Optimal regulation of the construction of reliable sea defences

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ABSTRACT

This article studies incentives to share risk as a risk management tool to address issues of interdependency between risk assessment, risk perception, and risk management in large civil engineering projects. We study the decision problem of an operator in charge of constructing reliable sea defences and show that operators have no incentive to reduce the likelihood of rare but extreme floods because their liability for damage costs cannot exceed the value of their private assets. We evaluate the level of liability that induces cost-effective safety measures to reduce the

probability of extreme events without bankrupting the operator and study its impact on the welfare of society. It turns out that society will be better protected at a significantly lower cost when tacitly retaining the residual risk of extreme damage costs. The findings offer an explanation as to why stakeholders tend to ignore the potential costly consequences entailed by the failure of civil engineering projects. Although these catastrophic failures are rare, this paper contends that society, as a whole, should bear the residual risk of such events.

INTRODUCTION

Motivation

The implementation of large civil engineering projects requires economic agents to assume responsibility for a range of activities that create a number of interrelated risks ranging from technical feasibility to costs. The risk management of such projects must therefore be concerned with developing strategies to reduce the probability of negative events while taking into account that they may occur nevertheless. Modern risk management of civil engineering projects must be aware of economic, environmental, engineering, and societal aspects and consider the full gamut of possible actions that mitigate risk. The design of risk management strategies for civil engineering projects as well as the achievement of its objectives requires the participation of various stakeholders of the general public and the private sector. The main stakeholders in large civil engineering projects are the government, a regulator, an operator, and society. Governments commission operators for the implementation of a project and use regulators and advisory bodies to supervise and manage the safety of the project. A typical example is portrayed in Figure 1.

A key responsibility of regulators is to protect society against the excessive risk taking of operators. The right to compensation against an operator is exercised in accordance to the Convention on Third Party Liability (Organisation For Economic Cooperation and Development (OECD) 1982). The operator of a nuclear installation, for example, is liable for loss of life of any person and damage to any property caused by the installation. The mechanism that protects society is the contractual relationship between the government, the regulator, and the operator, which determines the risk management strategy. A main feature of any contractual relationship is the existence of asymmetric information. (Xiang et al. 2012) point out that in the context of civil engineering, a contract between a government and an operator involves two types of informational asymmetries, which create uncertainty. At the bidding stage, the government is better informed regarding the technological know-how, the equipment, and the management abilities of the operator. At the performance stage, the operator has an informational advantage with regard to the expertise of the personnel and the quality of technology used.

An important issue in the construction of public facilities is the pressure on operators to complete a project on budget and on time. This common problem is often caused by narrow profit margins. Equally important to note is that monitoring operators is very costly for society and that regulators may not have the capacity to verify the effectiveness of implemented safety measures. Informational asymmetries alongside these issues thus entail a moral hazard problem in the sense that governments and regulators cannot observe whether the operator has implemented cost-effective risk mitigation measures.

A recent example of the consequences of moral hazard is the Fukushima accident. As argued in (Ramseyer 2012), moral hazard arises as soon as potential losses exceed the value of the company. As a private company, Tokyo Electric Power Company (TEPCO), the Japanese operator of the power plant, knew that it could not be made liable beyond the value of its net assets. Beyond that value, the company would be unable to pay for risks beyond a certain magnitude, the company would earn all returns but bear none of the costs. This observation explains why TEPCO underplayed the risk of large earthquakes and tsunamis. On March 2011, the magnitude 9.0 Tohoko-oki earthquake shook north-eastern Japan, unleashing a savage tsunami. A 15-meter high tsunami hit the Fukushima Daiichi nuclear power plant and triggered a nuclear accident by disabling the power supply and heat sinks, see (Kurokawa et al. 2012). Before the accident, TEPCO conducted an experimental risk analysis of a tsunami hitting the Fukushima site. In its report, TEPCO's experts estimated the probability of a tsunami hitting the Fukushima coast area above 5.7 meters within the next 50 years at 10 percent and the probability of a tsunami hitting above 10 meters at 1 percent. In 2006, TEPCO presented these results at the International Conference on Nuclear Engineering (ICONE14), where they fostered the belief that Fukushima was safe despite historical evidence that tsunamis of 9 meters or higher had occurred in the region, cf. (Acton and Hibbs 2012).

In 2006 and in 2008, civil engineering specialists at TEPCO carried out a more comprehensive risk assessment, called "Probabilistic Safety Assessment" (PSA), and compiled numerical evidence that the probability for tsunamis higher than 10 meters was significantly greater than in the original analysis, cf. (Acton and Hibbs 2012). TEPCO, however, decided that the risk of such extreme tsunamis was negligible and assumed full liability for possible accidents. By dismissing the findings of their risk assessment, TEPCO ignored best practices promulgated by the International Atomic Energy Association (IAEA) and the Japan Society of Civil Engineering.

(Acton and Hibbs 2012) identified a number of flaws in TEPCO's risk analysis. The risk assessment methodology adopted by TEPCO, for example, ignored important determinants, such as the hydrodynamic forces of a tsunami and the effects of debris and sediment transported in a tsunami run-up. A number of official reports, including the ones 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, came to the unanimous conclusion that TEPCO had implemented insufficient safety measures. These reports argue that elevating the power plant, building a higher seawall, and installing a back-up generator could have mitigated or even prevented the catastrophic consequences of the tsunami, see e.g. (Acton and Hibbs 2012; Weightman and Jamet 2011; Kurokawa et al. 2012; Miller et al. 2011).

Accidents, such as the Fukushima incident, reveal that there are several issues of interdependency between risk assessment, risk perception, and risk management. These interdependencies can be analysed using the conceptual framework of Paul Kleindorfer as described in (Cohen and Kunreuther 2007) and are illustrated in Figure 2.

