On Optimal Risk and Benefit Sharing in Engineering Projects

Thesis submitted in accordance with the requirements of
the University of Liverpool for the degree of Doctor in Philosophy
by

Oscar Nieto-Cerezo

September 2016

Abstract

This thesis applies agency theory to design risk regulatory policies in the implementation of sustainable sea defences. The aim is to investigate methods to reduce the probability of an accident inflicted on the society by resolving a downstream and an upstream moral hazard problem existing in engineering problems with an emphasis on the construction of sustainable sea defences.

The risk regulation aims at reducing the probability of damage cost associated with flooding by enhancing an operator's safety operational procedures. It is defined by three policies; a safety design, a transfer payment, and a fine. In the downstream moral hazard between an operator and a regulator, a risk neutral operator under full liability will implement a sea defence which is optimal from the regulator's point of view when a fine is set equal to damage cost without a cost for the regulator.

However, if the operator has limited assets to cover the damage cost, a cap on the operator's fine is placed to take into account that an operator may default if damage costs are too high. Limiting the responsibility of the operator in case of an accident decreases the strength of the incentive mechanism leading to the implementation of a sea defence below the socially optimum. This second best height of the sea defence involves an informational cost to the society in the form of a liability rent to guarantee the participation of the operator in the engineering project. The more we make the operator liable for the damage cost, the higher the liability rent. The society faces a trade off between liability rent and residual risk. The higher the residual risk, the lower the liability rent.

Unlike the limited liability case, an operator with averse attitude to uncertain payoffs will implement a sea defence higher than a risk neutral operator in order to reduce the weight on the upper extreme values of the tail of the fine. This is because the marginal fine decreases under risk aversion. Similarly to the limited liability case, the implementation of a second best height of the sea defence is not free for the society. The society will have to compensate the operator for participating in the project in the presence of uncertain payoffs. This compensation takes the form of a risk premium and is subject to the risk coefficient and the variance of the damage cost distribution.

Due to the lack of regulatory quality and independence, a pro-industry regulator and a government may have conflicting interest about the fine cap to impose to the

operator. While the regulator prefers a higher fine cap to induce a higher liability rent, the government seeks to impose a lower fine cap. The government faces a trade off problem between how much discretion should be given up and how much expert information should be used from the regulator. In the case when the government observes that any of the fine cap choices available to the regulator is higher than its ex-ante choice of the fine cap, no discretion will be granted because the cost to the society outweighs the benefits of using the regulator's expertise. Nevertheless, when the government observes that some of the fine cap choices available to the regulator are lower than its ex-ante choice of the fine cap some level of discretion can be granted. The limit on the fine caps that the regulator can announce is determined by how much the regulator is biased towards the interests of the nuclear industry. When the regulator's range of fine caps is optimally restricted, the objectives of the regulator and the operator will be aligned by encouraging the regulator to choose a fine cap that will not exceed the optimal fine cap of the government.

Contents

List of Figures

Nomenclature

Parameter	Description	Page
k	Safety design parameter.	10
$\tilde{h}$	Tsunami run up random variable	10
a	Height of the sea defence	10
b	Cost parameter	10
I	Labour income	10
T	Transfer payment	10
$\tilde{F}(a)$	Fine	10
$\tilde{D}(a)$	Damage cost	10
$\tilde{P_O}$	Operator's payoff	11
$\varphi(k)$	Cost function	11
$\tilde{P_S}$	Society's payoff	12
S	Project revenue	12
$\tilde{P_R}$	Regulator's payoff	12
α_R	Regulator's weight parameter on operator's payoff	12
$\tilde{P_G}$	Government's payoff	12
α_G	Government's weight parameter on operator's payoff	12
$\bar{k}$	Upper bound of the safety design parameter interval	13
H	CDF of the damage cost	16

Parameter	Description	Page
$\hat{b}$	Cost parameter announced by the regulator	18
δ_f	Fine parameter	18
c	Marginal cost	18
b^*	Upper bound of the cost parameter interval	18
b_*	Lower bound of the cost parameter interval	18
c	Marginal cost	18
$\pi(b)$	PDF of the cost parameter	19
a^*	Operator's optimal sea defence under risk neutrality	21
k^*	Operator's optimal safety design parameter under risk neutrality	21
T^*	Optimal transfer payment under risk neutrality	21
δ_f^*	Optimal fine parameter under risk neutrality	21
a^{**}	Regulator's optimal sea defence under risk neutrality	22
k^{**}	Regulator's optimal safety design parameter under risk neutrality	22
$\bar{F}$	Fine cap	29
$\bar{D}$	Converted fine cap	29
a_{ll}^*	Operator's optimal sea defence under limited liability	30
k_{ll}^*	Operator's optimal safety design parameter under limited liability	30
$\mathcal{R}(\bar{D})$	Liability rent	30
a_{ll}^{**}	Regulator's optimal sea defence under limited liability	31
k_{ll}^{**}	Regulator's optimal safety design parameter under limited liability	31

Parameter	Description	Page
$\bar{D}^{**}$	Optimal fine cap under limited liability	31
T^*_{ll}	Optimal transfer payment under limited liability	31
$\tilde{W}_O$	Wealth position of the operator	35
A_O	Assets of the operator before entering the project	35
β	Risk averse coefficient	35
CE	Certainty equivalent	35
$\rho(\tilde{W}_O)$	Risk premium	37
a^*_{ra}	Operator's optimal sea defence under risk aversion	38
k^*_{ra}	Operator's optimal safety design parameter under risk aversion	38
a^{**}_{ra}	Regulator's optimal sea defence under risk aversion	39
k^{**}_{ra}	Regulator's optimal safety design parameter under risk aversion	39
T^*_{ra}	Optimal transfer payment under risk aversion	39
$\bar{D}^*_{rig}$	Optimal fine cap under a rigid rule	46
a^*_{rig}	Operator's optimal sea defence under a rigid rule	46
k^*_{rig}	Operator's optimal safety design parameter under a rigid rule	46
T^*_{rig}	Optimal transfer payment under a rigid rule	46
$\bar{D}^*_{reg}$	Regulator's optimal fine cap under limited discretion	50
b^{**}	Optimal fine cap under a rigid rule	53
$\bar{D}^*_{gov}$	Government's optimal fine cap under limited discretion	53

Acknowledgement

First and foremost I want to thank my supervisor Professor Jan Wenzelburger. It has been an honor to be one of his Ph.D. students. He has taught me how mathematics and economics are done. I appreciate all his contributions of time and ideas to make my Ph.D. experience productive and stimulating. The joy and enthusiasm he has for his research was contagious and motivational for me, even during tough times in the Ph.D. pursuit. I am also thankful to his family for accommodating me during my visits to Germany.

I would also like to pay special thanks and appreciation to Dr. Edoardo Patelli for his vital support and assistance. His encouragement made it possible to achieve the goal.

I am especially grateful to Professor Michael Beer whose leadership and positive attitude helped me at every point during my research to accomplish this thesis.

My sincere thanks also goes to Dr. James Cooper for his advice and guidance.

The members of the Institute of Risk and Uncertainty have contributed immensely to my personal and professional time at The University of Liverpool. The group has been a source of friendships as well as good advice and collaboration.

I would also like to acknowledge the macroeconomics department research team from Kaiserslautern University, I very much appreciate their enthusiasm, help, kindness, and efforts to create a stimulating research environment and make me feel comfortable in Germany: Conrad, Gevorg, Helenna, Rebecca and Theresia.

My Mom and Dad, family members and friends, without whom I am nothing; they support me morally and emotionally.

Chapter 1

Introduction

The implementation of complex engineering projects such as the construction of sustainable sea defences creates a large number of interrelated risks affecting everything from technical feasibility to cost. The complexity of these projects requires a multidisciplinary approach to secure a robust balance among all parties in view of sharing risk and benefits.

Benefits and risks associated with large energy projects have to be considered from an economic, an environmental, an engineering and a societal point of view. A typical large civil engineering project requires the engagement of a large number of stakeholders such as developers, designers, builders, suppliers, regulators, and government administrative departments. The four main stakeholders in energy projects of most democracies are the parliament or the congress or the legislature, the society, a regulatory authority, and an operator.

The role of the parliament is to approve the bill introduced by the government before it becomes an Act of Parliament. The government will be responsible for contracting the industry to implement the project. Regulatory authorities including advisory bodies are commissioned by the government to conduct supervision and management of the project.

As a result of contractual relationships among the government, the regulatory authority and the industry, asymmetric information problems arise. The nature of this informational asymmetry can be thought as the industry's ability, quality, technology, equipment, management and services at the bidding stage and as the quality of the personnel, the quality of the materials, the construction methods and their technology at the performance stage. The regulatory authority cannot observe with certainty whether the contract has been strictly followed or the industry has shirked from the binding agreement.

An example of this information failure is the Fukushima Daiichi nuclear power plant accident. On March 2011, the Tohoko-oki earthquake with a magnitude 9.0 shook north-eastern Japan, unleashing a savage tsunami [38]. The 15-meter tsunami

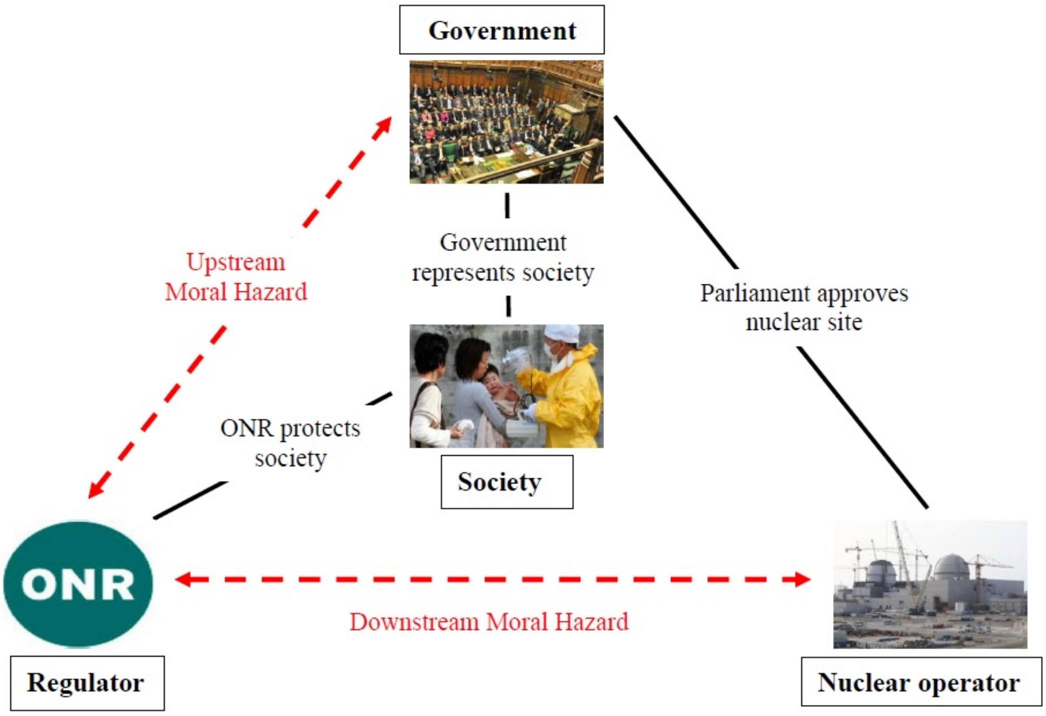

Figure 1.1: Information diagram.

hit the Fukushima Daiichi nuclear power plant disabling the power supply and heat sinks, thereby triggering a nuclear accident [39].

The findings of the reports carried out by The Japanese Nuclear Accident Investigation Commission, The Carnegie Endowment for International Peace, The European Nuclear Safety Regulators Group (ENSREG), the International Atomic Energy Agency (IAEA) and The United States Nuclear Regulatory Commission concur that the implementation of optimal safety design parameters, plant elevation, seawall elevation and location and status of a back-up generator, could have mitigated or prevented the catastrophic consequences of the tsunami [1, 19, 36, 37].

TEPCO, for example, had insisted that Fukushima Daiichi's 5.7m seawall was high enough to withstand a tsunami generated by a large quake in the area, despite a warning in 2008 by its own engineers that much bigger waves were possible. TEPCO's officials in charge of disaster planning chose to ignore the best practices promulgated by the International Atomic Energy Association and the Japan Society of Civil Engineering by dismissing such evidence pertaining to the implementation of safety design parameters below the optimum. Furthermore, some irregularities in the risk assessment methodology were flagged in several official Fukushima accident reports, pointing out that these models omitted variables of paramount importance such as the hydrodynamic forces of a tsunami and the effects of debris and sediment in the height of the tsunami run up [1].

In addition to the presence of information asymmetry between the stakeholders, there are upper bounds on damage costs that operators can cover for harm inflicted on third parties or on the environment. Economics refers to this as limited liability. Limited liability enables operator's shirk costs of an accident beyond the value of its net assets; this implies that beyond that point society will be responsible for any excess damage cost.

TEPCO's limited liability and the lack of incentives to address residual risk such as that of low probability tsunamis led TEPCO to ignore its safety responsibilities.

In the presence of limited liability and the existence of asymmetric information, operators face wrong incentives when making decisions on safety imposing a risk of catastrophic damages on the society which does not earn a contractual return for bearing that risk.

Moreover, the existence of conflicting objectives between the regulator and the parliament deriving from regulator's lack of independence and regulator's privileged information with respect to some parameters affecting the damage cost triggers an upstream moral hazard problem. This upstream moral hazard deters the regulator from asserting its authority to make rules, properly reviewing simulations conducted by the operator and fostering the development of appropriate computer modelling tools.

The Japanese regulator's interest in relaxing international safety regulations on the operator may be due to the lack of independence of the Japanese Nuclear and Industry Safety Agency (NISA) from the ministry of Economy, Trade and Industry's Agency for Natural Resources and Economy, the government body responsible for promoting nuclear power. Indeed, the regulator's independence can be compromised by three threats. Firstly, there is a risk that the regulated parties may try to capture the regulators, e.g.; by bribing them or by promising them well-paid jobs in the future, in order to influence their decisions [28, 33, 34]. Secondly, there is a risk that the industry uses asymmetric information and misinformation to manipulate the regulator [29].

Finally, there is a risk that the regulator's independence is compromised by the regulator's private interest in the sector, directly or indirectly, e.g., when the regulator holds stocks in a unit trust investing in the regulated industry [20].

Moreover, in some countries energy regulators may be pro-industry bias due too the close relationships with politicians. Those politicians in turn, tends to promote the interest of regulated energy operators [33, 34].

Thus, a critical issue is how, if at all, the regulator can best induce the regulated operator to employ its privileged information to further the broad interests of society, rather than to pursue its own interests and how the government can do the same with the regulator.

This thesis proposes a game-theoretic approach in the principal and agent framework to introduce incentive regulatory policies written as contracts that compensate the operator based on the quality of the performance in the construction of a sea defence to protect energy critical infrastructure. The thesis borrows, and builds on from Hiriart and Martimort (2012). They were the first to present the delegation problem to design risk regulatory policies. They also characterize the optimal interval delegation sets following Holmstrom's pioneering work. Holmstrom states that an optimal delegation set is determined by how much the agent's payoff function diverges from principal's payoff function. This is where the ally principle holds: The more aligned are the payoff functions, the more authority is granted to the regulator [12]. Unlike Hiriart and Martimort's model where the equilibrium is analysed from a single point in time, the model presented in this thesis is intertemporal. The impacts of the operator's decisions are assessed over lengthy periods of time.

This thesis is divided into 6 chapters: Chapter 3 introduces the elements of the economic model. Chapter 4 explores the optimal regulatory policies under full, limited liability, and risk aversion. Chapter 5 characterizes the set of transfers available to the regulator to impose risk regulatory policies on the operator. And finally, chapter 6 draws some conclusions from the previous chapters.

Chapter 2

Review of related literature

Traditional methods of regulation such as Ramsey-Boiteux pricing, marginal cost pricing, non-linear pricing, and the cost service regulation neglect the role of asymmetric information and incentive problems with regards to the technology, costs and consumer demand attributes facing the firms they regulate [8, 6, 7]. However, fully informed regulators is not a very realistic assumption. The regulated firm may find more profitable to exert too little safety effort to control the cost of running a power plant, increasing the potential realization of damage cost in case of an accident [26]. This is due to the fact that regulated firms have incentives to exploit their information advantage to extract profits by avoiding the cost of certain measures that may be vital to prevent harm to the society [28]. Incentive regulation has replaced rate of return regulation as the norm in many industries [32]. Incentive regulation can be defined as the implementation of rules that encourage a regulator firm to achieve desired goals by granting some, but not complete, discretion to the firm. The regulated firm is granted some discretion under incentive regulation. This feature of incentive regulation distinguishes it from command and control regulation, the regulator would specify the exact changes in operating procedures that the firm must undertake in an attempt to reduce the operating costs [32]. Furthermore, the regulator imposes checks and limits on relevant activities and/or outcome under incentive regulation. There are two reasons why the regulated firm is granted some, but not complete, discretion under incentive regulation. First, the firm has better information than the regulator about key aspects of the regulated industry. These aspects can include the firm's actions, its production technology (or cost structure), and customer preferences. Second, the firm's goals differ from those of consumers or society at large [20, 21, 22].

The development of contract theory, and information economics has provided the tools with which to address informational constraints problems in theoretical models of regulation. The main advantage of using game theory and principal-agent models in regulatory economics is that a strategic situation can be described as an optimal contract by choosing an appropriate model which delivers the desirable outcome [28, 24, 25]. Principal and agent relationship typically involve three types of partially conflicting objectives: risk must be distributed, appropriate effort levels must be induced (moral hazard), and truthful information must be elicited (adverse selection). For example, the moral hazard literature has focused on the trade off between incentives for effort and risk sharing. One of the main results shows that agents must bear more risk than in the first best, to induce reasonable effort level subject to the risk attitude of the agent.On the other hand, the adverse selection literature has studied how a principal should structure his offer of contracts to a privately informed agent, to optimize his own objective under the interim participation constraint of the agent. An informational rent must be given up by the principal to all types except the less efficient ones [24, 25, 28]. Laffont and Rochet explores a situation with both adverse selection and moral hazard for a risk averse agent, in which the contract is offered and signed before the agent knows his type. Since the principal is risk neutral and the agent risk averse, the optimal contract will involve some insurance-incentive trade off.

