinear increasing function of overtime. (3) Finally, in project management, the owner may encounter the scenario where asymmetric information between the owner and the contractor exists along two or more dimensions: the contractor's cost, constructability, time sensitivity, et cetera. Since the type of contractor is multidimensional in practice, solving this problem will be challenging.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Acknowledgments

We would like to thank the editor and the anonymous referees for their helpful comments. This research was supported in part by the National Natural Science Foundation of China (NSFC) under Grant Nos. as 71871166 and 71831007.

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