For instance, flaws in the risk assessment modelling such as omitting critical parameters, or an erroneous interpretation of the risk assessment due to biased perception of risk, e.g. underestimating residual risk, can lead to underinvestment in safety measures. In light of this observation, an important aspect of managing risk in highly interdependent systems is the provision of incentives to ensure appropriate levels of investment into safety measures that mitigate risk, see (Aven 2016; Cohen and Kunreuther 2007). In cases where operators do not implement these voluntarily, it may be necessary to utilize regulation and/or to impose standards that convince operators of the financial benefits of these measures, see (Aven 2016; Cohen and Kunreuther 2007). The efficiency of such a policy, however, needs to be evaluated from a societal viewpoint, in order to guarantee that its implementation does not leave society worse off than under the status quo. (Aven 2016) has pointed out that risk management has to balance out competing interest such as profits, safety, and reputation, while respecting the constraints imposed by risk acceptance criteria. Public risk acceptance has changed notably in recent times despite the fact that the frequency of accidents has not increased. This change was observed in local communities in South Korea, e.g. Yeongdok and Samcheok, whose residents had traditionally been supportive of nuclear technology. In April 2015, however, they opposed plans to build nuclear power plants in these regions because of safety concerns, see (Dalton 2016). If risk acceptance criteria are to be introduced as a risk management tool and formulated by the authorities as proposed by (Abrahamsen and Aven 2012), the implementation of protective measures that account for any conceivable event would make these projects economically unviable.

Motivated by the Fukushima accident, this article addresses the following issues. From the perspective of business management, we will evaluate the level of liability that induces cost-effective safety measures to reduce the probability of extreme events without bankrupting the operator in case of an accident. From a societal perspective, we explore the extent to which such risk regulatory policies will improve the welfare of society. Our analysis is particularly relevant for industries that are subject to a 'risk-informed, performance-based' regulatory approach, e.g. as pursued by the United States Nuclear Regulatory Commission, because it involves a risk-weighted analysis, whereas the classical compliance-based regulatory approach considers risk associated with rare events as negligible, see (Saji 2003).

Related literature

The business management literature has studied the relationship between regulatory policies and risk management. For instance, (Hausken and Zhuang 2013) analyse the trade-off between the safety demands by a government and production targets of a company. In their model, safety measures are strategic complements. They show how taxation can reduce the company's free riding on safety measures implemented by the government. Along these lines, (Cheung and Zhuang 2012) analyse the implemented safety effort and the level of production of competing companies in a regulatory game. They show that competition increases a company's threshold for risk exposure and therefore requires stricter regulation. In a different set-up, (Kleindorfer and Saad 2005) introduce a framework for managing disruptions in supply chains that arise from natural hazards, terrorism, or political instability. In their set-up, a company is interested in the trade-off between the costs of risk mitigation and expected disruption costs. The authors incorporate economic risk mitigation incentives in the form of risk sharing.

Another strand of literature relevant to our analysis is the design of incentives in risk management, such as subsidies and fines. In this regard, a number contributions offer narratives similar to ours. (Asche and Aven 2010) discuss business incentives for investing in safety. They argue that incentives to implement higher safety standards are effective only if the safety measures are profit enhancing. By contrast, (Kadambe and Segerson 1998) analyse the effects of a fine on the probability of a negative externality. They show that, in the absence of indirect effects, an increase in the fine reduces the probability of a violation and thus leads to a lower pollution. However, if indirect effects are positive and large, an increase in the fine may reduce the likelihood that a firm will comply with environmental regulation. Thus, increased fines do not necessarily enhance compliance.

Main contribution

The focus of our article is in the spirit of these contributions in considering the contractual relationship between a regulator and an operator. Optimal risk regulation trades off safety costs against marginal damage costs. The operator may exploit the informational asymmetries and limited liability arrangement by under-investing in safety measures to the detriment of society. Our article builds on (Hiriart and Martimort 2012) who analyse a moral hazard problem arising in the regulation of firms undertaking projects that are important for society. They show that under asymmetric information and limited liability the firm's investment into safety measures is below the socially optimal level. Their paper provides an in-depth analysis, but unfortunately, is not directly applicable to settings arising in engineering. Our article develops a refinement and modification of (Hiriart and Martimort 2012) by including scenarios in which an operator may involuntarily default and by adapting the setting to general probability distributions.

Given the standard assumptions of risk neutrality, informational asymmetry, and limited liability, we formulate a principal-agent model with three agents: a government, a regulator, and an operator. The regulator can allay the moral hazard problem, which is a source of uncertainty in the decision making process, by offering the operator a transfer payment. This transfer payment is performance based in that it relates the operator's wealth to an observable and verifiable state of possible environmental damage as proposed in (Laffont and Martimort 2002). (Laffont 1994) emphasises that payments based on safety performance require both the ability to determine the safety design parameters needed to mitigate risk ex ante and the ability to measure and verify environmental damage ex post. These requirements are difficult to fulfill because the knowledge of how accidents relate to environmental damage is limited and methods to estimate damage costs, such as replacement costs, are problematic.

Our analysis contributes to the risk management literature by offering an explanation as to why stakeholders tend to ignore the potential costly consequences entailed by the failure of civil engineering projects with the focus on rare but extreme natural hazards. This article is organised as follows. Section 2 introduces the basic elements of the model. Section 3 investigates the case of a risk-neutral operator with full liability. Section 4 considers scenarios in which the operator has limited assets to compensate the damage caused by floods. A welfare analysis between full and limited liability is carried out in Section 5. Conclusions are provided in Section 6.

GAME-THEORETIC SETTING

We consider a relationship between a regulator and an operator in which the operator is better informed with respect to safety design parameters that determine the effectiveness of a sea defence. The sea defence is needed to protect a critical infrastructure of a society such as a (nuclear) power plant. The effectiveness of the sea defence is defined by the maximum run-up height of a tsunami a up to which the infrastructure is protected. It is determined by parameters, such as the safety design, the quality of materials, the technology used, and the operator's expertise.

The game theoretic setting with the sequence of actions of our model is illustrated in Figure 3.

The asymmetric-information assumption necessitates a regulator whose task is to align the interests of society with the operator's objectives. To this end, the regulator offers the operator a contract for designing and building a sea defence to protect the infrastructure against floods caused by a tsunami. We assume that the regulator has not enough resources to validate the design parameters and thus cannot verify ex ante whether the infrastructure is protected effectively. The regulator, therefore, cannot directly condition the contract on the design parameters. The contract is instead conditioned on realised damage costs caused by floods as these are observable and thus can be verified. For simplicity, we assume that the fine F is proportional to the damage cost D, so that $F = \delta_f D$ with $0 \leq \delta_f \leq 1$.