In most of the literature, the goal of the regulator is to maximize the social welfare function by restricting the rents transferred from the society to the operator subject to the participation constraint [21]. The regulator's objective function is modelled as the weighted sum of the society's and operator's objective function. The regulator places more weight on the society's surplus than on the rents earned by the operator [3]. This can be interpreted as the higher the rent left to the operator, the lower the regulator's payoff because the increase in the transfer payment. Furthermore, the cost of raising funds from taxpayers is captured by introducing the parameter $\Lambda = 0$ [3]. In this formulation, taxpayers welfare is presumed to decline by $1 + \Lambda$ euros for each euro of tax revenue the government collects. The parameter Λ, often called the social cost of public funds, is strictly positive when taxes distort productive activity (reducing effort or inducing wasteful effort to avoid taxes, for example), and thereby create deadweight losses. The parameter Λ is viewed as exogenous in the regulated industry [3]. The literature generally adopts one of two approaches. The first approach introduced by Baron and Myerson (1982), assumes that the regulator strictly prefers society surplus to operator's rent by setting $\alpha < 1$ and that there is no any social cost of public funds by setting $\Lambda = 0$ [5]. The second approach, which follows Laffont and Tirole (1986), assumes that the regulator equally prefers the society surplus and the operator's rent by setting $\alpha = 1$ and strictly positive social cost of public funds $\Lambda > 0$ [26]. The central difference between the two basic approaches concerns the transfer payments that are optimal when the regulator and the operator are both perfectly informed about the sea defence implemented and the potential damage cost is case of accident [3].

Thus, bearing in mind the existence of uncertainty as a result of information asymmetry, the social welfare maximizing regulator will seek a regulatory mechanism that takes both the social costs of adverse selection and moral hazard into account, subject to the firm participation or budget balance constraint that it faces, balancing the costs associated with adverse selection and the costs associated with moral hazard [22].

We are concerned with the body of the literature focused on adverse selection and moral hazard motivated by the assumption that regulators can observe the realization of damage cost ex post and has also knowledge about the probability distribution of the damage cost ex ante. In addition, the effort exerted by the firm determines the potential damage cost but it is not observable by the regulator [26].

Although, most of the incentive regulation literature is static. Some researches have considered the issues associated with the dynamic interactions between the regulator and the regulated firm. As the relation prolongates over time, the regulator has more capacity to reduce its informational disadvantage. The observable realization of damage cost in the first period enables the regulator to gain more information on the effort implemented. This information update can be utilized to renegotiate the terms of the contract ex-post [4, 27].

Another extension of the canonical agency model is the introduction of higher dimensions. In that context, the regulator explores the incentive regulatory mechanism when a firm is expected to distribute her effort over different tasks. Increasing the incentive for one task could cause a contractor to devote too much time to that task neglecting the others [17].

Another strand of the literature relevant to the model in this thesis is that related to environments where limitations are imposed on the maximum fine that can be imposed to risk neutral firm with the main purpose of protecting firms from going bankrupt in case of an accident. Several author examines how liability constraint determines the rent left to the firm under moral hazard [31, 18, 15, 14].

A critical issue is how the parliament can make the most of regulator's expert information by granting some authority without compromising the interest of the society.

There are two major strands of delegation models in the framework of game theory; the delegation of authority game and the signalling game[13].

In this thesis we consider the first class of models. The parliament considers the delegation of authority for implementing regulatory policies to a regulatory body in order to take advantage of her knowledge and expertise. If the regulator is granted authority, then he can use his knowledge to gather information about the parameters of the damage cost function before he chooses the safety design parameter based on the potential damage cost. On the contrary, if delegation is not granted, the parliament must decide the acceptable level of residual risk in the face of uncertainty of the damage cost function parameters[16].

When the parliament enables the regulator to make a choice within a set of damage cost, the optimal delegation sets takes the form of a single interval if the regulator's payoff is similar to the parliament's payoff [2].

Chapter 3

The economic model

We consider the relationship between the parliament, a regulatory agency, and an operator in the implementation of sustainable sea defences to protect society from flooding associated with natural hazards.

This economic model has six main features.

1. An operator maintains a contract with the government that covers those disasters caused by events like earthquakes and tsunamis [30]. This contract takes into account that an operator has not sufficient solvency to fully compensate society for the damage cost in case of flooding of energy critical infrastructure.

2. The regulator cannot perfectly evaluate the effectiveness of the safety parameters chosen by the operator, because there is a positive cost of monitoring operator's parameters [10]. The survival of a sea defence due to an earthquake depends on how the ground moves. That movement depends on the earthquake's magnitude, the direction, the depth, the quality of local soil. The structural damage depends on the peak ground acceleration, the duration of any acceleration and the frequency of the shock waves. These factors determine the engineering safety design parameters to be implemented by the operator. The safety design parameters include the materials in the composition of cement, the thickness of the seawall, etc.

3. The combination of limited liability and asymmetric information results in regulatory failure. This regulatory failure is of the form of a downstream moral hazard where the operator may act in her own benefit to the detriment of the society.

4. The regulator is dominated by the energy industry implementing policies that are pro-operator.

5. The regulator possesses valuable information about the parameters determining the damage cost in case of flooding.

6. The government cannot evaluate whether the policies implemented are the most appropriate in light of the information possessed by the regulator. This triggers an upstream moral hazard between a regulator and the parliament.

The aim of this economic model is to design an incentive contract to reduce the vulnerability of a critical infrastructure facility. The economic model can be summarized by three variables:

1. the sea defence implemented by the operator denoted by a which is determined by the safety design parameter k,

2. a natural hazard $\tilde{h}$ which is modelled as a random variable, and

3. the outcome of the implementation of a sea defence is the probability of a damage cost as a result of a flooding and is denoted by $\tilde{D}$.

Throughout the model it is assumed that the function to reduce the vulnerability of a critical infrastructure facility is $\tilde{D} = b(\tilde{h} - a)$ where b is the cost parameter.

3.1 Principal and agent theory

The agency relationship is defined as one in which one or more persons named the principal delegate some decision making authority to the agent to carry out some economic activities or services on their behalf. The terms of the relationship between the government, a regulator, and an operator are determined by a contract given assumptions about people, organizations, information [11]. The principles of agency theory are presented in Table 3.1.

The cornerstone of agency theory is the presence of asymmetric information which is the source of uncertainty in the outcome of the model. Because the unit of analysis is the contract governing the relationship between the regulator and the operator, the focus of this thesis is on determining the most efficient form of contract.

3.1.1 Contracts

The contract can be thought of as a labour income and is of the linear form $I = T - \tilde{F}(a)$ where T is a fixed payment transfer payment and $\tilde{F}(a)$ is a fine which is proportional to the damage cost $\tilde{D}(a)$. The fine increases with the damage cost which in turn, decreases with the safety design parameter.

Linear contracts are simple to analyze, are observed in some real-world settings, and have the appealing property of creating uniform incentives.

The economic variables of the contract considered in this model are the potential damage cost $\tilde{D}$ inflicted on the society, the payment transfer of the operator T granted by society and the fine charged to the operator in case of an accident $\tilde{F}$.

Table 3.1: Overview of the components of the Agency theory.

Components of Agency Theory	Description
Key idea	Principal-agent relationships should reflect efficient organization of information and risk-bearing costs
Unit of analysis	Contract between principal and agent
Human self-interest assumptions	Self-interest, bounded rationality and risk aversion
Organizational assumptions	Partial goal conflict among participants, efficiency as the effectiveness criterion and information asymmetry between principal and agent
Information assumption	Information as a purchasable commodity
Contracting problems	Contracting Agency (moral hazard and adverse selection), risk sharing and limited liability
Problem domain	Relationships in which the principal and agent have partly differing goals and risk preferences

Let be $\mathcal{A}$ the set of feasible allocations. Formally, we have

$$\mathcal{A} = (\tilde{D}, T, \tilde{F}) : D \in \mathbb{R}_+, T \in \mathbb{R}_+, F \in \mathbb{R}_+. \tag{3.1}$$

These variables are both observable and verifiable by the regulatory agency and society. They can thus be included in a contract which can be enforced with appropriate penalties if the operator deviates from the requested sea defence.

3.1.2 Objective functions

Given a contract, the government, the regulator, an operator, and the society can evaluate which damage cost outcome inflicted by the operator's implemented sea defence is preferable in light with the payoff yielded as a result. In this model, the payoff of the government, the regulator, an operator, and the society is determined by the following payoff functions.

The operator's payoff function is

$$\tilde{P_O} = T - \varphi(k) - \tilde{F}. \tag{3.2}$$

This payoff is a function of the safety design parameter k, a transfer payment T, and a fine $\tilde{F}$. The operator's cost of implementing k is determined by the cost function

$\varphi(k)$. We assume that the cost function $\varphi(k)$ is strictly increasing in k, $\varphi' > 0$, and convex $\varphi'' \geq 0$.

The society's pay-off function is

$$\tilde{P_S} = S - T - \tilde{D} + \tilde{F}. \tag{3.3}$$

This payoff is a function of the revenue S, the transfer payment T, the damage cost $\tilde{D}$, and the fine $\tilde{F}$. The society receives a revenue S from the operator's implemented sea defence and the society pays a transfer payment T to the operator in exchange for his protective measures.

The regulatory agency wants to enhance the social welfare by maximizing the weighted sum of the society's payoff and the operator's payoff, where the weight parameter $0 \leq \alpha_R \leq 1$ is the value the regulator assigns to the operator's payoff in relation to the payoff of the society.

The regulator's payoff function is then the weighted sum $\tilde{P_R} = \tilde{P_S} + \alpha_R \tilde{P_O}$ and is conveniently rewritten as

$$\tilde{P_R} = S - \varphi(k) - \tilde{D} - (1 - \alpha_R)\tilde{P_O}. \tag{3.4}$$

The government's payoff function is also the weighted sum $\tilde{P_G} = \tilde{P_S} + \alpha_G \tilde{P_O}$ where parliament's weight parameter $0 \leq \alpha_G \leq \alpha_R \leq 1$, yielding

$$\tilde{P_G} = S - \varphi(k) - \tilde{D} - (1 - \alpha_G)\tilde{P_O}. \tag{3.5}$$

3.1.3 The sequence of actions

The elements of the model can be represented in a game theoretical setting as presented in Figure 3.1.

The sequence of actions is as follows.

- **Time 0** The regulator offers a contract to the operator before the realization of the damage cost in case of an accident is known (ex-ante) which has been previously agreed with the government. This ex-ante contract compensates the operator for implementing sea defences to protect society from accidents associated with natural hazards. The regulator is better informed than the government with respect to the parameters that determine the damage cost. This private information, held by the regulator, leads to an upstream moral hazard problem. The upstream moral hazard is the first source of uncertainty of the damage cost output.

- **Time 1** The operator can reject or accept the contract if the participation constraint is satisfied.

- **Time 2** Once the contract is signed, the operator implements a sea defence that reduces the probability of an accident and maximises her payoff. The operator

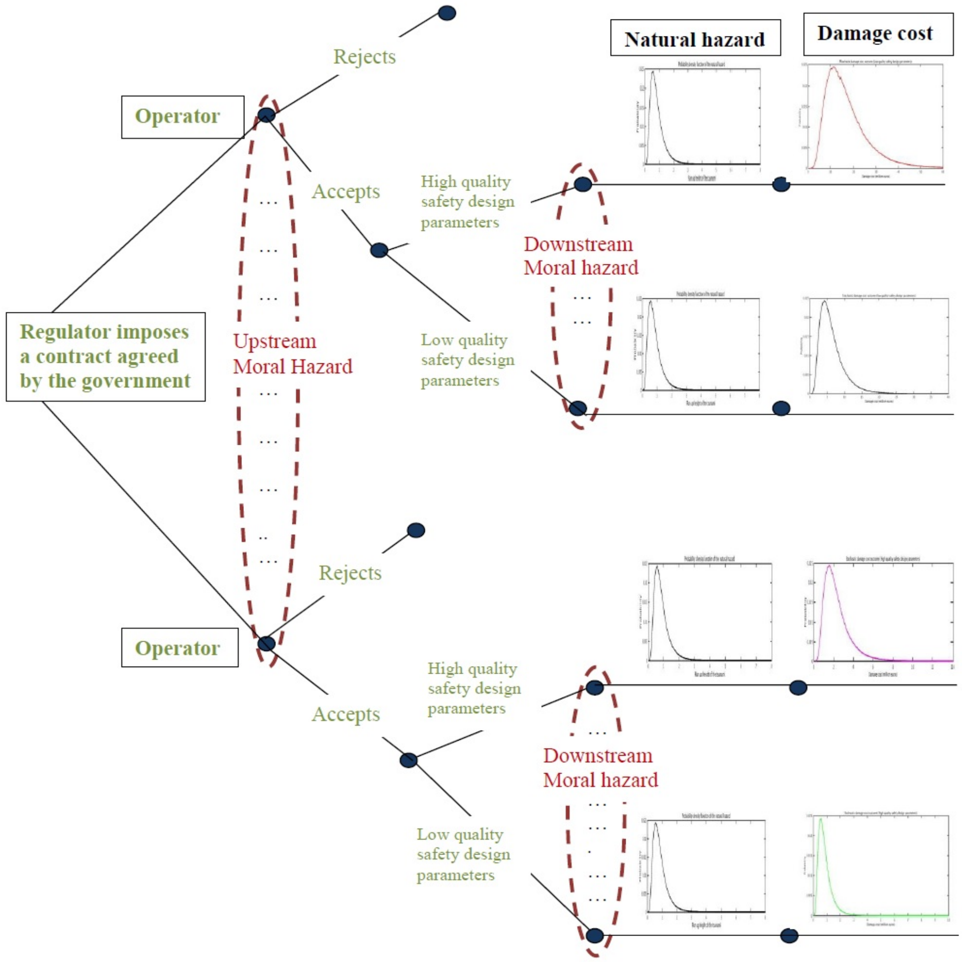

Figure 3.1: Game theoretical representation of the economic model.

faces a cost of implementing a safety design parameter k in the interval $k = [0, \bar{k}]$. This safety design parameter k determines the quality of the seawall a. The safety design parameter k is chosen on the basis of a risk assessment. As the regulator can not observe the quality of the sea defence implemented by the operator k a downstream moral hazard problem is unfolded. The moral hazard problem is the second source of uncertainty in the outcome of the model. The outcome of the implemented sea defence is an stochastic damage cost outcome. The damage cost is stochastic because it is a function of the height of the tsunami run up h which is modelled as a random variable. The link between the safety design parameter and damage cost distribution can be seen as follows; damage cost is a random variable and its probability distribution depends on the safety design parameter carried out by the operator. So, for instance, an operator could reduce the vulnerability by exerting a higher safety design parameter but she still faces risk because the performance measure is only stochastically related to the safety design parameter. In this view, the operator takes her safety design parameter before knowing the realization of the damage cost.

- **Time 3** Once the realization of the damage cost is known after an accident, the ex-post payoffs of the government, the regulator and the operator are revealed.

3.1.4 Moral hazard

The implementation of a sea defence by an operator, which is determined by the safety design parameter $k \in [0, \bar{k}]$, reduces the probability of damage cost imposed to the society in case of an accident. The implementation of a sea defence entails a monetary cost for the operator which is given by a cost function $\varphi(k)$. The cost function $\varphi(k)$ is common knowledge and satisfy the Inada conditions:

- the value of the function at 0 is zero, $\varphi(0) = 0$,
- the function is strictly increasing in a, $\varphi'(k) > 0$,
- the derivative of the function is decreasing so that the function is strictly concave, $\varphi''(k) < 0$,
- the limit of the derivative approaches zero when a goes to zero, $\lim \varphi'(k) = 0$ when $k \mapsto 0$, and
- The limit of the derivative approaches plus infinity when k goes to plus infinity, $\lim \varphi'(k) = +\infty$ when $k \mapsto +\infty$.

The effectiveness of the sea defence is not observable by either the regulator or the society. Thus, moral hazard might increase the vulnerability of the critical infrastructure by raising the residual risk.

3.1.5 Participation and incentive constraints

When the regulator can not observe the quality of the sea defence implemented by the operator, the regulator can only provide incentives to encourage the operator to implement the optimal quality of the sea defence. From section 3.1.1, we noticed that the incentive takes the form of a fine $\tilde{F}(a)$ imposed to the operator as function of the operator's implemented sea defence a.

When the operator has aversion to risk and/or limited assets to compensate the society in case of an accident, the regulator can not do better than a second best contract which satisfies the participation and incentive constraints of the operator. A second best contract implies that the optimal sea defence can not be implemented due to the existence of random damage cost outcomes. However, when the operator shows a risk neutral attitude to uncertain damage cost outcomes and has sufficient assets to cover the damage cost incurred, the regulator can achieve a first best contract which results in the implementation of optimal sea defences despite the existence of random damage cost outcomes.

The participation constraint states that given an implemented sea defence, an operator will demand a expected payoff from the implementation of sea defences that is at least equal to the value of the assets that she is able to use to cover excess damage cost.

$$T_i - E[F(\tilde{h}, a_i)] - \varphi(k_i) > 0 = p_0 \tag{3.6}$$

where p_0 is the value of the assets.

The incentive compatibility constraint states that an optimal contract must be that the increase in the operator's expected payoff is higher when the operator implements a better quality sea defence than when she implements a lower quality sea defence.

$$T_j - E[F(\tilde{h}, a_j)] - \varphi(k_j) > T_i - E[F(\tilde{h}, a_i)] - \varphi(k_i) \tag{3.7}$$

where $a_j > a_i$.

The incentive compatibility constraint depends only on the relative level (or marginal increase in the transfer payment) of the transfer payment for each expected damage cost outcome, while the participation constraint depends on the absolute payment transfer (the total increase in the payment transfer) for each expected damage cost outcome.

In light of this , if the constraints were not binding, the regulator can decrease the level of payment transferred for each realization of the tsunami run up height without affecting the relative (resp. absolute) level of the transfer payment, thereby satisfying both constraints at lower cost for the society.

3.1.6 Informational rent

As the contractable variable damage cost $\tilde{D}$ is stochastic and determines the payoff of the stakeholder, the optimal transfer payment allocated to the operator is distorted from the optimal transfer payment under incomplete information. This distortion is contingent on the risk attitude of the stakeholder with respect to uncertain payoffs.

Under the assumption of risk neutrality, stakeholders are indifferent between earning the same payoff through the stochastic payoff or sure payoffs, implying that informational rents are not necessary to recover efficiency. Nevertheless, risk averse stakeholders value the payoff less as the upper bound of the potential damage cost increases. Therefore, an informational rent will be included to the transfer payment to account for this loss in value.

The size of the informational rent is not only dependent upon the aversion of the stakeholder towards risk but also on the assets available to the operator to compensate for any harm inflicted to the society. Under limited liability, the regulator gives up some rent to the operator to guarantee a non negative payoff for all realizations of damage cost. This protects the society from paying the damage cost in case of accident if the damage cost exceeds the operator's resources.

3.1.7 First-Order stochastic dominance

The cumulative distribution function H of the damage cost $\tilde{D}$ is induced by $\tilde{h}$ and the sea defence a.

It is an assumption of the model that the cumulative distribution function $H(\tilde{D}, a_i)$ that is contingent on the sea defence a_i, first-order stochastically dominates the cumulative distribution function $H(\tilde{D}, a_j)$ that is contingent on a_j, whenever $a_i < a_j$. In order words, the higher the sea defence, the lower the damage cost. First-Order dominance means that for any value of the damage cost, the probability is higher under the cumulative distribution function $H(\tilde{D}, a_i)$ than under the cumulative distribution function $H(\tilde{D}, a_j)$. The cumulative distribution function $H(\tilde{D}, a_i)$ yields a lower payoff for the operator for each realization of the tsunami run up height than the cumulative density function $H(\tilde{D}, a_j)$ whenever $a_i < a_j$.