The contract between the government and the operator is specified by a transfer payment T that covers all costs of the operator and a fine F that the operator has to pay in case the sea defence fails to protect the infrastructure. The transfer payment T is the amount payed by society to the operator so that the operator is willing to carry out the task assigned to her. A transfer payment, therefore, has to cover all costs associated with implementing the project and the risk costs of contingent damages the operator is liable for. The fine F is the amount the operator has to pay in case the sea defence fails to protect the infrastructure. Since the magnitude of the tsunami is assumed to be predictable, the operator will be fined for events within and beyond design basis. The reason for this choice is the above mentioned moral hazard problem of the operator who has an incentive to underplay the residual risk of extreme events. In the context of our principal-agent framework, we will analyse and compare two cases. First, the case with full liability of the operator. Second, the case with limited liability. The case with limited liability takes into account the fact that the operator may financially not be able to cover extremely high losses. The fine, therefore, is capped. Losses below this cap, could thus be interpreted as failures within design basis for which the operator is liable, while losses above the cap may be interpreted as beyond design basis.

The Fukushima nuclear plant was subject to a 10 meters high tsunami and a 9.0 magnitude earthquake when the plant was built to withstand tsunamis with a maximum height of 5.7 meters and earthquakes with a maximum magnitude of 7.5. However, earthquakes of comparable magnitude have struck the northeast coast of Japan, on average, every 100 years, each one generating a devastating tsunami (Acton and Hibbs 2012). In fact, a tsunami in 1933 was almost precisely as high as the one that struck Japan on March 2011. Following this line of reasoning, the Fukushima nuclear accident occurred due to a poor design of the sea defence below the design basis.

The operator accepts the contract and implements the sea defence if the offered transfer payment is higher than the minimum payment she requires to receive. We will refer to this minimum payment as the *participation constraint* of the operator.

The probability distribution of the damage costs depends on the tsunami run-up height h, which in turn is modelled as a random variable. Since the probability of a flooding is a decreasing function of the effective sea defence a, the operator can reduce the likelihood of a flooding by enhancing a. Based on a risk assessment, the operator chooses an optimal effective sea defence a that maximises her pay-off before knowing the realisation of the damage costs. Since we assume that a sea defence that rules out a flooding with certainty is technologically impossible, society retains a residual flooding risk.

Given a contract, the regulator, the operator, and society can evaluate the damage cost distribution associated with a sea defence. The stakeholders' pay-offs are stipulated as follows. The operator's pay-off is the random variable

$$\tilde{P}_O = T - \varphi(a) - \tilde{F}. \tag{1}$$

This pay-off is a function of the effective sea defence a, the transfer payment T, and the fine $\tilde{F}$ which is a random variable. The operator's cost of implementing a is determined by the cost function φ.

The pay-off of the society is given by the random variable

$$\tilde{P}_S = S - T - \tilde{D} + \tilde{F}. \tag{2}$$

This pay-off is a function of society's revenue S, the transfer payment T, the damage cost $\tilde{D}$, and the fine $\tilde{F}$. The society receives a fixed revenue S from the infrastructure and pays a transfer payment T to the operator for the implementation of the sea defence. The regulator's objective is to enhance social welfare by maximizing the weighted sum of society's and the operator's pay-off, where the weight parameter $0 \leq \alpha_R \leq 1$ is the relative weight the regulator assigns to the operator's pay-off in relation to the pay-off of the society. The regulator's pay-off then is the weighted sum $\tilde{P}_R = \tilde{P}_S + \alpha_R \tilde{P}_O$ and conveniently rewritten as

$$\tilde{P}_R = S - \varphi(a) - \tilde{D} - (1 - \alpha_R)\tilde{P}_O. \tag{3}$$

REGULATION UNDER FULL LIABILITY

We consider an operator who cares only about expected pay-offs and thus, by definition, is risk neutral. The fine imposed on the operator is assumed to be proportional to the random damage, so that $\tilde{F} = \delta_f \tilde{D}$ with $0 \leq \delta_f \leq 1$ and $\tilde{D} = \psi(\tilde{h} - a)$, where $\tilde{h}$ is the random run-up height of a tsunami. Here, ψ takes into account only run-up heights exceeding the effective sea defence a because only these will incur damage costs. The following assumptions on cost functions are convenient and standard in the economics literature.

Assumption 1. *The cost of implementing the effective sea defence is determined by a convex cost function φ, such that $\varphi' > 0$, $\varphi'' \geq 0$, and $\varphi(0) = 0$.*

Assumption 2. *The damage cost incurred by a tsunami is a convex function ψ of a, such that $\psi' > 0$, $\psi'' \geq 0$, and $\psi(h) = 0$ for all $h \leq 0$.*

Assumption 3. *The tsunami run up height is log-normally distributed with probability density function f.*

Empirical observations of tsunamis on the coast of the Hawaiian Island in 1946 and 1957, 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 and 1981 confirm that the spatial distribution of tsunami run-up heights is reasonably well characterised by a log-normal distribution, see (Choi et al. 2002).

Assumption 4. *The regulator cannot verify ex ante how effective the implemented sea defence against tsunamis is.*

With these assumptions, the operator's pay-off (1) takes the form

$$\tilde{P}_O = T - \varphi(a) - \delta_f \psi(\tilde{h} - a). \tag{4}$$

The expected pay-off of the operator is

$$E[\tilde{P}_O] = T - \varphi(a) - \delta_f \int_a^\infty \psi(h - a) f(h) dh, \tag{5}$$

where expected damage costs

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

are a function of a. Given that the distribution of the run-up height is common knowledge, the operator will choose the effective sea defence a so as to maximize the objective function

$$E[\tilde{P}_O] = T - \varphi(a) - \delta_f \int_a^\infty \psi(h - a) f(h) dh.$$

Assuming that the operator believes that the probability of a negative pay-off is negligible, her optimization problem takes the form

$$max_{(a \geq 0)} E[\tilde{P}_O]. \tag{6}$$

Lemma 1. *Let the hypotheses of Assumption 1 and 2 be satisfied. Then the decision problem of the operator* (6) *has an unique solution a^*, which is determined by the first order condition (FOC)*

$$\varphi'(a^*) = \delta_f \int_{a^*}^\infty \psi'(h - a^*) f(h) \mathrm{d}h. \tag{7}$$

The optimal effective sea defence $a^* = a^*(\delta_f)$ *is an increasing function of* δ_f *and independent of* T.