3.1.8 Limited liability

The use of limits to liability is particularly justified in situations of moral hazard. The fact that implementing sea defences leads to stochastic payoffs could deter many operators from entering into contracts and probably be detrimental to economic activity. This is because spending resources on protection against natural hazards does not guarantee a positive outcome for every realization of the natural hazard as there will be always a residual risk.

Society can not deal with bankrupt operators because it will bear all excess cost. It is better to take into account bankruptcies by including a liability constraint. Two main forms of limited liability have been identified. The first form guarantees a certain level of payoff (or utility) and the second one guarantees a certain level of transfer payment (or fine).

A limited liability constraint on transfers can, in general, be interpreted as a result of the government's limited financial resources to compensate the operator for implementing sea defences; while the constraint on payoff corresponds to a minimum level of well-being of the operator[31]. The model proposed in this thesis guarantees a non-negative payoff of the operator for every potential realization of the damage cost.

The constraint on payoff or utility can also approximate a situation of extreme risk aversion beyond a certain level of damage cost. It is plausible that an operator may be unaffected by the uncertainty of the payoff but as the variance of the damage cost distribution increases may become concerned with the realization of extremely high damage cost .

3.2 Delegation theory

The government delegates to a regulator the task of imposing the contract on the operator. However, the regulator is better informed than the government about some parameters determining the damage cost outcome in case of accident. This informational asymmetry may lead to an upstream moral hazard problem if there exist a conflict of interest between the government and the regulator. The design of delegation mechanisms play an important role to minimize the negative effects of the upstream moral hazard. [13].

There are two major delegation models in the agency theoretical framework.

1. In the first class of models, the government considers the delegation of authority for implementing regulatory policies to a regulator in order to take advantage of her knowledge and expertise [2, 12].

If the regulator is granted discretion, then she can use his knowledge to gather information about the magnitude of the potential damage cost. On the contrary, if delegation is not granted, the parliament must decide the sea defence to implement in the face of uncertainty of the magnitude of the potential damage cost [2, 12].

2. In this second class of models, the sequence of actions start with a regulator who uses his knowledge to gather information about the magnitude of the potential damage cost and reports to the government. The government then processes the information provided and chooses a sea defence to implement. These are called signalling models. If the information with regards to the potential damage cost sent to the government does not require any informational rent, then it is a cheap-talk model [2, 12].

The model presented in this thesis belongs to the first class of models.

3.2.1 Delegation problem

The government has to make a decision about the quality of the sea defence to be implemented under uncertainty of the magnitude of the potential damage cost in case of flooding. The government has available a regulator whom it may consult in the process of making a decision because the regulator possess some relevant information about the cost and benefit analysis of the optimal policy or the cost parameters that determines the damage cost. The problem the government faces in using a regulator is that the regulator may have different objectives that the parliament. This conflict of interest may derive from the lack of independence of the regulator. Thus, the problem lies on the designing of a delegation mechanism that facilitates the use of regulator's knowledge without compromising the viability of the project by benefiting the regulator or the operator to detriment of the society.

3.2.2 Contract direct mechanism

A mechanism comprises the following elements:

- there are two stakeholders: the government and the regulator,
- the government does not have private information. The regulator has private information of the cost parameter $b \in \mathcal{B}$ which determines the damage cost function. b can be considered as a growth factor in the damage cost function and is drawn from a commonly known distribution,
- a set of potential damage cost values $\tilde{D}$,
- the objective function of the regulator when the regulator announces parameter $\hat{b}$ which may be different from the true parameter b and obtains a realization damage $\tilde{D}$

$$E[P_R] = S - \delta_f b \int_{a(k(\hat{b}))}^{\infty} (h - a(k(\hat{b})))f(h)dh - \frac{c}{2}k^2(\hat{b}) - (1 - \alpha_R)(R(k(\hat{b}))),$$

- and the objective function for the government

$$E[P_G] = S - \delta_f b \int_{a(k(\hat{b}))}^{\infty} (h - a(k(\hat{b})))f(h)dh - \frac{c}{2}k^2(\hat{b}) - (1 - \alpha_G)(R(k(\hat{b}))).$$

From our setting we can distinguished two conceptual issues.

First, there is an information extraction problem; how can the government find out about the regulator's true cost parameter?

Second, there is a contracting problem; how many different contracts (one contract for each different quality of the sea defence implemented) should the government allow the regulator to impose on the operator?

A fundamental result in contract theory is the Revelation Principle. It says that we can simplify the contracting problem substantially.

The revelation principle guarantees that there is no loss of generality in restricting the parliament to offer as many contracts as many options as the cardinality of the cost parameter space $\mathcal{B}$. The cost parameter space $\mathcal{B}$ is specified in the interval $[\underline{b}, \bar{b}]$ and represents the private information of the regulator.

A direct mechanism is a specification of the cost parameter space of the regulator $\mathcal{B}$ and a damage cost function that maps the regulator's announcement of the damage growth parameter $\hat{b}$ into an optimal sea defence and an optimal transfer payment. In order words, the mechanism stipulates the range of possible transfer payments available to the regulator. In line with this specification, the government can set restrictions of the transfer payment to be paid to the operator.

3.2.3 Bayesian incentive compatible mechanism

In contractual relationships where the information available to the government is incomplete, the mechanism combined with the cost parameter space $b \in \mathcal{B}$ and density $\pi(b)$ defines a Bayesian game with possibly different payoffs structure for every $b \in \mathcal{B}$.

In Bayesian games it is useful to distinguish between stages of the contractual relationship in terms of the knowledge sets of the regulator. The three stages of a Bayesian game are ex ante, interim, and ex post. The ex ante stage is before the cost parameter b is drawn from the distribution $\pi(b)$. In the ex ante stage the regulator and the government know this distribution $\pi(b)$ but no the actual cost parameter. The interim stage is immediately after the regulator finds out the actual cost parameter, but before the realization of a damage cost. The government knows the distribution $\pi(b)$. In the ex post stage the actual cost parameter is known by the regulator and the government after a realization of a damage cost. The proposed model is considered from an interim stage.

A solution to a Bayesian game is a Bayesian Nash equilibrium. A Bayesian Nash equilibrium is defined as the government's beliefs about the actual cost parameter of the regulator that maximizes the regulator's expected payoff. In a Bayesian Nash equilibrium the regulator has not incentive to announce a different cost parameter from the actual parameter.

Importantly, throughout in the Bayesian game, the possible sea defences, the payoff functions, possible cost parameters, and the probability distribution over the cost parameter are assumed to be known by both the regulator and the government.

The mechanism is Bayesian incentive compatible if the regulator yields a higher payoff by announcing the true cost parameter in a Bayesian Nash equilibrium.

An incentive compatible mechanism has to satisfy two conditions: the truth telling condition and the monotonicity condition.

1. Truth telling condition implies that the true cost parameter yields the highest payoff to the regulator.

2. Monotonicity condition implies that, as the cost parameter increases, the operator's optimal sea defence also increases.

Chapter 4

Risk regulatory policy

4.1 Risk neutrality and full liability

A risk-neutral operator has a constant marginal utility of payoff. Marginal utility is the change in total satisfaction for the operator from increasing the quality of the sea defence a. With a constant marginal utility of payoff a risk-neutral operator values a sure payoff of some amount exactly as much as it values a gamble that has 50 chance of paying twice that amount and a 50 chance of paying nothing at all. The expected utility of the stochastic damage cost is equal to the utility of the expectation of the stochastic damage cost.

$$u(E[\tilde{P}_O(T, \delta_f, a)]) = E(u[\tilde{P}_O(T, \delta_f, a)]). \tag{4.1}$$

The preference of a risk-neutral operator over the expected damage cost can be represented by a linear function. The slope of the line is the same at all levels of the payoff.

4.1.1 Optimal risk regulatory policy under full liability

We consider a risk-neutral operator who cares about the expected damage cost only and no about the variance of the damage cost. Because $\tilde{F} = \delta_f \tilde{D}$, δ_f is the proportional fine, $\tilde{D} = b(\tilde{h} - a(k))^+$, and $\tilde{h}$ is the height of the run up, where

$$(h-a)^+ = \begin{cases} h-a & \text{if} \quad h > a \\ 0 & \quad \text{otherwise.} \end{cases}$$

This implies no damage cost for $h \leq a(k)$.

The operator's payoff function takes the form

$$\tilde{P_O} = T - \varphi(k) - \delta_f b(\tilde{h} - a(k))^+. \tag{4.2}$$

The expected payoff of the operator takes the form

$$E[\tilde{P_O}] = T - \varphi(k) - \delta_f b E[(\tilde{h} - a(k)^+], \tag{4.3}$$

where

$$E[(\tilde{h}-a)^+] = \int_a^{\infty} (h-a) f(h) dh,$$

and $f(h)$ as the probability distribution of run up heights.

The operator's optimization problem is the optimal choice of the safety design parameter $k \geq 0$, which takes the form

$$max_{(k\geq 0)}\Big(T - \varphi(k) - \delta_f b \int_{a(k)}^{\infty} (h - a(k)) f(h) dh\Big). \tag{4.4a}$$

This objective function is strictly concave and differentiable, whenever $\varphi'(k) > 0$, $\varphi''(k) \leq 0$, and $a'(k) > 0$, $a''(k) \leq 0$.

The unique solution k^* is obtained from the first order condition (FOC), which is given by

$$Prob(\tilde{h} \geq a^*) = \frac{\varphi'(k^*)}{\delta_f b a'(k^*)}, \tag{4.4b}$$

where

$$a^* = a^*(k).$$

Analysing FOC we can see that k^* exists and is unique because the left hand side of the FOC is decreasing in k and the right hand side of the FOC is increasing in k, as well as assuming that $\varphi'(0) = 0$ and $a(0) = 0$.

The optimal safety design parameter k^* is a function of δ_f, and independent of T such that

$$k^* = k^*(\delta_f).$$

It follows from the FOC that k^* is increasing in δ_f.

Regulator's decision problem is the choice of a transfer payment T and the fine parameter δ_f that maximizes the expected payoff of the regulator such that

$$max_{(T,\delta_f)} E[\tilde{P_R}(T, \delta_f)].$$

We assume that the participation constraint of the operator is

$$E[\tilde{P_O}(T, \delta_f)] \geq p_0,$$

where p_0 may be thought of as either a mark up or the operator's assets that she could sell in order to meet her payment obligations.

This expression must hold with equality at an optimal T^* and δ_f^* if it is binding. The reason is that if the participation constraint were not binding $E[\tilde{P_O}(T, \delta_f)] > p_0$, then T could be lowered without violating the participation constraint because of the linearity.

In light of this, the regulator proceeds in two steps.

1. Because $k^*(\delta_f)$ is increasing in δ_f, there is a one-to-one correspondence between fines and safety design parameters. The regulator's choice of δ_f^* may therefore be transformed to an equivalent problem which determines the optimal safety design parameter $k \geq 0$ from the regulator's point of view. This optimization problem is given by

$$max_{(k\geq 0)}\Big(S - \varphi(k) - \int_{a(k)}^{\infty} b(h - a(k))f(h)dh - (1 - \alpha_R)p_0\Big). \tag{4.5a}$$

   This objective function is strictly concave and differentiable, as long as $\varphi'(k) > 0$, $\varphi''(k) \leq 0$ and $a'(k) > 0$, $a''(k) \leq 0$.

   The solution to the regulator's optimization problem (4.5a) is obtained from the first-order condition which takes the form

$$Prob(h \geq a^{**}) = \frac{\varphi'(k^{**})}{ba'(k^{**})}, \tag{4.5b}$$

   where

$$a^{**} = a(k^{**}).$$

   Analysing (4.5b) we can see that k^* exists and is unique because the left hand side of (4.5b) is decreasing in k and the right hand side of (4.5b) is increasing in k, and $\varphi'(0) = 0$ as well as $a(0) = 0$.

   The solution k^{**} is called the socially optimal safety design parameter.

   A comparison of (4.4b) with (4.5b) shows that

$$k^*(1) = k^{**}.$$

   Hence, when the regulator sets a $\delta_f^* = 1$, the operator will implement the socially optimal k^{**}.

2. Because the optimal fine is $\delta_f^* = 1$, it is optimal for the operator to implement the safety design parameter k^{**} which corresponds to the sea defence $a^{**} = a(k^{**})$. As a^{**} is independent of the transfer payment T , the regulator may set

$$T^* = \varphi(k^{**}) + E[D(\tilde{h}, a^{**})] + p_0. \tag{4.6}$$

   where $\varphi(k^{**})$ is the cost of implementing the social optimum k^{**}, $E[D(\tilde{h}, a^{**})]$ is the expected fine and p_0 is the mark up or the operator's assets. The operator accepts the first best transfer payment which is the minimum payment that satisfies her participation constraint. This implies that the expected payoff of the operator is

$$E[\tilde{P_O}(T^*, \delta_f^*)] = p_0.$$

   Because $\tilde{F} = \delta_f \tilde{D}$ where $\delta_f = 1$, the payoff of the operator in case of a flooding may be negative if the realization of the damage cost $D(\tilde{h}, a^{**})$ is higher than the expected damage cost $E[D(\tilde{h}, a^{**})]$.

Summarising, we obtain the following result.

Theorem 1 *The optimal regulatory policy under asymmetric information, risk neutrality and full liability is determined by the optimal fine δ_f^*, the optimal payment transfer T^* and the optimal safety design parameter k^{**}.*

1. *The regulator sets a fine equal to damage cost, that is, $\delta_f^* = 1$.*

2. *The operator finds it optimal to implement the socially optimal safety design parameter k^{**} that solves (4.5a), so that*

$$k^{**} = k^*(1).$$

   The socially optimal sea defence is implemented, that is

$$a^{**} = a(k^{**}).$$

3. *The optimal transfer payment T^* set by the regulator is equivalent to the sum of the cost of implementing the safety design parameter, the expected fine and the markup, so that*

$$T^* = p_0 + \varphi(k^{**}) + E[D(\tilde{h}, a^{**})].$$

4. *The random payoff of the operator in case of flooding is negative for some realizations of h that exceeds the optimal sea defence a^{**}. That is when the realization of damage cost is higher than the sum of the expected damage cost and the value of the operator's assets.*

$$\tilde{P_O^*}(T^*, 1) = p_0 + E[D(\tilde{h}, a^{**})] - D(\tilde{h}, a^{**}).$$

5. *The random payoff of the society in case of flooding is protected from a negative payoff if the realization of the damage cost does not exceed the operator's payoff plus the difference between the society's revenue from sea defences and the transfer payment.*

$$\tilde{P_S^*}(T^*, 1) = S - T^* + min\{p_0 + E[D(\tilde{h}, a^{**})] - D(\tilde{h}, a^{**}), 0\}.$$

4.1.2 Example

General assumptions:

- the regulator cannot observe the safety design parameter that determines the quality of the sea defence chosen by the operator,

Table 4.1: Notation

Parameter (1)	Description (2)	Value (3)
$\tilde{h}$	Tsunami run up random variable	$ln\ \mathcal{N}(4.5, 0.89)$
a_0	Sea defence parameter	$a_0 = 1.7$
k	Safety design parameter	$0 \leq k \leq 7$
c	Marginal cost	$c = 0.3$
δ_f	Initial fine parameter	$\delta_f = 0.75$
b	Cost parameter	$b = 200$
T	Transfer payment	$T = 200$
S	Society revenue from sea defences	$S = 300$
β	Risk coefficient of the relative risk aversion (CRRA) function	$\beta = 0.7$
α_G	Government's weight parameter over operator's surplus	$\alpha_G = 0.60$
α_R	Regulator's weight parameter over operator's surplus	$\alpha_R = 0.80$
p_0	Value of operator's assets or mark up	$p_0 = 30$

- the heights of the tsunami run up are lognormally distributed. Empirical observations of tsunamis on the coast of the Hawaiian Islands in 1946 and 1957, in the Japanese coast (mainly along the sariku coast) in 1896, 1933, 1946,1960,1964 and 1968, and on the coast of the Kurile Island between 1896 1981 shows that the spatial distribution of the tsunami run up heights is well characterised by the lognormal distribution [23, 9], and

- the realization of damage cost $\tilde{D}$ is induced by $\tilde{h}$ and the safety design parameter k. The conditional cumulative distribution function $H(\tilde{D}, a_i)$ first order stochastically dominates the conditional cumulative distribution function $H(\tilde{D}, a_j)$, that is $H(tildeD, a_i) \geq H(\tilde{D}, a_j)$ whenever $a_i \leq a_j$. See Fig. 4.1.

Suppose that the relationship between the sea defence a and the safety design parameter k is given by the linear function

$$a(k) = a_0 k.$$

The cost function is of the quadratic form

$$\varphi(k) = \frac{c}{2} k^2.$$

Given that the fine parameter of the fine function is $\delta_f = 0.75$, the operator chooses a safety design parameter k^* that maximizes her payoff function. An optimal solution

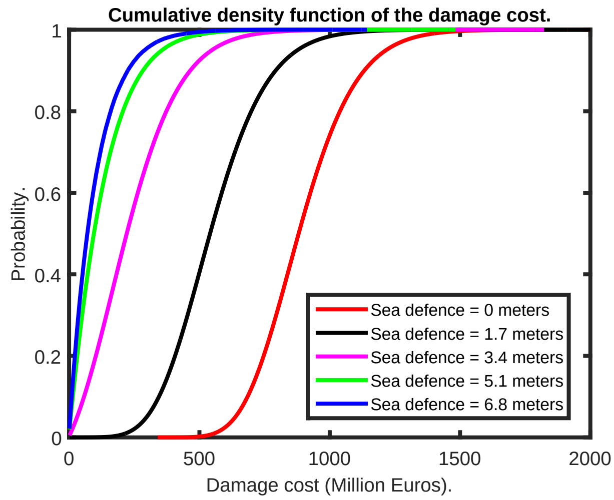

Figure 4.1: First-Order stochastic dominance of five cumulative density functions conditional on the height of the sea defence.

to the optimization problem is

$$k^*(0.75) = 4.300.$$

This implies that the sea defence will have a height of

$$a^* = a_0 k^*(0.75) = 7.310\,\mathrm{m}\,.$$

The optimal safety design parameter satisfies the incentive constraint of the operator.

Given that the optimal sea defence chosen by the operator is $a^* = 7.310\,\mathrm{m}$, the regulator's decision problem is to choose (1) an fine parameter δ_f that induces the operator to implement the height of the sea defence that maximizes the regulator's payoff function and (2) a minimum transfer payment T that satisfies the participation constraint of the operator.

The optimal safety design parameter of the regulator is presented in Fig. 4.2 where the x-axis represents the height of the sea defence implemented by the operator and the y-axis represents the payoff of the regulator.