Proof. The l.h.s. of the first order condition (7), which is $\varphi'(a)$, is by assumption increasing in a, while the r.h.s. $RHS(a) = \delta_f \int_a^\infty \psi'(h-a) f(h) \mathrm{d}h$ is decreasing in a. Moreover, $RHS(0) > 0$ and $\lim_{a\to\infty} RHS(a) = 0$, while $\varphi'(0) = 0$. Hence a^* with $\varphi'(a^*) = RHS(a^*)$ exists. Moreover, a^* is unique because the objective function (6) is strictly concave. The last statement follows from the fact that the RHS of (7) is increasing δ_f, so that $a^* = a^*(\delta_f)$ is an increasing function of δ_f. □

Given a transfer payment T and a fine δ_f, denote by

$$\Pi_O(T, \delta_f) = T - \varphi(a^*) - \delta_f \int_{a^*}^\infty \psi(h - a^*) dh$$

the expected pay-off of the operator that implements $a^* = a^*(\delta_f)$. The corresponding expected payoff of society then is

$$\Pi_S(T, \delta_f) = S - T - (1 - \delta_f) \int_{a^*}^\infty \psi(h - a^*) dh.$$

In view of the fact that the operator maximizes its own profit irrespective of social welfare, the regulator designs a contract by setting a transfer payment T and a fine δ_f so as to maximize

$$\Pi_R(T, \delta_f) = \Pi_S(T, \delta_f) + \alpha_R \Pi_O(T, \delta_f), \tag{8}$$

while satisfying the participation constraint of the operator. More formally, the regulator's decision problem is

$$max_{(T,\delta_f)} \Pi_R(T, \delta_f)$$

subject to the operator's *participation constraint*

$$\Pi_O(T, \delta_f)] \geq p_0. \tag{9}$$

Here, p_0 is the reservation pay-off of the operator. Given a fine, the transfer payment must be large enough to guarantee that the expected pay-off of the regulator is at least as high as the reservation pay-off.

It is not difficult to see that in an optimum $(T^* \delta_f^*)$, inequality (9) must hold with equality. The reason is that Π_O is linear in T. If the participation constraint were not binding $\Pi_O(T^*, \delta_f^*) > p_0$, then T^* could be lowered by a small amount ϵ without violating the participation constraint, thereby increasing the regulator's pay-off (8). Hence, given δ_f^*, the optimal transfer payment T^* is determined by the binding participation constraint.

The regulator's decision problem can now be addressed as follows. Since $a^*(\delta_f)$ is an increasing function of δ_f, there is an one-to-one correspondence between fines and effective sea defences. The regulator's problem may therefore be transformed to an equivalent problem that determines the optimal effective sea defence a from the regulator's point of view. Using (3), this optimization problem is given by

$$max_{(a \geq 0)} \Big(S - \varphi(a) - \int_a^{\infty} \psi(h-a) f(h) dh - (1-\alpha_R) p_0 \Big). \tag{10}$$

Theorem 1. *Let the hypothesis of Lemma 1 be satisfied. Then the optimal regulatory policy under asymmetric information, risk neutrality, and full liability is determined by an optimal fine δ_f^* and an optimal transfer payment T^*, such that the following holds true:*

1. *The regulator sets a fine equal to damage costs, that is, $\delta_f^* = 1$.*
2. *The optimal transfer payment is*

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

where a^{**} solves (10).

3. *The socially optimal sea defence a^{**} is determined by the first order condition*

$$\varphi'(a^{**}) = \int_{a^{**}}^{\infty} \psi'(h - a^{**}) f(h) \mathrm{d}h, \tag{11}$$

so that $a^{**} = a^*(\delta_f^*)$, where $a^*(\delta_f)$ was defined in Lemma 1.

Proof. The l.h.s. of the first order condition (11), i.e. $\varphi'(a)$, is by assumption increasing in a, while the r.h.s. $RHS(a) := \int_a^\infty \psi'(h-a)f(h)\mathrm{d}h$ is decreasing in a. Moreover, $RHS(0) > 0$ and $\lim_{a\to\infty} RHS(a) = 0$, while $\varphi'(0) = 0$. Hence a^{**} with $\varphi'(a^{**}) = RHS(a^{**})$ exists. Moreover, a^{**} is unique because the objective function (11) is strictly concave. A comparison of the FOCs (7) and (11) shows that $a^*(\delta_f^*) = a^{**}$ with $\delta_f^* = 1$. □

Since the optimal fine is $\delta_f^* = 1$, it is optimal for the operator to implement the socially optimal effective sea defence a^{**}, provided that the participation constraint holds. As a^{**} is independent of transfer payments, the regulator may simply set

$$T^* = p_0 + \varphi(a^{**}) + E[\psi(\tilde{h} - a^{**})], \tag{12}$$

where $\varphi(a^{**})$ is the cost of implementing a^{**}, $E[\psi(\tilde{h} - a^{**})]$ is the expected fine and p_0 is the reservation pay-off. The transfer payment T^* is the minimum payment that satisfies the participation constraint, so that in an optimum, the operator will on average earn her reservation pay-off p_0. Economists refer to T^* as the first-best payment.

Next, we present a numerical example of an implementation of an optimal effective sea defence for the protection of a critical energy infrastructure, e.g. a nuclear power plant from tsunamis.