The numerical solution in Fig. 4.2 shows that the regulator chooses a safety design parameter that is

$$k^{**} = 4.385.$$

This implies that the sea defence will have a height of

$$a_0 k^{**} = 7.455\,\mathrm{m}\,.$$

We note that the operator finds it optimal to implement a sea defence below the social optimum. In order to incentivize the operator to implement the socially optimal

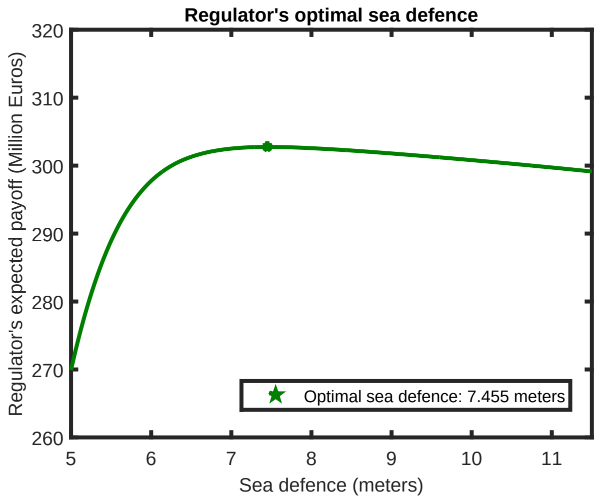

Figure 4.2: Regulator's optimal sea defence under full liability.

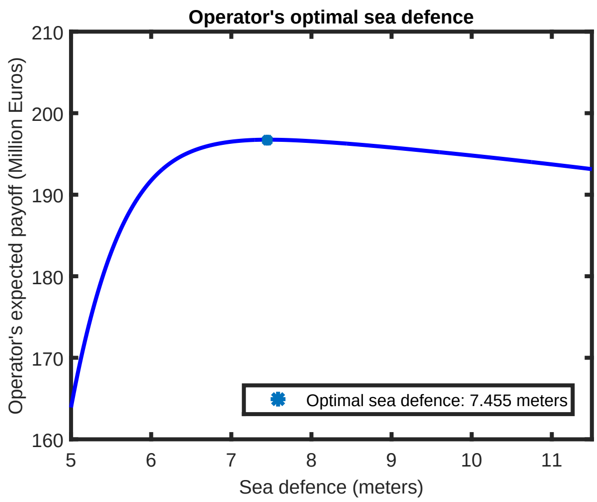

Figure 4.3: Operator's optimal sea defence under full liability.

sea defence, the fine parameter δ_f is raised to 1, such that

$$k^{**} = k^*(1) = 4.385,$$

$$a^{**} = a_0 k^{**} = 7.455\,\mathrm{m}\,.$$

The optimal choice of the safety design parameter of the operator when $\delta_f = 1$ is presented in Fig 4.3 where the x-axis represents the height of the sea defence implemented by the operator and the y-axis represents the payoff of the operator.

Given that the regulator has set a fine equal to damage cost, the optimal transfer payment to the operator has to guarantee that the expected payoff of the operator is at least as large as p_0. The numerical solution is presented in Fig. 4.4 where the x-axis represents the height of the sea defence implemented by the operator and the y-axis represents the transfer payment to the operator.

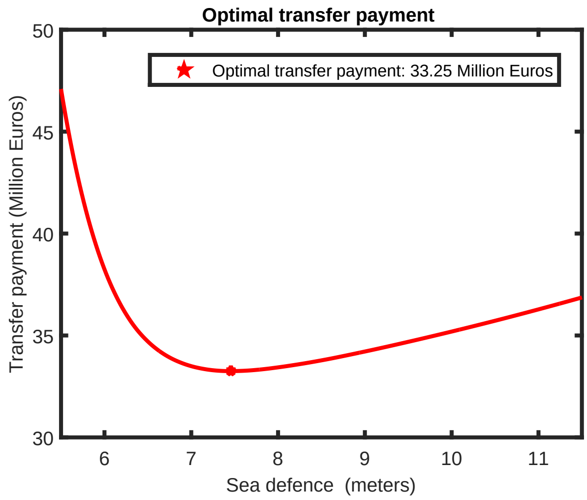

Figure 4.4: Optimal transfer payment under full liability.

The numerical solution in Fig. 4.4 shows that the regulator chooses a transfer payment of

$$T^* = 33.25 \,\text{million}\, €,$$

that is the minimum amount of money that the operator will accept to take on the construction of the sea defence.

4.1.3 Dynamic setting: ratchet effect

This section attempts to discuss the ratchet effect in dynamic settings under moral hazard.

Let's suppose that the operator works in two different periods, 1 and 2, implementing safety design parameter, k_1 and k_2, respectively.

As usual, the safety design parameter k is not observed by the regulator, the regulator can only observe the stochastic damage cost output

$$\tilde{D} = b(\tilde{h}_j - a(k_j)), \qquad\qquad j = 1, 2,$$

$\tilde{h}$ is assumed to be lognormally distributed and j is the time period.

The contract in period one will have the standard form

$$T_j - \delta_f b(\tilde{h}_j - a(k_j)), \qquad\qquad j = 1, 2,$$

where T_j is the transfer payment and $\delta_f b(\tilde{h}_j - a(k_j))$ is the fine imposed to the operator at period j.

Since the operator is performing the same task over two periods, it is reasonable to assume that the performance in period 1 is positively correlated with the performance in period 2. Therefore, the regulator may use the stochastic damage cost output in period 1 to estimate the stochastic damage cost output in period 2 and set the contract accordingly.

Let $\hat{h}_2 = \psi + \phi b(\tilde{h}_1 - a(k_1))$ be the estimate of $\tilde{h}_2$. The regulator can use this to create an adjusted estimate of $\tilde{D}_2$

$$\hat{D}_2 = \tilde{D}_2 - \hat{h}_2 = b(\tilde{h}_2 - a(k_2)) - \hat{h}_2.$$

The informativeness principle says that if the correlation between h_1 and h_2 is high the output from period one should be used in the contract for period 2.

If the second period has the same form as the first-period contract, then the agent's total wage will be

$$[T_1 - \delta_1 b(\tilde{h}_1 - a(k_1))] + [T_2 - \delta_2(b(\tilde{h}_2 - a(k_2)) - \psi - \phi b(\tilde{h}_1 - a(k_1))))].$$

This can be rewritten as

$$T_1 + T_2 + (\delta_1 - \psi\delta_2)(b(\tilde{h}_1 - a(k_1)) + \delta_2 b(\tilde{h}_2 - a(k_2) - \phi).$$

It is worth noting that the coefficient on $a(k_1)$ is not δ_1, but rather $\delta_1 - \psi\delta_2 < \delta_1$.

Since the regulator uses previous damage cost output to judge how to compensate the operator for the safety design parameter implemented, this will mean that the standard by which damage cost is evaluated in period two goes down by ψ.

This in turn reduces the incentive to implement a good level of safety design in the initial period, as the operator anticipates this effect.

Hence we can define the effective incentives for the operator as $\delta_1^E = \delta_1 - \psi\delta_2$ and $\delta_2^E = \delta_2$.

In line with this, is it possible to design a contract which maximises total wealth and achieve the first best safety design parameter? This is equivalent to the regulator being able to commit himself to setting the contractual terms in both period 1 and 2 before the relationship begins.

The regulator will optimize its payoff function to the usual incentive constraints (marginal cost equal to marginal benefit). If there is an optimal level of $a(k_1)$ and $a(k_2)$, it must be such that $a(k_1) = a(k_2)$ and $\delta_1^E = \delta_2^E$.

The absence of commitment power from the part of the regulator leads to a distortion of incentives to the operator in that $a(k_2) > a(k_1)$.

4.2 Risk neutrality and limited liability

As we have seen in the previous scenario, the fine imposed to the operator is proportional to the expected damage cost. However, the extent of the damage that could be realized upon the natural hazard could be extremely high, thus bankrupting the operator.

It follows from Theorem 1 that in an optimum

$$\tilde{P_O} = p_0 + E[D(\tilde{h}, a(k^*))] - D(\tilde{h}, a(k^*)) < 0$$

for all sufficient large run-up heights $\tilde{h}$, the realization of the fine will result in negative payoffs for the operator.

Society can not be interested in bankrupt operators because they will bear all excess cost. It is better to take into account bankruptcies by including a liability constraint. This liability constraint guarantees a non-negative payoff of the operator for every potential realization of the damage cost.

The liability constraint takes the form of a cap on the operator's fine for any potential realization of the damage cost.

In order to cap the operator's fine, we assume that

$$\tilde{P_O} = \begin{cases} T - \varphi(k) - \tilde{F} & \text{if} \quad \tilde{F} < \bar{F} \\ T - \varphi(k) - \bar{F} & \quad \text{otherwise.} \end{cases}$$

4.2.1 Optimal risk regulatory policy under limited liability

Let $\tilde{F} = min\{\tilde{D}, \bar{D}\}$ and as before, $\tilde{D} = b(\tilde{h} - a(k))^+$ where $\tilde{h}$ is the height of the run up. Then, the operator is fined up to the cap $\bar{D}$; beyond that point the society will bear this risk of flooding. This residual risk of damage incurring costs above $\bar{D}$ has possibly a very low probability but may have severe economic consequences. In engineering projects, a typical residual risk is less than 1%.

The operator's payoff function is now

$$\tilde{P_O} = T - \varphi(k) - min\{b(\tilde{h} - a(k))^+, \bar{D}\}, \tag{4.7}$$

where, as before,

$$(h-a)^+ = \begin{cases} h - a & \text{if} \quad h > a \\ 0 & \quad \text{otherwise.} \end{cases}$$

This indicates that the operator's payoff is capped to non-negative values.

The operator's expected payoff is

$$E[\tilde{P_O}] = T - \varphi(k) - E[min\{b(\tilde{h} - a(k))^+, \bar{D}\}], \tag{4.8}$$

with

$$E[min\{b(\tilde{h} - a(k))^+, \bar{D}\}] = \int_{a(k)}^{a(k)+\frac{\bar{D}}{b}} b(h - a(k))^+ f(h)dh + \bar{D} \int_{a(k)+\frac{\bar{D}}{b}}^{\infty} f(h)dh.$$

In light of this, the operator's optimization problem is the choice of the safety design parameter $k \geq 0$ and takes the form

$$max_{(k\geq 0)}\Big(T - \varphi(k) - \int_{a(k)}^{\infty} min\{b(\tilde{h} - a(k))^+, \bar{D}\} f(h)dh\Big). \tag{4.9a}$$

This objective function is strictly concave and differentiable, $\varphi'(k) > 0$, $\varphi''(k) \leq 0$ and $a'(k) > 0$, $a''(k) \leq 0$.

The solution is obtained from the first-order condition (FOC) for an optimal k which takes the form

$$Prob(a^*_{ll} \leq \tilde{h} \leq a^*_{ll} + \frac{\bar{D}}{b}) = \frac{\varphi'(k^*_{ll})}{ba'(k^*_{ll})}, \tag{4.9b}$$

where

$$a^*_{ll} = a(k^*_{ll}).$$

Thus, an optimal safety design parameter under limited liability (ll) is a function of $\bar{D}$, such that

$$k^*_{ll} = k^*_{ll}(\bar{D}).$$

Under limited liability, we now require that

$$\tilde{P_O} \geq p_0 \qquad \text{(Participation constraint)}, \tag{4.10}$$

where p_0 is the value of assets that the operator is able to use to cover excess damage cost.

If k^*_{ll} is implemented then

$$\tilde{P_O}^*(T, \bar{D}) = T - \varphi(k^*_{ll}) - min\{b(\tilde{h} - a(k^*_{ll}))^+, \bar{D}\} \qquad \text{for all } \tilde{h}.$$

Observe that

$$\tilde{P_O}^*(T, \bar{D}) \geq T - \varphi(k^*_{ll}) - \bar{D}$$

so that the limited liability constraint is satisfied whenever

$$T \geq T^*_{ll} = \varphi(k^*_{ll}) + \bar{D} + p_0.$$

Observe that T^*_{ll} is the minimum transfer payment that satisfies the operator's participation constraint which because of $k^*_{ll} = k^*_{ll}(\bar{D})$ is a function of $\bar{D}$.

Setting $T = T^*_{ll}$, the expected payoff becomes a function of $\bar{D}$ and given by

$$E[\tilde{P_O}^*] = \bar{D} - E[min\{b(\tilde{h} - a^*_{ll})^+, \bar{D}\}] + p_0.$$

We may define the liability rent $\mathcal{R}(\bar{D})$ to be

$$\mathcal{R}(\bar{D}) = \bar{D} - E[min\{b(\tilde{h} - a^*_{ll})^+, \bar{D}\}] + p_0,$$

where

$$a^*_{ll} = a(k^*_{ll}(\bar{D})).$$

The regulator's decision problem is the choice of the fine cap $\bar{D}$ that maximizes the expected payoff

$$E[\tilde{P_R}(\bar{D})] = S - \varphi(k_{ll}^*(\bar{D})) - \int_{a(k_{ll}^*(\bar{D}))}^{\infty} b(h - a(k_{ll}^*(\bar{D})))^+ f(h)dh - (1-\alpha_R)\mathcal{R}(\bar{D}). \quad (4.11)$$

This objective function is strictly concave and differentiable whenever $\varphi'(k) > 0$, $\varphi''(k) \leq 0$ and $a'(k) > 0$, $a''(k) \leq 0$.

The regulator's maximization problem takes the form

$$max_{(\bar{D}\geq 0)} E[\tilde{P_R}(\bar{D})]. \quad (4.12a)$$

The solution of the regulator's optimization problem is an optimal fine cap $\bar{D}^{**}$ and obtained from the first-order condition which takes the form

$$Prob(\tilde{h} \geq a_{ll}^{**}) - \frac{\varphi'(k_{ll}^{**})}{ba'(k_{ll}^{**})} = (1-\alpha_R)\frac{Prob(h \leq a_{ll}^{**} + \frac{\bar{D}^{**}}{b})}{ba'(k_{ll}^{**})\frac{dk_{ll}^*}{d\bar{D}}(\bar{D}^{**})} + Prob(0 \leq \tilde{h} - a_{ll}^{**} \leq \frac{\bar{D}^{**}}{b}), \quad (4.12b)$$

where

$$k_{ll}^{**} = k_{ll}^*(\bar{D}^{**}) \quad \text{and} \quad a_{ll}^{**} = a(k_{ll}^{**}).$$

k_{ll}^{**} is the socially optimal safety design parameter and a_{ll}^{**} is the optimal sea defence under limited liability. Observe that both values k_{ll}^{**} and a_{ll}^{**} are also influenced by α_R.

A comparison of (4.5b) and (4.12b) shows that the socially optimal safety design parameter under limited liability is less than under full liability, that is

$$k^{**} \geq k_{ll}^{**}.$$

This is because

$$(1-\alpha_R)\frac{Prob(h \leq a_{ll}^{**} + \frac{\bar{D}^{**}}{b})}{ba'(k_{ll}^{**})\frac{dk_{ll}^*}{d\bar{D}}(\bar{D}^{**})} + Prob(0 \leq \tilde{h} - a_{ll}^{**} \leq \frac{\bar{D}^{**}}{b}) \geq 0$$

or, equivalently, the marginal liability rent is positive $\mathcal{R}'(\bar{D}^{**}) > 0$.

The optimal transfer payment is a function of $\bar{D}^{**}$ and takes the form

$$T_{ll}^* = \varphi(k_{ll}^{**}) + \bar{D}^{**} + p_0. \quad (4.13)$$

This implies that the expected payoff of the operator is

$$E[\tilde{P_O}(\bar{D}^{**})] = p_0 + \bar{D}^{**} - E[min\{b(\tilde{h} - a(k_{ll}^{**}))^+, \bar{D}^{**}\}].$$

The regulator can no longer achieve the first best safety design parameter k^{**} but the second best transfer k_{ll}^{**} that accounts for the fact that the operator will not be able to cover losses above $\bar{D}^{**}$.

Summarising, we obtain the following result.

Theorem 2 *The optimal regulatory policy under asymmetric information, risk neutrality and limited liability is determined by*

1. *The regulator sets an optimal maximum fine $\bar{D}^{**}$.*
2. *The operator finds it optimal to implement the safety design parameter, that is*

$$k_{ll}^{*}(\bar{D}^{**}) = k_{ll}^{**}.$$

The optimal operator's sea defence is implemented, that is

$$a_{ll}^{**} = a(k_{ll}^{**}).$$

3. *The optimal transfer set by the regulator is equivalent to the cost of exerting a safety design parameter, the capped fine, and a markup.*

$$T_{ll}^{*} = \varphi(k_{ll}^{**}) + \bar{D}^{**} + p_0.$$

4. *The random payoff of the operator under limited liability is protected from negative payoff in case of flooding. This is because the fine is limited by a cap.*

$$\tilde{P_O^*}(T_{ll}^*, \bar{D}^{**}) = p_0 + \bar{D}^{**} - min\{D(\tilde{h}, a_{ll}^{**}), \bar{D}^{**}\}.$$

5. *The random payoff of the society under limited liability is negative for some realizations above the fine cap in case of flooding.*

$$\tilde{P_S^*}(T_{ll}^*, \bar{D}^{**}) = S - T_{ll}^* - D(\tilde{h}, a_{ll}^{**}) + min\{D(\tilde{h}, a_{ll}^{**}), \bar{D}^{**}\}.$$

4.2.2 Example

Given that the operator's liability is constrained by an initial fine cap of $\bar{D} = 100$ million €, the operator chooses a safety design parameter k that maximizes her payoff function and minimizes his cost function $\varphi(a(k))$, that is

$$k_{ll}^{*}(100) = 4.260.$$

This implies that the operator will implement a height of the sea defence, that is

$$a_0 k_{ll}^{*}(100) = 7.243\,\mathrm{m}.$$

The optimal $k_{ll}^{*}(100)$ satisfies the incentive constraint of the operator, that is when the marginal cost equalizes the marginal benefit.

The decision problem of the regulator is to choose a fine cap $\bar{D}$ that maximizes its payoff and minimizes the liability rent of the operator. The optimal fine cap $\bar{D}^{**}$ induces the operator to implement a sea defence that is socially optimal. The second

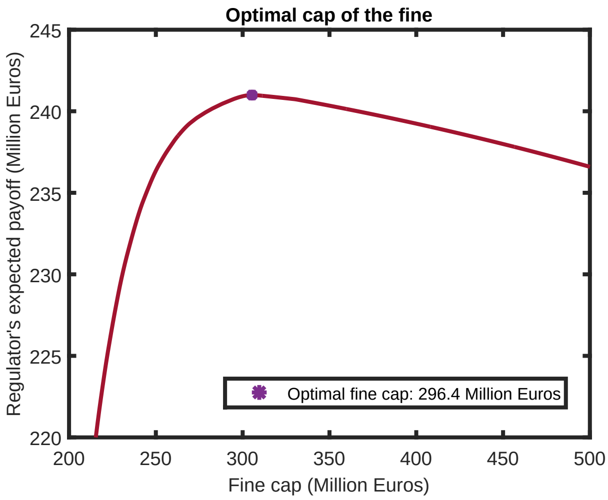

Figure 4.5: Optimal fine cap under limited liability.

.

decision problem of the regulator is to choose a minimum transfer payment to the operator that will satisfy the limited liability constrain of the operator.

An optimal solution to the optimization problem of the regulator is presented in Fig. 4.5 where the x-axis represents the fine cap in million euros and the y-axis represents the expected payoff of the regulator.