Example 1. *Suppose that the damage cost function is given by the power function*

$$\psi(\tilde{h} - a) = b(\tilde{h} - a)^\beta, \tag{13}$$

where the effectiveness of the sea defence a can take any value in the interval $[0, 10]$, $\tilde{h}$ is a *truncated log-normally distributed run-up height (*meters*) with parameters* $\mathcal{N}(4.5, 0.9)$ *whose support is* $(0, 10)$*, and* $b > 0$ *and* $\beta \geq 1$ *are cost parameters (*million €*). The costs of implementing an effective sea defence a is of the quadratic form*

$$\varphi(a) = \frac{c}{2}a^2, \tag{14}$$

where c is the marginal cost with a value of 0.05 million €*. The revenue of society from running the nuclear power plant for a period of 50 years is* $S = 400$ million €*. The regulator's decision problem is to design a contract consisting of (1) a fine parameter* δ_f *that induces the operator to implement the socially optimal effective sea defence and (2) a transfer payment T (*million €*) that satisfies the operator's participation constraint. We note that, in the presence of asymmetric information, the operator implements a sea defence below the social optimum,* $a^* < a^{**}$*. In order to incentivize the operator to implement the socially optimal sea defence, the fine parameter has to be raised. By setting* δ_f *equal to* 1*, the operator implements the socially optimum effective sea defence, such that* $a^*(\delta_f^*) = a^{**}$*. Because the fine is equal to damage cost, the optimal transfer payment has to guarantee that the expected pay-off (*million €*) of the operator is at least as large as* 4 million €*, which is the value of the reservation pay-off* p_0*. To do so, society pays a transfer* T^**, which is the minimum amount of money that the operator will accept in order to implement the sea defence.*

Table 1 analyses the socially optimal effective sea defence, the transfer payment, and the exceeding probability of occurrence in a year (residual damage risk) when the cost parameters b takes the values $b = 50, 100, 200$ *and* β *the values* $\beta = 1, 1.5, 2$*. The residual damage risk is the probability that the socially optimal sea defence will fail to protect the energy infrastructure from flooding.*

We observe that the operator will enhance the effectiveness of the socially optimal sea defence as the cost parameter b increases. Clearly, a higher socially optimal sea defence results in a lower residual damage risk. In practice, the frequency of floods is measured by means of a recurrence *interval, which is defined as the average number of years between floods of a certain height. For example, the recurrence interval of 100 years for a flood of a certain height suggests that in any year, a flood of that magnitude has a 1% exceedance probability of occurrence, e.g. (Holmes and Dinicola 2010). The observable realizations of damage costs in an initial period enables the regulator to gain more information on implemented safety measures for later periods. This information can be utilized ex post to renegotiate the terms of the contract, cf. (Baron and Besanko 1987; Laffont and Tirole 1988).*

REGULATION UNDER LIMITED LIABILITY

In the previous scenario, the fine imposed on the operator was equal to the damage costs incurred by a natural hazard. These costs could, in principle, exceed the operator's private assets, thus bankrupting the operator. Indeed, it follows from Theorem 1 that in an optimum, the realized pay-off of the operator is determined by the random variable

$$\tilde{P}_O^* = p_0 + E[\psi(\tilde{h} - a^{**})] - \psi(\tilde{h} - a^{**}). \tag{15}$$

This shows that $\tilde{P}_O^*$ is negative for all sufficiently large run-up heights $\tilde{h}$. We assumed that the risk of such an event is negligibly small so that it is ignored by both the operator and the regulator. The society, however, has no interest in insolvent operators because it would have to bear all excess costs. Therefore, it should take possible bankruptcies into account along with the excess costs an operator would not be able to cover. To ensure that the pay-off of the operator is always non-negative, we therefore introduce a liability constraint, which in our setting takes the form of a fine cap $\overline{D}$.

Let $\tilde{F} = \min\{\tilde{D}, \overline{D}\}$ denote the possible fine charged to the operator, where $\tilde{D} = \psi(\tilde{h} - a)$ is the damage costs incurred by the random height $\tilde{h}$ of the tsunami run up. The operator can now be fined up to the cap $\overline{D}$ only so that the society will bear all damage costs exceeding $\overline{D}$. It is clear that the probability of costs exceeding the cap $\overline{D}$ is decreasing in $\overline{D}$ and may become arbitrarily small. We are interested in the case in which the probability of costs exceeding $\overline{D}$ is positive no matter how large $\overline{D}$ is. The operator's pay-off now accounts for the cap on the fine that can be imposed and takes the form

$$\tilde{P}_O = T - \varphi(a) - \min\{\psi(\tilde{h} - a), \overline{D}\}. \tag{16}$$

The cap on the fine allows the regulator to ensure that the operator's pay-off is always non-negative by setting T sufficiently high. Under limited liability, the operator takes into account that she cannot be made liable for costs exceeding $\overline{D}$, so that her expected pay-off becomes

$$E[\tilde{P}_O] = T - \varphi(a) - E[\min\{\psi(\tilde{h} - a), \overline{D}\}]. \tag{17}$$

The operator's optimization problem is the choice of an effective sea defence a so as to maximize her expected pay-off $E[\tilde{P}_O]$. Formally, the optimization problem reads

$$max_{(a\geq 0)} E[\tilde{P}_O]. \tag{18}$$

Lemma 2. *Let the hypothesis of Assumption 1 be satisfied. Then the decision problem of the operator has an unique solution a^*_{ll}, which is determined by the first order condition*

$$\varphi'(a^*_{ll}) = \int_{a^*_{ll}}^{a^*_{ll}+\bar{h}} \psi'(h - a^*_{ll}) f(h) dh, \tag{19}$$

where $\psi(\bar{h}) = \overline{D}$. The optimal sea defence is an increasing function of $\overline{D}$, i.e. $a^*_{ll} = a^*_{ll}(\overline{D})$ and independent of T.