Fig. 4.5 shows that when the operator chooses a safety design parameter $k_{ll}^*(100) = 4.260$, the optimal cap that maximizes the regulator's payoff is

$$\bar{D}^{**} = 296.4\,\text{million}\,€.$$

Observe from Fig. 4.6 where the x-axis is the fine cap in million euros and the y-axis is the operator's optimal sea defence that is a function of the fine cap.

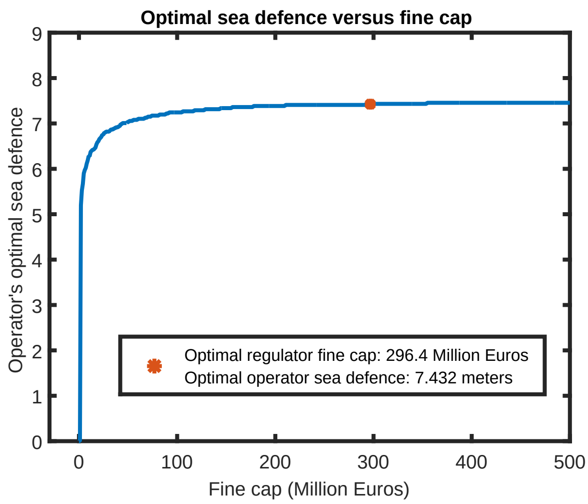

Figure 4.6: Operator's optimal sea defence induced by the optimal fine cap.

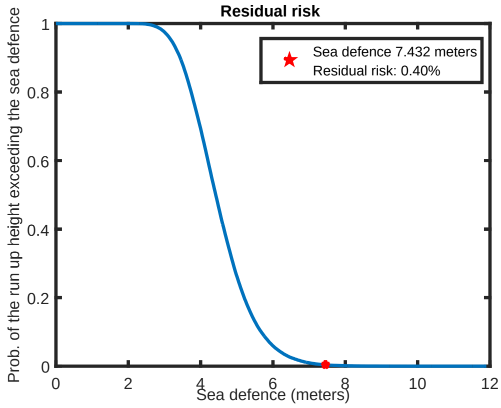

Figure 4.7: Residual risk borne by the society corresponding to the implementation of operator's optimal sea defence under limited liability.

The numerical result from Fig. 4.6 shows that when the regulator imposes a fine of $\bar{D}^{**} = 296.4\,\text{million}\,€$ to the regulator, the operator will choose a safety design parameter, that is

$$k_{ll}^{**}(296.4) = 4.371.$$

This implies that the operator will implement a height of the sea defence, that is

$$a_{ll}^{**} = 7.432\,\text{m}.$$

The residual risk when the operator implements a sea defence a_{ll}^{**} is presented in Fig. 4.7 where x-axis represents the height of the sea defence and the y-axis represents the probability of run up height exceeding the sea defence.

By comparison, the residual risk associated with the implementation of a_{ll}^{**} under limited liability is higher than the residual risk when a^{**} is implemented under full liability

$$a_{ll}^{**} = 7.432\,\text{m.} \Rightarrow 0.40\% \qquad \text{and} \qquad a^{**} = 7.455\,\text{m.} \Rightarrow 0.38\% \qquad \text{(Residual risk).}$$

Under limited liability, the society pays a transfer payment as a function of $\bar{D}^{**}$, that is much higher than the transfer payment under full liability.

$$T_{ll}^{*} = 329.26\,\text{million}\,€ \qquad\qquad \text{and} \qquad\qquad T^{*} = 33.25\,\text{million}\,€.$$

When the run up height exceeds the sea defence implemented by the operator, the ex-post payoff of the society under full liability and limited liability is presented in Fig. 4.8 where the x-axis is the height of the run up above the sea defence and the y-axis is the payoff of the society.

For any realization of the run up height exceeding the optimal sea defence (residual risk) by less than 0.819 m , the society prefers the operator to be full liable for the damage cost. Any other realization exceeding the optimal sea defence beyond 0.819 m

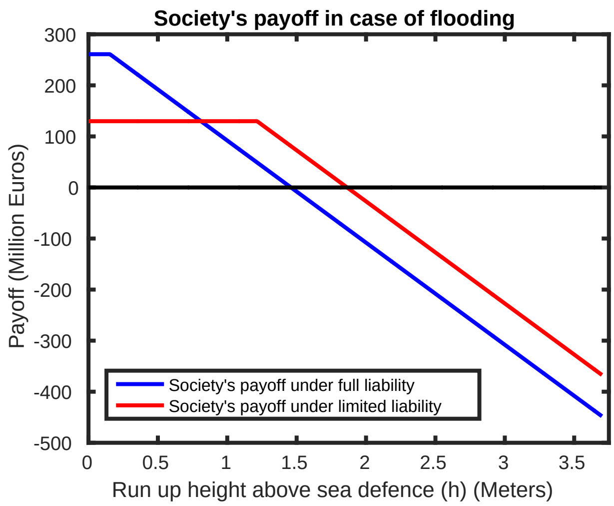

Figure 4.8: Society's payoff in case of flooding under full and limited liability.

.

the society would rather have an operator with limited liability. The society is also better protected from negative payoff under limited liability than under full liability.

4.3 Risk aversion and full liability

An operator with an averse attitude to risk will value certain payoff outputs over uncertain ones. As a result of this, a risk averse operator will have a decreasing marginal utility.

The preferences of a risk averse operator over the expected payoff can be represented by a strictly increasing, strictly concave and twice differentiable Bernoulli utility function. This thesis assumes that the operator's preferences are represented by a Constant Relative Risk Aversion (CRRA) utility function. This implies that as the payoff increases, the risk aversion of the stakeholder involved in the project remains constant. Therefore, the operator will invest the same percentage of the payoff in sea defences. This is also a convenient assumption in economic analysis when the tsunami run up height random variable is lognormally distributed.

The Constant Relative Risk Aversion (CRRA)utility function

The Constant Relative Risk Aversion (CRRA) utility function takes the form

$$u(\tilde{W_O}) = \begin{cases} \frac{(\tilde{W_O})^{1-\beta}}{1-\beta} & \text{if} \quad \beta > 0 \ \beta \neq 1 \\ \\ ln\tilde{W_O} & \text{if} \qquad \beta = 1, \end{cases}$$

where $\tilde{W_O}$ is the wealth position of the operator and β is the risk averse coefficient which determines the curvature of the utility function reflecting the operator's attitude towards risk.

A concave function has a positive first derivative

$$u'(W_O) = W_O^{-\beta} > 0$$

and a negative second derivative.

$$u''(W_O) = -\beta W_O^{-\beta-1} < 0.$$

Despite the curvature of a function is contained in its second derivative. It is not invariant to positive linear transformations of the utility function. Invariance to an affine transformation is an essential property of the Von Neuman Morgansten utility function. The Arrow and Pratt's measure of risk-aversion is widely used instead because it remains the same even after an affine transformation of the utility function.

The third and fourth derivatives of the CRRA utility function are

$$u'''(W_O) = \beta\,(\beta+1)\,W_O^{-\beta-2} > 0$$

and

$$u''''(W_O) = -\beta\,(\beta+1)\,(\beta+2)\,W_O^{-\beta-3} < 0.$$

Observe that stakeholders whose preferences are represented by a CRRA utility function like positive skewness and dislike positive kurtosis.

The Arrow and Pratt's measure of CRRA is to divide the second derivative

$$u''(W_O(T,D)) = \beta W_O^{-\beta-1}$$

by the first derivative

$$u'(W_O) = W_O^{-\beta}.$$

However, this would give us a negative number as a risk-averse person's measure. As the utility funtion must be increasing with the payoff and must have a positive first derivative because of the property of monotonicity, the sign is changed, so that a larger number indicates a more risk-averse consumer.

Given this, the Arrow and Pratt's measure of CRRA takes the form

$$\beta = -W_O \frac{\beta W_O^{-\beta-1}}{W_O^{-\beta}}. \tag{4.14}$$

When $\beta > 1$, the utility level is bounded from above, but not below. Nonetheless, when $\beta < 1$ the utility level is bounded below, but not above. In the logarithmic case, when $\beta = 1$ the utility level is neither bounded above or below.

4.3.1 Optimal risk regulatory policy risk aversion

In this case, a risk-averse operator is concerned about the expectation and the variance of the payoff. When an operator is averse to risk, the utility of his payoff is larger that expectation of the utility of his payoff.

$$u(E[\tilde{W_O}]) > E[u(\tilde{W_O})].$$

The amount of money that yields the same utility that the expected utility of the payoff is called certainty equivalent (CE), that is

$$u(CE) = E[u(\tilde{W_O})].$$

A CE makes the operator indifferent between a payoff with uncertainty and a certain payment. CE can be defined as a sure money metric measure of utility and can be formulated as

$$CE = u^{-1}(E[u(\tilde{W_O})]).$$

In order to encourage the operator to bear some risk associated with the uncertainty of the payoff, the operator has to receive a rent to compensate for the risk taken. We may define this rent as the risk premium ρ that increases with $\bar{D}$. The risk premium is the minimum amount of money by which the expected payoff must exceed the payoff without uncertainty in order to induce the operator to bear the risk of the project. The risk premium is mathematically formulated as the expectation of the payoff minus the certainty equivalent

$$\rho(\tilde{W_O}) = E[\tilde{W_O}] - CE(\tilde{W_O}).$$

The participation constraint of the operator is defined as

$$\begin{aligned} E[u(\tilde{W_O})] &\geq u_0 \qquad \text{where} \qquad u(p_0) = u_0 \\ \Leftrightarrow CE(\tilde{W_O}) &\geq p_0 \\ \Leftrightarrow E[\tilde{W_O}] - \rho(\tilde{W_O}) &\geq p_0 \\ \Leftrightarrow E[\tilde{W_O}] &\geq p_0 + \rho(\tilde{W_O}). \end{aligned}$$

Therefore, in order to satisfy the participation constraint, the operator's expected payoff needs to be at least as large as the sum of the mark up and a risk premium.

As the CRRA utility function is infinitely often differentiable and defined in the region near $E[\tilde{W_O}]$, the utility function $u(\tilde{W_O})$ can be approximated by using a finite number of terms of its Taylor series $T_M(\tilde{W_O}, u)$.

$$u(W_O) \simeq T_M(W_O, u).$$

This expression can be written in the more compact sigma notation as

$$T_M(W_O, u) = \sum_{m=1}^{M} \frac{u^m(E[\tilde{W_O}])}{m!}(W_O - E[\tilde{W_O}])^m.$$

The derivative of the function $u^{(m)}(E[\tilde{W_O}])$ is given by

$$u^{(m)}(E[\tilde{W_O}]) = (-\beta)^m \beta(\beta+1)...(\beta+m-1)E[\tilde{W_O}]^{1-\beta-m}, \qquad m = 0, 1, ...$$

Using the Taylor expansion of order M with respect to $\tilde{W_O}$ around $E[\tilde{W_O}]$. The expected utility takes the form

$$E[u(\tilde{W_O})] = \sum_{m=1}^{M} \frac{u^{(m)}(E[\tilde{W_O}])}{m!} E[(\tilde{W_O} - E[\tilde{W_O}])^m].$$

The total initial wealth position of the operator $\tilde{W_O}$ can be defined as

$$\tilde{W_O} = (T - \varphi(k) - \delta_f b(\tilde{h} - a(k))_+ + A_0)_+,$$

where A_0 is the assets of the operator before entering the project and guarantees that the total initial wealth of the operator remains positive for any realization of $\tilde{h}$. $T - \varphi(k) - b(\tilde{h} - a(k))_+$ is the payoff of the operator and $b(\tilde{h} - a(k))_+$ is the fine $\tilde{F}$ that is equal to the damage cost $\tilde{F} = \tilde{D}$. The height of the sea defence a is a function of k.

The expected wealth position of the operator $E[\tilde{W_O}]$ is

$$E[\tilde{W_O}] = \int_0^{\infty} (T - \varphi(k) - \delta_f b(h - a(k))_+ + A_0)_+ f(h) dh.$$

The operator's optimization problem is the choice of the safety design parameter $k \geq 0$ that maximizes its expected utility.

$$max_{(k \geq 0)} E[u(\tilde{W_O})].$$

A solution to the optimization problem is

$$k^*_{ra} = k^*_{ra}(\delta_f).$$

An optimal k^*_{ra} induces a sea defence, that is

$$a^*_{ra} = a(k^*_{ra}).$$

In this setting, it is assumed that the society also has risk aversion to uncertain payoffs. Thus, the utility of the regulator is presented as

$$u(\tilde{W_S}, \tilde{W_O}) = u(\tilde{W_S}) + \alpha_R u(\tilde{W_O}). \tag{4.15}$$

The utility function of the society is the same as the operator's CRRA function and has the same risk coefficient

$$u(\tilde{W_S}) = \frac{(\tilde{W_S})^{1-\beta}}{1-\beta}. \tag{4.16}$$

As previously, using the Taylor expansion of order M with respect to $\tilde{W_R}$ around $E[\tilde{W_R}]$. The expected utility of the society takes the form

$$E[u(\tilde{W_S})] = \sum_{m=0}^{M} \frac{u^{(m)}(E[\tilde{W_S}])}{m!} E[(\tilde{W_S} - E[\tilde{W_S}])^m].$$

The total initial wealth position of the society $\tilde{W_S}$ can be defined as

$$\tilde{W_S} = S - T - (1-\delta_f)b(\tilde{h} - a(k))_+.$$

The expected wealth position of the society $E[\tilde{W_S}]$ is

$$E[\tilde{W_S}] = \int_0^{h_{max}} S - T - (1-\delta_f)b(h - a(k))_+ f(h)dh.$$

The regulator's optimization problem is the choice of the fine parameter δ_f that maximizes its expected utility.

$$max_{(T,\delta_f)} E[u_R(\tilde{W_S}, \tilde{W_O})].$$

The solution of the regulator's optimization problem is an optimal cap δ_f^* where

$$k_{ra}^{**} = k_{ra}^{**}(\delta_f^*) \qquad \text{and} \qquad a_{ra}^{**} = a(k_{ra}^{**}(\delta_f^*)).$$

The regulator sets a transfer payment T_{ra} for the operator, that is

$$T_{ra}^* = \varphi(k_{ra}^{**}) + E[D(\tilde{h}, ara^{**})] + p_0 + \rho(\tilde{W_O}), \tag{4.17}$$

where $\varphi(k_{ra}^{**})$ is the cost of implementing the social optimum k_{ra}^{**}, $E[D(\tilde{h}, a^{**})]$ is the expected fine and p_0 is the mark up or the operator's assets and $\rho(\tilde{W_O})$ is the risk premium. The operator accepts the second best transfer payment which is the minimum payment that satisfies her participation constraint. This implies that the expected payoff of the operator is

$$E[\tilde{W_O}(T_{ra}^*, \delta_f^*)] = p_0 + \rho(\tilde{W_O}).$$

Summarising, we obtain the following result.

Theorem 3 *The optimal regulatory policy under asymmetric information, risk neutrality and full liability is determined by the optimal fine δ_f^*, the optimal payment transfer T^*, and the optimal safety design parameter k^{**}.*

1. *The regulator sets a fine equal to damage cost, that is $\delta_f^* = 1$.*

2. *The operator finds it optimal to implement the socially optimal safety design parameter k^{**}, so that*

$$k_{ra}^{**} = k_{ra}^*(1).$$

   The socially optimal sea defence is implemented, that is

$$a_{ra}^{**} = a_{ra}(k^{**}).$$

3. *The optimal transfer payment T^* set by the regulator is equivalent to the sum of the cost of implementing the safety design parameter, the expected fine and the markup, so that*

$$T_{ra}^* = \varphi(k_{ra}^{**}) + E[D(\tilde{h}, a_{ra}^{**})] + p_0 + \rho(\tilde{W_O}(\tilde{h}, a_{ra}^{**})). \tag{4.18}$$

4.3.2 Example

The decision problem of the operator is to choose a safety design parameter k^* that maximizes her utility function and minimizes the cost of implementing the sea defence. In this setting, it is assumed that society and the operator share the same risk averse coefficient, that is $\beta = 0.7$. An optimal solution to the optimization problem of the operator is presented in Fig.4.9 where the x-axis represents the height of the sea defence implemented by the operator and the y-axis represents the expected utility of the operator.

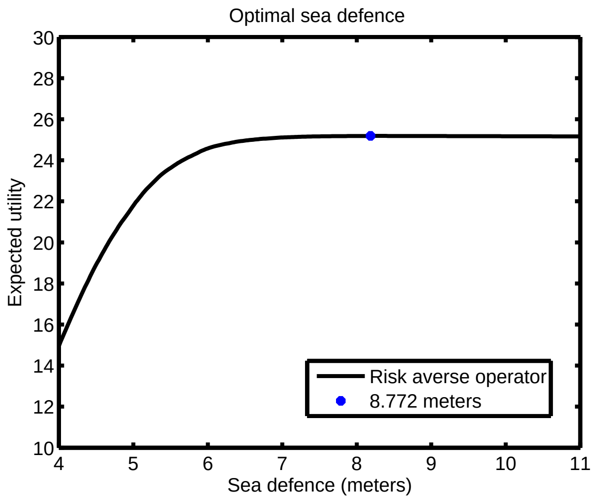

Figure 4.9: Operator's optimal sea defence under risk aversion when $\delta_f = 1$.

Given that $\delta_f = 1$, Fig. 4.9 shows that the operator will choose a safety design parameter, that is

$$k^*_{ra}(\delta_f) = 5.160.$$

This implies that the sea defence will have a height of

$$a^*_{ra} = a_0 k^*_{ra}(\delta_f) = 8.772\,\mathrm{m}\,.$$

The optimal sea defence satisfies the incentive constraint of the operator.

By comparing the optimal choice of the safety design parameter of the operator under risk aversion and under risk neutrality, we observe that the decreasing marginal utility of the damage cost enhances the strength of the incentive inducing the operator to implement a higher sea defence to make up for the loss of payoff. This is presented in Fig. 4.10.

Given that the optimal sea defence chosen by the operator is $a^*_{ra} = 7.310\,\mathrm{m}$, the regulator's decision problem is to choose (1) an fine parameter δ_f that induces the operator to implement the height of the sea defence that is socially optimum and (2) a minimum transfer payment T_{ra} that satisfies the participation of the operator.

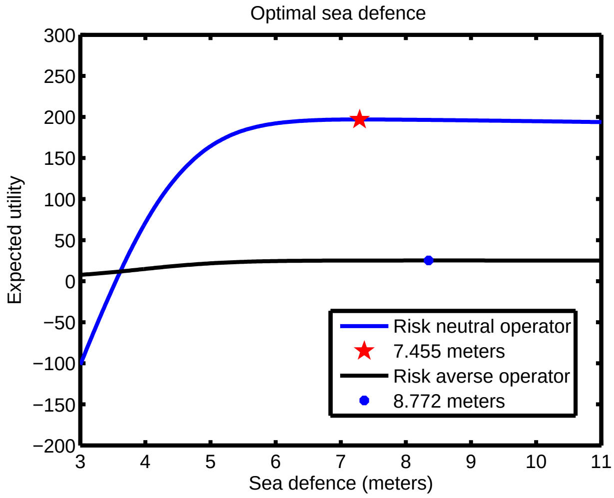

Figure 4.10: Optimal sea defence of a risk averse and a risk neutral operator.

The optimal safety design parameter of the regulator is presented in Fig. 4.11 where the x-axis represents the height of the sea defence implemented by the operator and the y-axis represents the payoff of the regulator.

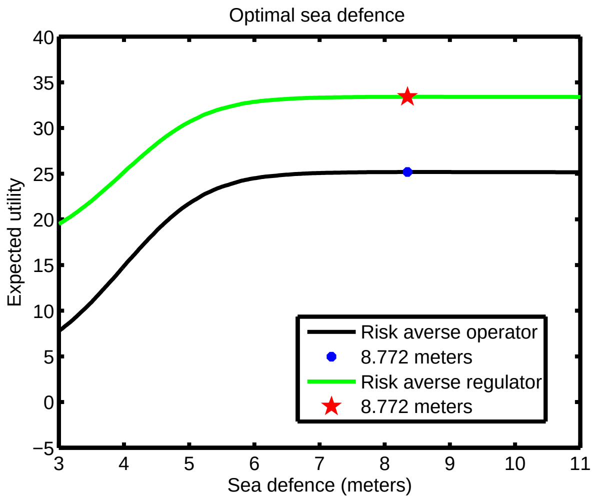

Figure 4.11: Optimal sea defence of a risk averse operator and the risk averse regulator.

Observe that the optimal choice of the safety design parameter of the regulator is the same as the operator's optimal sea defence, that is

$$k_{ra}^{**} = k_{ra}^{*} = 5.160.$$

Therefore, following the linear relationship between the safety design parameter and the height of the sea defence the operator will implement a height of the sea defence, that is

$$a_0 k_{ra}^{**} = a_0 k_{ra}^{*} = 8.772\,\mathrm{m}\,.$$

This numerical result implies that the regulator chooses a fine parameter $\delta_f = 1$ under the assumption that the society's and the operator's preference are represented by a power utility function.

The implementation of a sea defence of a height of $a^*_{ra} = 8.772\,\text{m}$ considerably reduces the residual risk of the engineering project compared to the risk neutrality case. The residual risk in the risk averse case is presented in Fig. 4.12 where the x-axis represents the height of the sea defence and the y-axis represents the probability that the run up will exceed the sea defence.

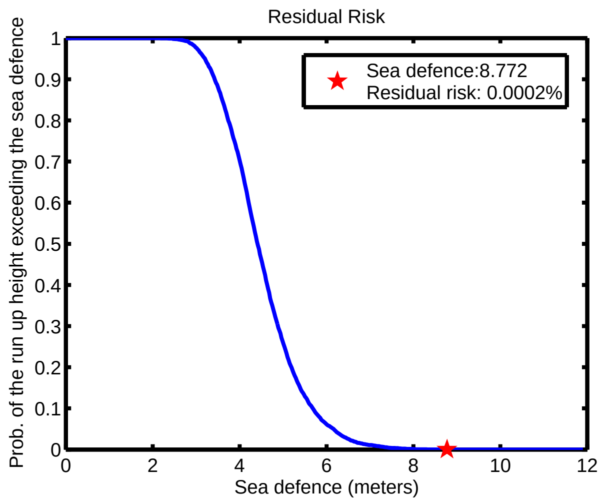

Figure 4.12: Residual risk under risk aversion.

Fig.12 indicates that the residual risk under risk aversion is much lower than under risk neutrality

$$a^{**}_{ra} = 8.772\,\text{m.} \Rightarrow 0.002\% \qquad \text{and} \qquad a^{**} = 7.455\,\text{m.} \Rightarrow 0.38\% \qquad \text{(Residual risk).}$$

A low residual risk also implies a higher cost to the society. Given that the regulator has set a fine equal to damage cost, the optimal transfer payment to the operator has to guarantee that the expected payoff of the operator is at least as large as the risk premium $\rho(\tilde{W}_O)$ and the mark up p_0. The numerical solution is presented in Fig. 4.16 where the x-axis represents the height of the sea defence implemented by the operator and the y-axis represents the transfer payment in million euros to the operator.

The numerical solution in Fig. 4.16 shows that the regulator under risk aversion chooses a transfer payment, that is

$$T^*_{ra} = 34.17\,\text{million}\,€.$$

Note that the transfer payment under risk aversion is approximate the transfer payment under risk neutrality as shown in Fig 6

$$T^*_{ra} \approx T^* = 33.25\,\text{million}\,€.$$

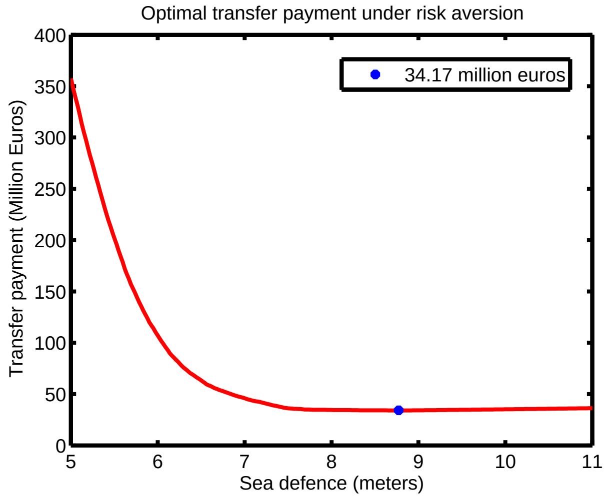

Figure 4.13: Optimal transfer payment under risk aversion when $\delta_f = 1$.

Similar to the risk neutrality case, the transfer payment T^*_{ra} is the minimum amount of money that the operator will accept to take on the construction of the sea defence.

Chapter 5

Delegation regulatory policy

Let us consider a pro-operator regulator who is better informed than the government with regard to the damage cost in case of flooding. Due to this informational asymmetry the regulator can manipulate the cost parameter in the damage cost function to benefit the operator at the expense of the society. In order to remove this incentive, the government can either impose a fixed transfer payment or restrict the range of payments that the regulator can transfer to the operator.

5.1 No discretion - rigid policy

In this case, a regulator is not granted any authority and the government sets a cap of the fine $\bar{D}$ that determines the transfer payment to the operator $T(\bar{D})$. We assume that the society and the operator have a neutral attitude to risk and that the operator has limited liability.

Let $\tilde{F} = min\{\tilde{D}, \bar{D}\}$ and $\tilde{D} = b(\tilde{h} - a(k))^+$. As before, $\tilde{h}$ is the height of the run up but the operator is fined only up to an upper bound $\bar{D}$ and $a(k)$ is the height of the sea defence built by the operator. The cost parameter b is common knowledge for the regulator and the operator but not for the government.

The operator's payoff function is again

$$\tilde{P_O} = T - \varphi(k) - min\{b(\tilde{h} - a(k))^+, \bar{D}\}. \tag{5.1}$$

The operator's expected payoff is

$$E[\tilde{P_O}] = T - \varphi(k) - E[min\{b(\tilde{h} - a(k))^+, \bar{D}\}]. \tag{5.2}$$

In light of this, the operator's optimization problem is the choice of the safety design parameter $k \geq 0$ and takes the form

$$max_{(k\geq 0)}\Big(T - \varphi(k) - \int_{a(k)}^{\infty} min\{b(\tilde{h} - a(k)), \bar{D}\}f(h)dh\Big). \tag{5.3a}$$

The solution is obtained from the first order condition for an optimal k^*_{ll} which takes the form

$$Prob(a^*_{ll} \leq \tilde{h} \leq a^*_{ll} + \frac{\bar{D}}{b}) = \frac{\varphi'(k^*_{ll})}{ba'(k^*_{ll})}, \tag{5.3b}$$

where

$$a_{ll}^* = a(k_{ll}^*).$$

Thus, an operator's optimal safety design parameter under a rigid rule is a function of $\bar{D}$, such that

$$k_{ll}^* = k_{ll}^*(\bar{D}).$$

We again require that

$$\tilde{P_O} \geq p_0 \qquad \text{(Participation constraint)}, \tag{5.4}$$

where p_0 is the value of assets that the operator is able to use to cover excess damage cost. If k_{ll}^* is implemented then

$$P_O(T, \bar{D}) = T - \varphi(k_{ll}^*) - min\{b(\tilde{h} - a_{ll}^*)^+, \bar{D}\} \qquad \text{for all } \tilde{h}.$$

Observe that

$$P_O(T, \bar{D}) \geq T - \varphi(k_{ll}^*) - \bar{D},$$

so that the limited liability constraint is satisfied whenever

$$T \geq T_{ll}^* = \varphi(k_{ll}^*) + \bar{D} + p_0.$$

Observe that T_{ll}^* is the minimum transfer payment that satisfies the operator's participation constraint because k_{ll}^* is a function of $\bar{D}$.

This implies that the expected payoff of the operator is

$$E[\tilde{P_O}(T_{ll}^*, \bar{D})] = p_0 + \bar{D} - E[min\{\tilde{b}(\tilde{h} - a_{ll}^*)^+, \bar{D}\}].$$

The government does not observe the true cost parameter b. Therefore, it models the uncertain cost parameter as a random variable $\tilde{b}$ taking values in the interval $[\underline{b}, \bar{b}]$ and distributed according to a probability distribution function $g(b)$. The government's expected payoff is

$$E[\tilde{P_G}(k, \bar{D})] = S - \varphi(k) - E[\tilde{b}(\tilde{h} - a(k))^+] - (1 - \alpha_P)E[\mathcal{R}(k, \bar{D})], \tag{5.5}$$

with

$$E[\tilde{b}(\tilde{h} - a)^+] = \int_{\underline{b}}^{\bar{b}} \int_{a(k)}^{\infty} b(h - a(k))g(b)f(h)dbdh$$

and

$$E[\mathcal{R}(k, \bar{D})] = \bar{D} - \int_{\underline{b}}^{\bar{b}} \int_{a(k)}^{\infty} min\{\tilde{b}(\tilde{h} - a(k)), \bar{D}\}g(b)f(h)dbdh + p_0.$$

Taking into account the optimal response of the operator, the government's expected payoff takes the form

$$\begin{aligned} E[\tilde{P_G}] = S - \varphi(k_{ll}^*(\bar{D})) - \int_{\underline{b}}^{\bar{b}} \int_{a(k_{ll}^*(\bar{D}))}^{\infty} b(h - a(k_{ll}^*(\bar{D}))g(b)f(h)dhdb \\ - (1 - \alpha_G)\left[\bar{D} - \int_{\underline{b}}^{\bar{b}} \int_{a(k_{ll}^*(\bar{D}))}^{\infty} min\{b(h - a(k_{ll}^*(\bar{D})), \bar{D}\}g(b)f(h)dhdb + p_0\right]. \end{aligned} \tag{5.6}$$

The government's decision problem for the rigid rule is now the choice of the fine cap $\bar{D}$ that maximizes the expected payoff

$$max_{(\bar{D})} E[P_G(k_{ll}^*(\bar{D}), \bar{D})]. \tag{5.7}$$

The solution of the government's optimization problem is an optimal fine cap $\bar{D}_{rig}^*$, where

$$k_{rig}^* = k_{rig}^*(\bar{D}_{rig}^*) \quad \text{and} \quad a_{rig}^*(k_{rig}^*).$$

k_{rig}^* is the socially optimal safety design parameter and a_{rig}^* is the optimal sea defence under the rigid rule with limited liability for the operator. Observe that both values k_{rig}^* and a_{rig}^* are influenced by the government's weight α_G which reflects the importance that the government attaches to the operator's payoff. The optimal transfer payment is a function of $\bar{D}_{rig}^*$ and takes the form

$$T_{rig}^* = \varphi(k_{rig}^*) + \bar{D}_{rig}^* + p_0. \tag{5.8}$$

This implies that the expected payoff of the operator is

$$E[\tilde{P_O}(\bar{D}_{rig}^*)] = p_0 + \bar{D}_{rig}^* - E[min\{b(\tilde{h} - a(k_{rig}^*))^+, \bar{D}_{rig}^*\}].$$

Under a rigid policy, the regulator will be left without discretion to use its bias or its expert information. The benefit of this rigid policy is that the rent/efficiency trade-off is evaluated in line with the government's choice of the fine cap.

Summarising, we obtain the following results

Theorem 4 *The non-discretionary policy corresponds to the ex ante rule that would be chosen by the parliament without any expert information and is determined by the parliament's optimal fine cap $\bar{D}_{rig}^*$, the optimal payment transfer T_{rig}^*, and the optimal safety design parameter $k_{rig}^*(\bar{D}_{rig}^*)$.*

1. *The parliament sets a fine cap $\bar{D}_{rig}^*$.*

2. *The operator finds optimal to implement the safety design parameter, that is*

$$k_{rig}^* = k_{rig}^*(\bar{D}_{rig}^*).$$

The optimal parliament's sea defence is implemented, that is

$$a_{rig}^* = a(k_{rig}^*).$$

3. *The optimal transfer is set by the parliament is the sum of the cost of implementing the optimal safety design parameter, the optimal cap of the fine, and the markup.*

$$T_{rig}^* = \varphi(k_{rig}^*(\bar{D}_{rig}^*)) + \bar{D}_{rig}^* + p_0.$$

5.1.1 Example

The government's decision problem of setting a cap to the operator's fine $\bar{D}$ is presented in Fig. 5.1 where the x-axis represents the cap on the operator's fine in million euros and the y-axis represents the expected payoff of the government.

The cap of the fine that maximizes the government's payoff in this convex optimization numerical example is

$$\bar{D}^*_{rig} = 279.6\,\text{million}\,€.$$

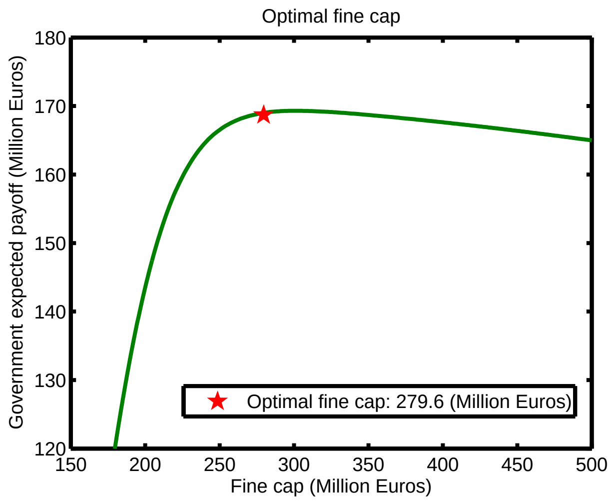

Figure 5.1: Government's optimal cap of the fine under a rigid rule.

.

The operator's reaction to the optimal cap $\bar{D}^*_{rig} = 279.6\,\text{million}\,€$ imposed by the government is to choose a safety design parameter that maximizes her expected payoff as shown in Fig 5.2 where the x-axis represents the height of the sea defence and the y-axis represents the expected payoff of the operator.

Fig 5.2 shows that the optimal safety design parameter chosen by the operator in this numerical example is

$$k^*_{rig}(279.6) = 4.357.$$

A safety design parameter k^*_{rig} corresponds to the a height of the sea defence, that is

$$a^*_{rig}(279.6) = 7.408\,\text{m}.$$

By comparing the optimal choice of the height of the sea defence of the operator in Fig 5.2 and the optimal choice of the height of the sea defence of the government in Fig 5.3 where the x-axis represents the height of the sea defence and the y-axis the expected payoff of the government, we observe that the optimal choice of the operator is lower than the optimal choice of the government, that is

$$Operator : a^*_{rig} = 7.408\,\text{m} < Government : a^*_{rig} = 7.596\,\text{m}.$$

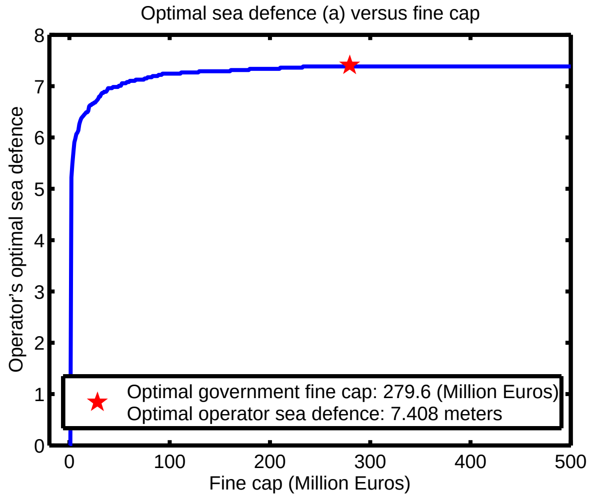

Figure 5.2: Operator's optimal sea defence induced by the government's fine cap.

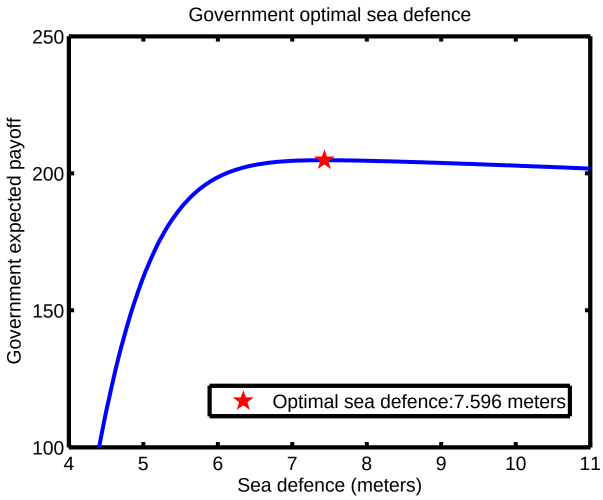

Figure 5.3: Government's optimal sea defence.

.

The implementation of a sea defence of 7.408 m height leaves some residual risk. The probability that the run up height will exceed a sea defence of 7.408 m is shown in Fig 5.4.

By comparison, the residual risk associated with the implementation of the sea defence a^*_{rig} under a rigid rule is higher than the residual risk when the sea defence a^{**}_{ll} is implemented under limited liability, that is

$$a^*_{rig} = 7.408\,\text{m.} \Rightarrow 0.42\% \qquad \text{and} \qquad a^{**}_{ll} = 7.432\,\text{m.} \Rightarrow 0.40\% \qquad \text{(Residual risk).}$$

As we decrease the residual risk, the cost to the society increases. This is because the transfer payment increases with the cap of the fine $T(\bar{D}^*_{rig})$ and the residual risk decreases as the fine cap increases.

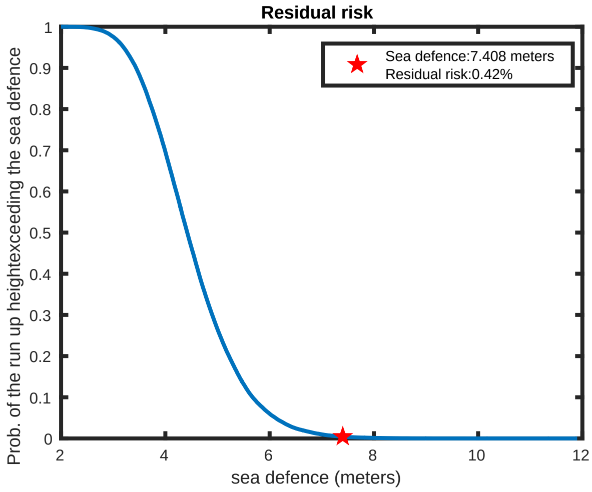

Figure 5.4: Residual risk under a rigid rule.