Proof. The proof is analogous to the proofs of Lemma 1 and Theorem 1. Observe to this end that

$$\begin{aligned} E[\min\{\psi(\tilde{h} - a), \overline{D}\}] &= \int_a^\infty \min\{\psi(h - a), \overline{D}\} f(h) dh \\ &= \int_a^{a+\bar{h}} \psi(h - a) f(h) dh + \overline{D} \int_{a+\bar{h}}^\infty f(h) dh \end{aligned}$$

with $\psi(\bar{h}) = \overline{D}$. The l.h.s. of the first order condition (19) is increasing in a, while the r.h.s. is decreasing in a, and $\lim_{a\to\infty} RHS(a) = 0$. Furthermore, the marginal cost and the marginal fine at $a = 0$ are $\varphi'(0) = 0$ and $RHS(0) > 0$, respectively. Hence a^*_{ll} exists. Moreover, a^*_{ll} is unique because the objective function (18) is strictly concave. A comparison of the FOCs (11) and (19) shows that $a^{**} > a^*_{ll}(\overline{D})$ because the cap on the fine induces a distortion from the socially optimal sea defence. □

Corollary 1. *For each $\overline{D} > 0$, the optimal sea defence is smaller than the social optimum, i.e. $a^{**} \geq a^*_{ll}(\overline{D})$.*

Under limited liability, any realization of the operator's pay-off must be non-negative. Formally, this limited liability constraint is

$$\tilde{P}_O \geq 0. \tag{20}$$

If a^*_{ll} is implemented, then the operator's pay-off becomes

$$\tilde{P}_O = T - \varphi(a^*_{ll}) - \min\{\psi(\tilde{h} - a^*_{ll}), \overline{D}\},$$

which is positive for any realization of $\tilde{h}$, provided that the transfer payment T is large enough. Indeed, since $\tilde{P}_O \geq T - \varphi(a^*_{ll}) - \overline{D}$, the liability constraint (20) is fulfilled whenever the transfer payment covers the implementation costs and the maximum fine, i.e.

$$T \geq \varphi(a^*_{ll}) + \overline{D}.$$

The expected pay-off of the operator then becomes

$$E[\tilde{P}_O] = T - \varphi(a^*_{ll}) - E\left[\min\{\psi(\tilde{h} - a^*_{ll}), \overline{D}\}\right]$$

and the participation constraint $E[\tilde{P}_O] \geq p_0$ is fulfilled, if and only if

$$T \geq p_0 + \varphi(a^*_{ll}) + E\left[\min\{\psi(\tilde{h} - a^*_{ll}), \overline{D}\}\right].$$

It follows that the limited-liability and the participation constraint are both satisfied whenever

$$T \geq T_{ll}^* := \varphi(a_{ll}^*) + \max\left\{\overline{D},\ p_0 + E\left[\min\{\psi(\tilde{h} - a_{ll}^*), \overline{D}\}\right]\right\}, \tag{21}$$

where $a_{ll}^* = a_{ll}^*(\overline{D})$ as before. The amount T_{ll}^* is the minimum payment for a sea defence a society has to pay to the operator. Observe that T_{ll}^* is a function of the fine cap $\overline{D}$. Inserting T_{ll}^*, the expected pay-off of the operator becomes

$$E[\tilde{P}_O] = \max\left\{\overline{D} - E[\min\{\psi(\tilde{h} - a_{ll}^*), \overline{D}\}], p_0\right\}, \tag{22}$$

where $a_{ll}^* = a_{ll}^*(\overline{D})$. Since the r.h.s. of (22) is a function of the fine cap $\overline{D}$, it is convenient to set

$$\mathcal{R}(\overline{D}) := \max\left\{\overline{D} - E[\min\{\psi\left(\tilde{h} - a_{ll}^*(\overline{D})\right), \overline{D}\}]\,, p_0\right\}. \tag{23}$$

This definition reveals that the participation constraint of the operator is always satisfied, because $\mathcal{R}(\overline{D}) \geq p_0$. Contrary to the full-liability case, the operator will, on average, earn more than her reservation pay-off p_0. In economics, the difference $\mathcal{R}(\overline{D}) - p_0 \geq 0$ is referred to as the *liability rent* of the operator. Since the $\mathcal{R}$ is non-decreasing in fine caps $\overline{D}$, so is the liability rent. Moreover, a straightforward calculation reveals that there exists a largest fine cap $\overline{D}_0$ with $\mathcal{R}(\overline{D}_0) = p_0$ so that $\mathcal{R}$ is increasing for all $\overline{D} \geq \overline{D}_0$

The question of which fine cap $\overline{D}$ is socially optimal arises. Using (22), the expected pay-off of the regulator takes the form

$$\Pi_R(\overline{D}) = S - \varphi(a_{ll}^*(\overline{D})) - \int_{a_{ll}^*(\overline{D})}^{\infty} \psi(h - a_{ll}^*(\overline{D}))f(h)dh - (1-\alpha_R)\mathcal{R}(\overline{D}). \tag{24}$$

Since the liability constraint (20) is by construction always satisfied, the regulator's maximization problem takes the form

$$max_{(\overline{D} \geq \overline{D}_0)} \Pi_R(\overline{D}). \tag{25}$$

In other words, the optimal contract under limited liability is a fine cap $\overline{D}$ that maximizes the weighted sum of the expected pay-offs of society and the operator.

Theorem 2. *Let Assumptions 1 and 2 be satisfied. Then, a uniquely determined optimal regulatory policy under asymmetric information, risk neutrality, and limited liability exists. It is determined by the following:*

1. *The regulator sets the optimal fine cap $\overline{D}^* \geq \overline{D}_0$ that solves* (25)*. This fine cap is uniquely determined.*
2. *The optimal transfer payment set by the regulator consists the implementation costs and the optimal fine cap and is given by $T_{ll}^{**} = \varphi(a_{ll}^{**}) + \overline{D}^*$, where $a_{ll}^{**} = a_{ll}^*(\overline{D}^*)$ is the optimal effective sea defence.*
3. *If the participation constraint is not binding, i.e. $\overline{D}^* > \overline{D}_0$, then $\overline{D}^*$ is determined by the first order condition*

$$\varphi'(a_{ll}^{**}) = \int_{a_{ll}^{**}}^{\infty} \psi'(h - a_{ll}^{**}) f(h) dh - (1 - \alpha_R) \frac{\mathcal{R}'(\overline{D}^*)}{(a_{ll}^*)'(\overline{D}^*)}, \tag{26}$$

where $a_{ll}^{**} = a_{ll}^*(\overline{D}^*)$.