.

The transfer payment is a function of the fine cap. Under a rigid rule, the society pays a higher transfer payment than under limited liability liability. This is because the difference between α_G and α_R outweigh the difference between the expectation of the cost parameter $\tilde{b}$ and the true value of the cost parameter b.

$$T^*_{rig}(\bar{D}^*_{rig}) = 317.83\,\text{million}\,€ \qquad \text{and} \qquad T^*_{ll} = 329.26\,\text{million}\,€.$$

5.2 Limited discretion to the regulator

In this case, the government restricts the range of payments that the regulator can transfer to the operator. As in the previous case, we assume that the society and the operator have a neutral attitude to risk and that the operator has limited liability.

The regulator's expected payoff is

$$E[\tilde{P_R}(k^*_{ll}(\bar{D}_{reg}), \bar{D}_{reg})] = S - \varphi(k^*_{ll}(\bar{D}_{reg})) - E[b(h - a(k^*_{ll}(\bar{D}_{reg})))^+] - (1-\alpha_R)\mathcal{R}(k^*_{ll}(\bar{D}_{reg}), \bar{D}_{reg}) \quad (5.9)$$

where the expected damage cost is

$$E[b(\tilde{h} - a(k^*_{ll}\bar{D}_{reg}))^+] = \int_{a(k^*_{ll}(\bar{D}_{reg}))}^{\infty} b(h - a(k^*_{ll}(\bar{D}_{reg})))f(h)dh$$

and the liability rent is

$$\mathcal{R}(k^*_{ll}(\bar{D}_{reg}), \bar{D}_{reg}) = \bar{D}_{reg} - \int_{a(k^*_{ll}(\bar{D}_{reg}))}^{\infty} min\{b(h - a(k^*_{ll}(\bar{D}_{reg}))), \bar{D}_{reg}\}f(h)dh + p_0.$$

Therefore, the regulator's payoff function can we rewritten as

$$E[\tilde{P_R}(k_{ll}^*(\bar{D}_{reg}), \bar{D}_{reg})] = S - \varphi(k_{ll}^*(\bar{D}_{reg})) - \int_{a(k_{ll}^*(\bar{D}_{reg}))}^{\infty} b(h - a(k_{ll}^*(\bar{D}_{reg})))f(h)dh$$

$$- (1 - \alpha_R)\left[\bar{D}_{reg} - \int_{a(k_{ll}^*(\bar{D}_{reg}))}^{\infty} min\{b(h - a(k_{ll}^*(\bar{D}_{reg}))), \bar{D}_{reg}\}f(h)dh + p_0\right]. \quad (5.10)$$

The regulator's decision problem is the choice of the fine cap that maximizes her expected payoff. The regulator's optimization problem takes the form

$$max_{(\bar{D}_{reg} \geq 0)}[\tilde{P_R}(\bar{D}_{reg})]. \quad (5.11)$$

The solution to the regulator's optimization problem is an optimal fine cap $\bar{D}_{reg}^*(b)$ and is obtained from the first order condition which takes the form

$$Prob(\tilde{h} \geq a_{ll}^{**}) - \frac{\varphi'(k_{ll}^{**})}{ba'(k_{ll}^{**})} = (1-\alpha_R)\frac{Prob(h \leq a_{ll}^{**} + \frac{\bar{D}_{reg}^*}{b})}{ba'(k_{ll}^{**})\frac{\partial k_{ll}^*}{\partial \bar{D}_{reg}^*}(b, \bar{D}_{reg}^*)} + Prob(0 \leq \tilde{h} - a_{ll}^{**} \leq \frac{\bar{D}_{reg}^*}{b}). \quad (5.12)$$

The socially optimal safety design parameter is $k_{ll}^{**} = k_{ll}^{**}(\bar{D}_{reg}^*)$ and the optimal sea defence is $a_{ll}^{**} = a(k_{ll}^{**})$. Observe that the optimal fine cap $\bar{D}_{reg}^*$ depends on the cost parameter b. This implies that restricting the cost parameter the government also restricts the cap of the fine and, consequently the transfer payment to the operator.

Incentive compatibility for truth telling

When the regulator finds more beneficial to announce a cost parameter $\hat{b}$ that is equal to the true value of the cost parameter b, the operator's choice of the safety design parameter $k_{ll}^*(\bar{D}_{reg}^*) = k_{ll}^*(\bar{D}_{reg}^*(b))$ can be regarded as incentive compatible because it will achieve the highest payoff for the regulator. On the contrary, if the regulator has incentives to manipulate the cost parameter in order to increase its payoff, the safety design parameter $k_{ll}^*(\bar{D}_{reg}^*(b))$ is not incentive compatible. The conditions for the safety design parameter $k_{ll}^*(\bar{D}_{reg}^*(b))$ to be an incentive compatible mechanism are the truth telling condition and the monotonicity condition.

1. Truth telling condition

   The choice of the safety design parameter $k_{ll}^*(D_{reg}^*(\hat{b}))$ induced by the regulator's announcement of the cost parameter $\hat{b}$ yields the following payoff for the regulator

$$E[\tilde{P_R}(\hat{b}, b)] = S - \varphi(k_{ll}^*(D_{reg}^*(\hat{b}))) - \int_{a(k_{ll}^*(D_{reg}^*(\hat{b})))}^{\infty} b(h - a(k_{ll}^*(D_{reg}^*(\hat{b}))))^+ f(h)dh -$$

$$(1-\alpha_R)(D_{reg}^*(\hat{b}) - \int_{a(k_{ll}^*(D_{reg}^*(\hat{b})))}^{\infty} min\{b(\tilde{h} - a(k_{ll}^*(D_{reg}^*(\hat{b}))), D_{reg}^*(\hat{b})\}f(h)dh + p_0). \quad (5.13)$$

The incentive compatibility constraints that are necessary to induce truth telling by the regulator can thus be written as

$$b \in argmax_{\hat{b}\in\mathcal{B}} E[\tilde{P_R}(\hat{b}, b)]. \tag{5.14}$$

The first order necessary conditions for truth telling to be the regulator's most profitable choice is:

$$\frac{\partial E[\tilde{P_R}(b, b)]}{\partial \hat{b}} = 0, \qquad\qquad \forall b \in \mathcal{B}.$$

This is clear an identity in b.

2. The monotonicity condition can be written as

$$\frac{dk^*_{ll}(D^*_{reg}(b))}{d\hat{b}} \geq 0. \tag{5.15}$$

The monotonicity condition implies that, as the cost parameter b increases, the operator's safety design parameter $k^*_{ll}(D^*_{reg}(b))$ weakly increases and thus almost differentiable with, at any point of differentiability.

Given that the government's expected payoff is a function of the cost parameter announced by the regulator as shown in Eq. 5.17.

$$\begin{aligned} E[\tilde{P_G}(k^*_{ll}(\bar{D}^*_{reg}(\hat{b})), \bar{D}^*_{reg}(\hat{b}))] = S - \varphi(k^*_{ll}(\bar{D}^*_{reg})) - E[\tilde{b}(\tilde{h} - a(k^*_{ll}(\bar{D}^*_{reg}))^+] \\ - (1-\alpha_G)\mathcal{R}(k^*_{ll}(\bar{D}^*_{reg}), \bar{D}^*_{reg}). \end{aligned} \tag{5.16}$$

Observe that when the regulator announces the true cost parameter $\hat{b} = b$, the optimal safety design parameter $k^*_{ll}(\bar{D}^*_{reg}(\hat{b}))$ is not incentive compatible. This is because the first order condition of Eq. 5.18 with respect to the cost parameter that the regulator can announce is greater than 0.

$$\frac{\partial}{\partial \hat{b}} E[P_G(k^*_{ll}(\bar{D}^*_{reg}), \bar{D}^*_{reg})]\bigg|_{\hat{b}=b} > 0 \tag{5.17}$$

This loss of efficiency is as result of the difference between the regulator's weight α_R and the government's weight α_G allocated to the liability rent of the operator. This difference is $\triangle\alpha = \alpha_R - \alpha_G > 0$.

In order to account for the incentive of the regulator to announce a higher cost parameter, the government can restrict the level of discretion of the regulator. This restriction takes the form of a cap on the range of cost parameters that the regulator can announce. The optimal cap of the cost parameter limits from above the number of feasible height of sea defences that the regulator can induce the operator to implement and, consequently the payments to be transferred to the operator.

Characterization of the mechanism

As the transfer payment is a function of the fine cap and the fine cap depends on the cost parameter b, the government must restrict the set of feasible transfer payments available to the regulator by setting a cap b^* and a floor b_* on the cost parameter that the regulator can announce $\hat{b}$.

More formally, the characterization of the restriction of possible cost parameters takes the form

$$\bar{D}^*_{reg}(\hat{b}, b_*, b^*) = \begin{cases} \bar{D}^*_{reg}(b_*) & \hat{b} \leq b_* \\ \bar{D}^*_{reg}(\hat{b}) & b_* \leq \hat{b} \leq b^* \\ \bar{D}^*_{reg}(b^*) & \hat{b} \geq b^*. \end{cases} \tag{5.18}$$

By restricting the interval of the cost parameter $\hat{b}$, the government restricts the regulator's optimal fine cap to the interval $\bar{D}^*_{reg} \in [\bar{D}^*_{reg}(b_*), \bar{D}^*_{reg}(b^*)]$. Within the interval $b^* \leq \hat{b} \leq b_*$, however, the regulator has full discretion in setting up transfer payments in accordance to its own announcement of the cost parameter $\hat{b}$.

By restricting the regulator's response to $\bar{D}^*_{reg}(\hat{b}, b_*, b^*)$, the government's expected payoff function takes the form

$$E[\tilde{P_G}(k^*_{ll}(\bar{D}^*_{reg}), \bar{D}^*_{reg})] = S - \varphi(k^*_{ll}(\bar{D}^*_{reg})) - E[\tilde{b}(\tilde{h} - a(k^*_{ll}(\bar{D}^*_{reg})))^+] - (1 - \alpha_G)E[\mathcal{R}(k^*_{ll}(\bar{D}^*_{reg}), \bar{D}^*_{reg})], \tag{5.19}$$

where $\bar{D}^*_{reg} = \bar{D}^*_{reg}(\hat{b}, b_*, b^*)$.

However, as it shown in Eq. 5.19, it is not necessary to set a floor b_* because the regulator has only an incentive to overstate the cost parameter b.

Optimization problem of the government

Despite the government does not observe the true value of the cost parameter b, the range of values that the cost parameter can take is common knowledge. The government thus models the cost parameter as a random variable $\tilde{b}$ taking values in the interval $[b_*, b^*]$ and distributed according to a probability density function $g(b)$.

Simplifying the notation, the government's expected payoff is now

$$E[\tilde{P_G}(\bar{D}^*_{reg}(\tilde{b}, b^*))] = S - \varphi(k^*_{ll}(\bar{D}^*_{reg}(\tilde{b}, b^*))) - E[\tilde{b}(\tilde{h} - a(k^*_{ll}(\bar{D}^*_{reg}(\tilde{b}, b^*))))^+] - (1 - \alpha_G)E[\mathcal{R}(k^*_{ll}(\bar{D}^*_{reg}(\tilde{b}, b^*)), \bar{D}^*_{reg}(\tilde{b}, b^*))], \tag{5.20}$$

where the expected damage is of the form

$$E[\tilde{b}(\tilde{h} - a(k^*_{ll}(\bar{D}^*_{reg}(\tilde{b}, b^*))))^+] = \int_{\underline{b}}^{\bar{b}} \int_{a(k^*_{ll}(\bar{D}^*_{reg}(\tilde{b}, b^*)))}^{\infty} b(h - a(k^*_{ll}(\bar{D}^*_{reg}(\tilde{b}, b^*)))g(b)f(h)dhdb$$

and the liability rent is

$$E[\mathcal{R}(k^*_{ll}(\bar{D}^*_{reg}(\tilde{b},b^*)),\bar{D}^*_{reg})] =$$
$$\int_{\underline{b}}^{\bar{b}}\Big[\bar{D}^*_{reg}(b,b^*) - \int_{a(k^*_{ll}(\bar{D}^*_{reg}(b,b^*))}^{\infty} min\{b(\tilde{h}-a(k^*_{ll}(\bar{D}^*_{reg}(b,b^*))),\bar{D}^*_{reg}(b,b^*)\}f(h)dh\Big]g(b)db+p_0.$$

The government's decision problem for the limited discretion case is now the choice of the cost parameter cap b^* that maximizes its expected payoff

$$max_{(b^*)}E[\tilde{P_G}(\bar{D}_{reg}(\tilde{b},b^*))]. \tag{5.21}$$

The solution to the government's optimization problem is an optimal cap of the cost parameter b^{**}. Given the government's optimal cap of the cost parameter b^{**} and the regulator's announcement of $\hat{b}$, the optimal safety design parameter and the optimal sea defence are

$$k^*_{ll} = k^*_{ll}(\bar{D}^*_{reg}(\tilde{b},b^{**})) \quad \text{and} \quad a^*_{ll} = a(k^*_{ll}).$$

Theorem 5 *The optimal policy can be characterized as follows:*

- *The optimal fine cap $\bar{D}^*_{reg}$ set by the regulator is not incentive compatible because $\alpha_R > \alpha_G$.*
- *When $\bar{D}^*_{reg}(\alpha_R,\underline{b}) \geq \bar{D}^*_{rig}$, the regulator has no discretion and the government forces the regulator to impose a cap fine $\bar{D}^*_{rig}$ to the operator before the cost parameter b is announced by the regulator. This is ex ante optimal from the parliament's viewpoint (Rigid rule).*
- *When $\bar{D}^*_{reg}(\alpha_R,\underline{b}) \leq \bar{D}^*_{rig}$, the regulator is given some authority to choose the fine cap to impose on the operator but this authority will be restricted to some level depending on how misaligned the objectives of the regulator and government are.*
- *The government restricts the fine cap $\bar{D}^*_{reg}(\alpha_R,b^{**})$ that the regulator can impose on the operator to induce a height of the sea defence $a^*_{ll}(\bar{D}^*_{reg}(\alpha_R,b^{**}))$, where $b^{**}(\alpha_R) \in (b_*,b^*)$ is the unique solution to*

  $$E[b(\tilde{h}-a^*_{ll}(\bar{D}^*_{reg}(\alpha_R,b(\alpha_R))))|b \geq b^{**}) =$$
  $$\varphi'(a^*_{ll}(\bar{D}^*_{reg}(\alpha_R,b^{**}(\alpha_R)))) + (1-\alpha_G)R'(a^*_{ll}(\bar{D}^*_{reg}(\alpha_R,b^{**}(\alpha_R))))$$

  where $\bar{D}^*_{reg}(\alpha_R,b^{**}) \leq \bar{D}^*_{gov}(\alpha_G,\bar{b})$.

5.2.1 Example

The government is facing an asymmetric information problem where it has not experience in understanding the value of the cost parameter b that determines the damage cost output. However, the government has some primary knowledge which enables it to have some believes about the range of possible values of the cost parameter can take $[b_*, b^*]$. The government attaches a probability to each possible value by randomizing over the cost parameter b. In light of this, the cost parameter is modelled as a random variable $\tilde{b}$. It is assumed that the random variable is normally distributed in the interval $[20, 700]$ with parameters $(\mu = 300, \sigma^2 = 0.89)$.

The decision problem to the government starts by evaluating the optimal fine cap in the interval of the cost parameter $[b_*, b^*]$ that maximizes its payoff. The optimal cost parameter b^{**} will determine the level of discretion granted to the regulator in order to impose a fine cap to the operator. This is because the fine cap $\bar{D}^*_{gov}$ is a function of b^{**}. This is presented in Figure 5.5 where the x-axis represents the fine cap in million euros and the y-axis represents the government's expected payoff in million euros.

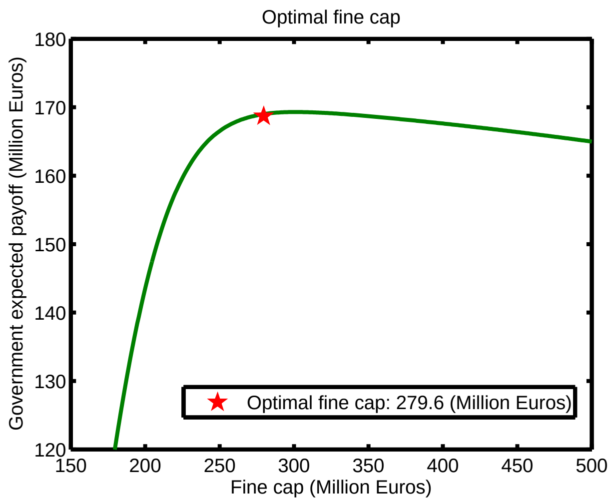

Figure 5.5: Government's optimal fine cap when the government randomizes over the cost parameter $\tilde{b}$.

Fig. 5.5 shows that the government's optimal fine cap when randomizes over b is

$$\bar{D}^*_{gov}(\tilde{b}, b_*, b^*) = 279.6\,\text{million}\,€.$$

The government's optimal sea defence is presented in Fig. 5.6 where the x-axis represents the height of the sea defence and the y-axis represents the government's expected payoff in million euros.

From Fig. 5.6 we can observe that the optimal height of the sea defence takes the value of

$$k^*_{gov}(\tilde{b}, b^*, b_*) = 4.468 \quad \text{and} \quad a^*_{gov} = a(k^*_{gov}) = 7.596\,\text{m}\,.$$

The regulator has privilege information about the cost parameter b that determines the damage cost outcome. Because of the difference in the regulator's and government's weight parameter $\triangle\alpha = \alpha_R - \alpha_G > 0$, the regulator has an incentive to overstate the

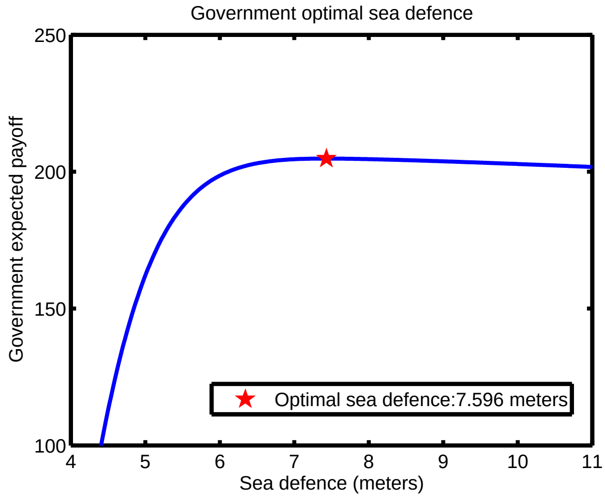

Figure 5.6: Government's optimal sea defence when the government randomizes over the cost parameter $\tilde{b}$.

value of the cost parameter. How much the regulator wants to overstate the value of the cost parameter depends on $\triangle\alpha$. The value of the regulator's weight parameter α_R is 0.80 and the value of the government's weight parameter is α_G is 0.60. These values are common knowledge.

Given that the regulator announces a cost parameter $b = 500$, the regulator chooses the fine cap that maximizes its expected payoff. The solution to the optimization problem is presented in Fig. 5.7 where the x-axis represents the fine cap in million euros and the y-axis represents the expected payoff of the regulator. .

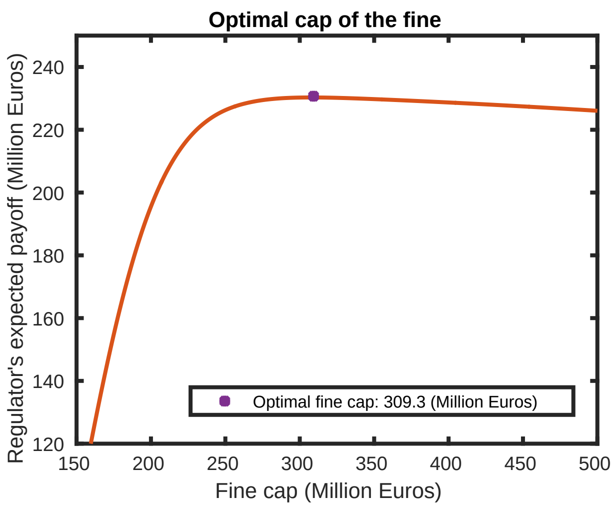

Figure 5.7: Regulator's optimal fine cap when the regulator announces a cost parameter $b = 500$.

As shown in Fig. 5.7, a solution to the regulator's optimization is the choice of an optimal fine cap at

$$\bar{D}^*_{reg}(\tilde{b}, b^*, b_*) = 309.3\,\text{million}\,€.$$

The regulator's optimal sea defence is presented in Fig. 5.8 where the x-axis represents the height of the sea defence and the y-axis represents the regulator's expected payoff in million euros.

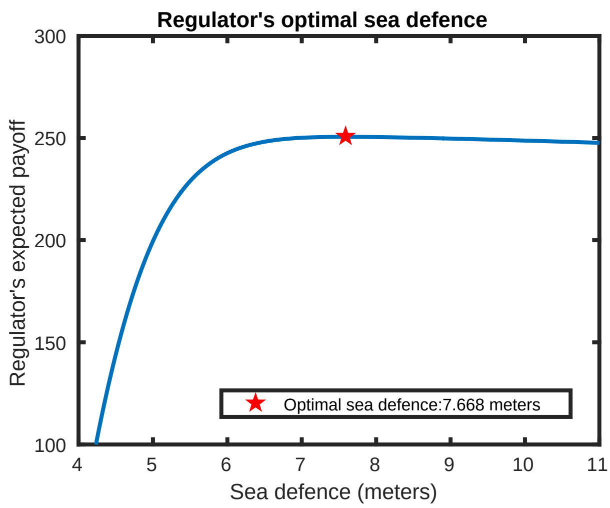

Figure 5.8: Regulator's optimal sea defence when the regulator's announcement of $b = 500$.

.

From Fig. 5.8, we can observe that the optimal height of the sea defence takes the value of

$$k^*_{reg}(\tilde{b}, b^*, b_*) = 4.510 \quad \text{and} \quad a^*_{reg} = a(k^*_{reg}) = 7.668\,\text{m}\,.$$

By comparing Fig. 5.5 and 5.7 we note the government's optimal fine cap is not aligned with the regulator's optimal fine cap. This implies that the regulator will induce the operator to implement higher sea defences. This implies that the transfer payment paid to the operator will also increase making the society bear higher costs. Taking this into account, capping the cost parameter will enable to align the objectives of the regulator and the government.

The government's decision problem is to choose the cost parameter cap that will aligned the regulator's and the government's objectives with respect to the fine cap to impose to the operator. This is presented in Figure 5.9 where the x-axis represents the cost parameter cap in million euros and the y-axis represents the optimal sea defence of the regulator.

Given that the optimal cap of the cost parameter is $b^{**} = 365.2\,\text{million}\,€$, the regulator's discretion will be bounded in the interval $[D^*_{reg}(\alpha_R, b_*), D^*_{reg}(\alpha_R, 365.2)]$. When the cost parameter announced by the regulator is higher than optimal cost parameter cap $b^{**} = 365.2\,\text{million}\,€$, the fine cap that the regulator will impose to the operator

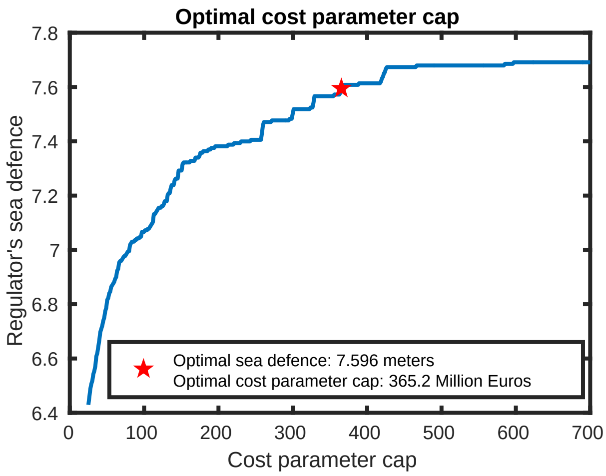

Figure 5.9: Optimal cost parameter cap set by the Government.

is $D^*_{reg}(\alpha_R, 365.2)$. This fine cap is higher than $D^*_{gov}(\alpha_{gov}, 365.2)$. Nevertheless, as the announcement of the cost parameter increases the fine cap chosen by the regulator gets closer to the fine cap chosen by the government up to a certain threshold . After that threshold the fine cap of the regulator will fall below the government's choice of the fine cap.

Chapter 6

Conclusion

This thesis has shown that the provision of incentives in the form of a risk sharing mechanism can be effective in order to achieve a desirable safety scenario under uncertainty. In the more naive case where the society and the operator show a neutral attitude to uncertain payoffs and the operator is full liable for the damage cost incurred due to flooding, a first best sea defence (e.g., height of the sea defence) is implemented by the operator. Using as an example the implementation of a sea defence, the first best height of the sea defence has no informational cost for the regulator because it can extract all the rents from the operator. The operator's full liability implies that in the case that a realization of the run up height exceeds the first best height of the sea defence implemented by the operator, the operator will be financially responsible to fully compensate for the damage cost. Taking into account that the economic damages inflicted by natural hazards could reach 300 billion in the context of nuclear safety, it is unreasonable to consider the full liability scenario. This has been proven in the Fukushima nuclear accident where despite the operator claiming that she would be able to provide full compensation for the damage cost in case of an accident, she has had to be bailed out by the government because the damage cost exceeded by far her total assets.

Bearing in mind the magnitude of the damage cost in nuclear accidents, it is more realistic to assume that the liability of the operator to compensate is limited to some extent. Limiting the responsibility of the operator in case of an accident has some implications to the safety of the project and the cost to the society. Since the fine to be imposed to the operator can not be equivalent to the damage cost as this will exceed the assets of the operator, the strength of the incentive mechanism will decrease leading to the implementation of a sea defence below the socially optimum. This second best height of the sea defence involves an informational cost to the society in the form of a liability rent to guarantee the participation of the operator in the engineering project. The more we make the operator liable for the damage cost, the higher the liability rent. The society faces a trade off between liability rent and residual risk. The higher the residual risk, the lower the liability rent.

The society demands that critical infrastructures such as chemical plants or nuclear power plants to be safe. Nevertheless, if we want to implement protective measures to account for the possibility of any possible rare event, most projects would be economically non viable. This means that as the society demands higher levels of safety, the liability rent left to the operator increases as an exchange of reducing the residual risk. In line with this, the society is challenged with the following dilemma; how much residual risk is the society willing to accept in light of the economic benefits arisen from running nuclear power plants such as affordable electricity, low carbon emissions, creation of jobs, etc...? The answer to this question can be translated into a trade off problem between liability rent and residual risk.

This thesis also considers the case where the operator and the society have an averse attitude to risk in the presence of uncertain payoffs. It has been shown that the risk averse assumption has a beneficial impact to the performance of the operator. As a risk averse operator is particularly concerned with the tale of the distribution of the fine, the operator will increase the height of the sea defence to reduce the weight on the upper extreme values of the tail. This is because the marginal fine decreases under risk aversion. The rate at which the marginal fine decreases is determined by the risk coefficient of the power utility function. A higher risk coefficient implies a higher sea defence and therefore, a lower residual risk. However, the risk coefficient does not play any role in the society payoff function as the fine and the damage cost functions cancel each other out eliminating the random elements of the function. Similarly to the limited liability case, the implementation of a second best height of the sea defence is not free for the society. The society will have to compensate the operator for participating in the project in the presence of uncertain payoffs. This compensation takes the form of a risk premium and is subject to the risk coefficient and the variance of the damage cost distribution.

Undoubtedly the risk sharing incentive mechanism has proven useful to reduce the negative incentives in both the downstream and upstream moral hazard. In particular, the regulator's wrong incentives arising in the presence of regulatory capture can be eliminated to enhance the implementation of protective measures in line with the safety standards. Granting discretion to the regulator can bring benefits to the practicability and efficiency of the project but once again, the existence of asymmetric information between the regulator and the government with respect to certain parameters determining the damage cost makes this a non-trivial problem. As a consequence of this, the government faces a trade off problem between how much discretion should be given up and how much expert information should be used from the regulator. It has been shown that granting authority to the regulator to decide the fine cap to impose on the operator is not always recommended despite the benefits highlighted previously. In the case when the government observes that any of the fine cap choices available to the regulator is higher than its ex-ante choice of the fine cap, no discretion will be granted because the cost to the society outweighs the benefits of using the regulator's expertise. Nevertheless, when the government observes that some of the fine cap choices available to the regulator are lower than its ex-ante choice of the fine cap some level of discretion can be granted. The limit on the fine caps that the regulator can announce is determined by how much the regulator is biased towards the interests of the nuclear industry. When the regulator's range of fine caps is optimally restricted, the objectives of the regulator and the operator will be aligned by encouraging the regulator to choose a fine cap that will not exceed the optimal fine cap of the government.

6.1 Future work

This thesis can be extended in several directions. In order to account for the limitation of knowledge and understanding of how a nuclear accident relates to environmental damage and the lack of accuracy of the methods to estimate environmental damage cost (e.g., replacement cost methods), the regulator can model the damage cost using imprecise probabilities where an upper and lower bound is set to the distribution of damage cost output. In line with this, the assumption of global rationality has to be relaxed in favour of a bounded rationality assumption. This implies that the contract cannot be complete any longer. Under incomplete contracts, the operator will react to this contract by implementing a sea defence that may not be optimal necessarily but which provides a good practical solution.

Another area of work is to include more dimensions in the model by adding more complex safety design parameters and establishing technical relationships between them for a complete specification of the engineering problem. Because of the complexity of the parameters and their level of uncertainty, this research can adopt agent-based modelling. Agent-based models (ABMs) are useful to reproduce many systems related to economics and social sciences, where the structure can be designed through a network. ABMs consist of a set of elements (agents), characterized by some attributes, which interact with each other through the definition of appropriate rules in a given environment. Typically, the agent behaviour rules, attributes and the environment are setup using empirical data or theory. Broadly, ABMs can be used first, to explore and explain the mechanism of a theory of individual behaviour on the whole system, or second, to describe and forecast the behaviour of a system, or third, in a participatory context to explore a system and its behaviour with stakeholders.

A different research stream is to extend this model to a dynamic setting in order to explore how the safety design parameters to be implemented change over time and how the stochastic outcome is affected by this in view of the ratchet effect introduced in section 4.1.3.

Bibliography

[1] Acton, J. M., Hibbs, M. (2012). Why fukushima was preventable, *Carnegie Endowment for International Peace*, [online] Available at: http://carnegieendowment.org/2012/03/06/why-fukushima-was-preventable-pub-47361 [accessed 20 October 2016].

[2] Alonso, R., Matouscheck, N. (2008). Optimal delegation. *The Review of Economics Studies*, 75, 1.

[3] Armstrong, M., Sappington, D. (2005). Recent developments in the theory of regulation, in: M. Armstrong, and R. Porter, ed., *Handbook of Industrial Organization*, Elsevier Science Publishers.

[4] Baron, D. P., Besanko, D. (1987). Commitment and fairness in a dynamic regulatory relationship. *Review of Economic Studies*, 54(3), 413-436.

[5] Baron, D. P., Myerson, R. B. (1982). Regulating a monopolist with unknown costs. *Econometrica*, 50(4), 413-436.

[6] Boiteux, M. (1960). Peak load pricing. *Journal of Business*, 33, 157-79.

[7] Boiteux, M. (1971). On the management of public monopolies subject to budget constraint. *Journal of Economic Theory*, 3, 219-40.

[8] Braeutigam, R. R. (1989). Optimal prices for natural monopolies, in: R. Schmalensee and R. Willig, ed., *Handbook of Industrial Organization*, Elsevier Science Publishers, Amsterdam.

[9] Choi, B.H., Pelinovski, E. , Ryabov. I., Hong, S.J. (2002). Distribution functions of tsunami wave heights. *Natural Hazards*, 25, 1-21.

[10] Choi, K.S., Lee, Y. E., Ryu, Y. H. (2010). Review of nuclear regulation using principal and agent model. *Transactions of the Korean Nuclear Society*, Korean Institute of Nuclear Safety.

[11] Eisenhardt, K. M. (1989). Agency theory: an assessment and review. *Academy of Management Review*, 14(1), 57-74.

[12] Epstein, D., O'Halloran, S. (1999). *Delegation powers: A transaction cost politics approach to policy making under separate power.* Cambridge University Press, 312.

[13] Glazer, A., Bendor, J., Hammond, T. (2001). Theories of delegation. *Annual Review of Political Science*, 4, 235-269.

[14] Hiriart, Y., Martimort, D. (2008). The benefits of extended liability. *RAND Journal of Economics*, 37(2), 562-582.

[15] Hiriart, Y., Martimort, D. (2012). How much discretion for risk regulators? *RAND Journal of Economics*, 2(43), 283-314.

[16] Holmstrom, B. (1982). Models in economic theory. On the theory of delegation. In: M. Boyer, and R. Kihlstrom, eds, *Bayesian Models in Economic Theory.* New York: North-Holland, 317.

[17] Holmstrom, B., Milgrom, P. (1991). Multitask principal-agent analyses: incentive contracts, asset ownership, and job design. *Journal of Law Economics and Organisation*, 7, 24-52.

[18] Innes, R. D. (1990). Limited liability and incentives contracting with ex-ante action choices. *Journal of Economic Theory*, 52, 45-67.

[19] International Atomic Energy Agency. (2011). *The IAEA International Fact Finding Expert Mission of the Fukushima Daiichi NPP Accident Following the Great East Japan Earthquake and Tsunami.*Vienna: IAEA, 160.

[20] Johannsen, K. Larsen, A. (2001). The independent regulatory agencies in the liberalised energy market: theory, rhetoric, and empirical evidence. *29th European Consortium for Political Research Workshop*, Grenoble, France.

[21] Joskow, P. L. (2005). Incentive regulation in theory and practice: electricity distribution and transmission networks, in: N. L. Rose, ed., *NBER book Economic Regulation and Its Reform: What Have We Learned?*, Chicago: National Bureau of Economics Research conference on economic regulation, 291 - 344.

[22] Joskow, P. L. (2007). Regulation of natural monopoly, in: M. Polinsky, S. Shavell, ed., *Handbook of Law and Economics*, North-Holland Publishers.

[23] Kajiura, K. (2008). Some statistics related to observed tsunami heights along the coast of Japan, Tsunamis. in: I. Kumiji, ed.,*Their Science and Engineering*, Tokyo: Terra publication, 131-145.

[24] Laffont, J. J. (1994). The new economics of regulation ten years after.*Econometrica*,62, 507-537.

[25] Laffont, J. J., Martimort,D. (2002). *The theory of incentives: the principal-agent model*. Princeton: Princeton University Press.

[26] Laffont, J. J., Tirole, J. (1986). Using cost observations to regulate firms. *Journal of Political Economy*, 94(3), 614-641.

[27] Laffont, J. J., Tirole, J. (1988). The dynamics of incentive contracts. *Econometrica*, 56(5), 1153-1176.

[28] Laffont, J. J., Tirole, J. (1993). *A theory of incentives in procurement and regulation*. Massachusetts: MIT-Press.

[29] Mitnick, B. (1980). *The political economy of regulation*. New York: University Press.

[30] Ramseyer, J. M. (2012). Why power companies build nuclear reactors on fault lines? The case of Japan. *Journal of Theoretical Enquiries in Law*, 13, 2.

[31] Sappington, D. E. M. (1983). Limited liability contracts between principal and agent. *Journal of Economic Theory*, 29, 1-21.

[32] Sappington, D. E. M. (1995). Designing incentive regulation. *Review of Industrial Organization*, 9(3), 245-272.

[33] Stigler, G. J. (1971). The theory of economic regulation. *The Bell Journal of Economic and Management Science*, 2(1), 3-21.

[34] Peltzman, S., Levine, M. E., Noll, R. G. (1989). The economic theory of regulation after a decade of deregulation. *Brookings Papers on Economic Activity; Microeconomics*, 1-59.

[35] TEPCO. (2012). Fukushima nuclear accident analysis report, *Tokyo Electric Power Company, Inc.*, [online] Available at: http://www.tepco.co.jp/en/press/ [accessed 20 November 2015].

[36] The National Diet of Japan. (2012). The Official Report of the Fukushima Nuclear Accident Independent. *Investigation Commission Tokyo*, [online] Available at: http://warp.da.ndl.go.jp/info:ndljp/pid/3856371/naiic.go.jp/en/report/ [accessed 13 January 2015].

[37] United States Nuclear Regulatory Commission. (2011). Recommendations for enhancing reactor safety in the 21st century: the near-term task force review of insights from the Fukushima Dai-Ichi accident. *United States Nuclear Regulatory Commission*, [online] Available at: http://pbadupws.nrc.gov/docs/ML1118/ML111861807.pdf [accessed 16 January 2015].

[38] U.S. Geological Survey, National Earthquake Information Center. (Undated). The 03/11/2011 Mw9.0 Tohoku, Japan Earthquake. *USGS*, [online] Available at: http://earthquake.usgs.gov/learn/topics/Tohoku2011.pdf [accessed 23 April 2015].

[39] World Nuclear Association. (Undated). The situation at Fukushima. *WNA*, [online] Available at: http:/www.world-nuclear.org/focus/fukushima/the-situation-at-fukushima.aspx [accessed 20 January 2015].

[40] Xiang, P., Zhou, J., Zhou, X., Ye, K. (2012). Construction project risk management based on the view of asymmetric information. *Journal of Construction Engineering Management*, 138, 1303-1311.