Proof. The proof is analogously to the proof of Theorem 1. The l.h.s. of the first order condition (26) is increasing in a, while the r.h.s. is decreasing in a, and $\lim_{a\to\infty} RHS(a) = 0$. Furthermore, the marginal cost and the RHS at $a = 0$ are $\varphi'(0) = 0$ and $RHS(0) > 0$, respectively. Hence a_{ll}^{**} exists. Moreover, a_{ll}^{**} is unique because the objective function (25) is strictly concave. Moreover, we deduce that the optimal effective sea defence a_{ll}^{**} is increasing in $\overline{D}$ and independent of T, such that $a_{ll}^{**} = a_{ll}^*(\overline{D}^*)$.

Since $\overline{D}^* \geq \overline{D}_0$, we have

$$\overline{D}^* \geq p_0 + E\left[\min\{\psi(\tilde{h} - a_{ll}^{**}), \overline{D}^*\}\right].$$

It thus follows from (21) that the optimal transfer payment is $T_{ll}^{**} = \varphi(a_{ll}^{**}) + \overline{D}^*$. □

Corollary 2. *The effectiveness of the sea defence under limited liability is lower than under full liability, i.e.* $a_{ll}^{**} < a^{**}$.

Proof. This follows from a comparison of the first order conditions (11) and (26), the fact that $\mathcal{R}(\overline{D})$ and $a_{ll}^{*}(\overline{D})$ are both increasing for $\overline{D} \geq \overline{D}_0$. □

Corollary 2 implies that the regulator can only implement a second best protection against floods, as the effective see defence under limited liability is lower. This result is caused by the positive liability rent that accounts for the fact that the operator will not be able to cover losses above $\overline{D}^{*}$.

Example 2. *The limited liability scenario is computed using the damage cost function* (13) *and the cost function* (14) *from Example 1. The numerical values and units of the parameter values are also adopted from this example. Contrary to the full liability case, the regulator now sets a fine cap to avoid negative pay-offs of the operator. This optimal fine cap* $\overline{D}^{*}$ *(*million €*) is analysed in Table 2, for different weight parameters* $\alpha_R = 0.2, 0.5, 0.8$.

We observe from Table 2 that the fine cap increases with the cost parameters b *and* β *and decreases with the weight parameter* α_R*. Table 3 lists the levels of effectiveness under limited liability* a_{ll}^{**} *(lower row) and the levels of effectiveness under full liability* a^{**} *(upper row) for the same parameter values as in Table 2.*

A fine cap under limited liability causes a distortion, inducing the operator to implement an effective sea defence lower than the socially optimal level under full liability. Table 3 shows that this difference increases with the weight parameter α_R*. This finding demonstrates that the transfer payment under limited liability is always higher than under full liability. The reason is that the fine cap* $\overline{D}^{*}$ *is always larger than the expected damage cost* $E[\tilde{D}(\tilde{h}, a^{**})]$*. Since the transfer payment under limited liability* T_{ll}^{**} *is a function of the fine cap and the transfer payment under full liability* T^{*} *is a function of the expected damage cost,* T_{ll}^{**} *is always larger than* T^{*}*. The intuition for this finding is that the transfer payment under limited liability must prevent the operator from insolvency. This result is illustrated in Table 4 for the values of the weight parameter* α_R*, where the upper row is the* *optimal transfer payment under full liability T^* and the lower row is the optimal transfer payment under limited liability T_{ll}^{**}.*

We observe from Table 4 that the optimal transfer payment under limited liability T_{ll}^{**} increases significantly as the cost parameter b increases and the weight parameter α_R decreases.

The residual damage risk for floods after the implementation of sea defences are presented in Table 5. Herein, the upper row corresponds to full liability and the lower row corresponds to limited liability case. Consistent with the observations in Table 3, the probability that the optimal effective sea defence fails is higher under limited liability than under full liability. The difference in residual damage risk between full and limited liability significantly increases with the weight parameter α_R and decreases with the cost parameter b.

WELFARE ANALYSIS

In the full liability section we observed that imposing a fine which is proportional to damage costs may induce negative pay-offs for the operator whenever the run-up height is sufficiently high. In large engineering projects, such events are frequently ignored, because they are thought to occur with negligible likelihood. The limited liability case discussed above demonstrated that ignoring this residual risk leads to more effective sea defences. In terms of damage costs, however, the economic consequences of neglecting residual risk may be quite severe.

To illustrate this point, let us discuss a potential scenario for the two regulatory regimes. Recall that under the assumption of full liability, the operator's payoff is positive

$$\tilde{P}_O^* = p_0 + E[\psi(\tilde{h} - a^{**})] - \psi(\tilde{h} - a^{**}) \geq 0 \quad \text{if and only if} \quad p_0 + E[\psi(\tilde{h} - a^{**})] \geq \psi(\tilde{h} - a^{**}),$$

where $T^* = p_0 + \varphi(a^{**}) + E[\psi(\tilde{h} - a^{**})]$ is the optimal transfer payment. The operator will only be able to cover damage costs up to $p_0 + E[\psi(\tilde{h} - a^{**})]$ and the upper bound of the fine the operator is able to pay is $p_0 + E[\psi(\tilde{h} - a^{**})]$. The effective pay-off of the society thus becomes

$$\begin{aligned}\tilde{P}_S^e &= S - T^* - \psi(\tilde{h} - a^{**}) + \min\left\{\psi(\tilde{h} - a^{**}), p_0 + E[\psi(\tilde{h} - a^{**})]\right\} \\ &= S - \varphi(a^{**}) - \max\left\{\psi(\tilde{h} - a^{**}), p_0 + E[\psi(\tilde{h} - a^{**})]\right\}. \end{aligned} \tag{27}$$

Recall that the pay-off of a fully protected society would be $P_S = S - T^*$. Since

$$\tilde{P}_S^e = \tilde{P}_S + \min\left\{0,\ p_0 + E[\psi(\tilde{h} - a^{**})] - \psi(\tilde{h} - a^{**})\right\},$$

we see that the effective pay-off $\tilde{P}_S^e$ is lower than the pay-off of a fully protected society, whenever the damage costs exceed the amount that can be covered by the operator.

In the limited-liability case, these low-probabilities high-costs events have been taken into account by capping the fines. In this case, the operator's pay-off is positive with certainty, because

$$\tilde{P}_O^* = \overline{D}^* - \min\{\psi(\tilde{h} - a_{ll}^{**}), \overline{D}^*\} \geq 0,$$

where the optimal transfer payment is T_{ll}^{**} is given in Theorem 2. In an optimum, the pay-off of the society then is

$$\begin{aligned}\tilde{P}_S &= S - T_{ll}^{**} - \psi(\tilde{h} - a_{ll}^{**}) + \min\{\psi(\tilde{h} - a_{ll}^{**}), \overline{D}^*\} \\ &= S - \varphi(a_{ll}^{**}) - \max\{\psi(\tilde{h} - a_{ll}^{**}), \overline{D}^*\}. \end{aligned} \tag{28}$$

A comparison of (27) and (28) shows that, a priori, its unclear which of the two pay-offs is higher.

Example 3. *Following on from Examples 1 and 2, we compare the pay-off* (27) *of society in the full liability case with the pay-off* (28) *in the limited liability case. As before, the pay-offs are computed using the damage cost function* (13) *and the cost function* (14)*. The results are presented in Figures 4–7, where the x-axis is the height of the run up h and the y-axis is the random pay-off of society P_S.*

In the full-liability case, the pay-off of society (27) is represented by a solid black curve and depends on the cost parameters b and β, but is independent of the weight parameter α_R. The reason is that under the assumptions of full liability, all rents are extracted from the operator. In the limited-liability case, by contrast, the pay-off of society case depends on α_R. This pay-off (28) is presented by a dashed-dotted red curve for a weight parameter $\alpha_R = 0.2$, a dotted green curve for a weight parameter $\alpha_R = 0.5$, and a dashed blue curve for a weight parameter $\alpha_R = 0.8$. In each of the figures, the black horizontal line at $P_S = 0$ marks the distinction between positive and negative pay-offs.

We observe that under full liability, society is better protected from physical damage associated with flooding and its wealth is always higher. However, if the weight parameter α_R for the operator's wealth is sufficiently low, e.g. $\alpha_R = 0.2$, the society is protected against financial losses for a wider range of run-up heights.

Furthermore, the size of the reservation pay-off p_0 plays a pivotal role for the safety and welfare of society. Under full liability, an increase in p_0 has no effect on the implemented sea defence but reduces society's exposure to financial loss. In the limited-liability case, an increase in p_0 increases the optimal fine cap, which in turn leads to a higher effective sea defence. However, as it increases the operator's liability for damage cost, it also increases the transfer payment to the operator.

Confirming the results for the limited liability case, a low weight parameter, e.g. $\alpha_R = 0.2$, cost parameters set at $b = 100, 200$ reflecting high damage costs, and a reservation pay-off of $p_0 = 4\,\text{million}\,€$ imply high fine caps and consequently high transfer payments. The numerical results for this case are presented in Table 6 which displays the relationship between liability protection, residual risk, and transfer payment under full (upper row) and limited liability (lower row). The liability protection is the run-up height up to which society is financially protected. The residual financial risk is the probability of a financial loss for society due to flooding. Table 6 reveals that the cost parameters b and β have contradictory effects on the residual financial risk in the limited liability case. While b lowers the residual financial risk, β increases it in the extreme *damage scenario. This contradictory effect also occurs for transfer payments under full liability but not in the limited liability case. This exemplifies situations in which it is very costly to ensure the liability of an operator. A small reduction in the residual damage risk may cause a huge increase in the liability rent. Society therefore faces a trade-off dilemma between bearing residual risk of extreme flooding and paying huge liability rents. Note that under limited liability* ($\beta = 0.2$)*, society is better protected from financial losses but less protected from physical damage.*

As reported in Table 4, it is important to note that placing more weight on the operator's payoff lowers the transfer payments and thus the fine caps. As a consequence, the residual damage risk born by society is then significant higher so that from the point of view of safety, the project may become unacceptable.

Our analysis demonstrates that a risk-neutral society may be better off ignoring the residual risk of infrequent accidents ex ante and bearing the damage costs ex post. Otherwise, the social benefits of a public project may easily be annihilated by costly liability rents that have to be paid upfront to operators.

CONCLUSION

This article studied the effectiveness of risk sharing incentives as a risk management tool in an uncertain environment with risk-neutral stakeholders. It argues that residual risks in large civil engineering projects are often underestimated. Operators, which are either too big or too important to fail, tend to be overly confident that a public infrastructure facility in question is safe and assume full liability. When rare but catastrophic events strike nevertheless, society may have to bail out operators in order to keep the facility in operation.

This article finds that taking into account that operators may not be able to cover the damage costs for rare but extreme events may have adverse effects on the safety of a facility as well as on the costs for society. If society wants to reduce the residual risk of rare but extreme events, it has to enable the operator to cover the incurred damage costs. As these can be very high, the society will have to pay for an extremely high liability rent upfront while the safety of the facility is negatively affected. Therefore, society is better off ignoring the residual risk by pretending that operators are full liable ex ante and paying the excess damage costs ex post in those cases in which the operator is bankrupt. This insight of our article contradicts the conventional wisdom that society is fully protected when imposing full liability on operators. Modern societies are challenged with the dilemma of how much residual risk they are willing to accept, given the economic benefits from public projects such as affordable electricity, low carbon emissions, or the creation of jobs. The present article translates this issue into a trade-off problem between an acceptable level of residual risk and the costs of further risk reduction.

The approach of this article can be extended in several directions. First, the approach could be easily generalized to any contracted project aimed at risk reduction. This could be achieved simply by changing a to a generic output parameter and h to a generic variable that captures uncertainty. Second, from an economic viewpoint, the strong economic rationality assumption could be relaxed to bounded-rationality to better account for the complexity of the problem. The regulatory policy could then be based on imprecise probabilities for damage costs, implying that an operator implements a structural project which may not be optimal, but from a practical point of view is more realistic. As failure risk was at the centre of this investigation, it would be interesting to explore scenarios with risk-averse stakeholders. Third, from the standpoint of operations management, agent-based modelling can allow enhancement of reliability analysis by integrating technical, economic and contractual aspects. Agent-based modelling can be designed to include a dynamic relationship between the operator and the regulator to understand how time-dependant risk mitigation measures determine the reliability of infrastructure projects within a regulatory framework. Finally, from an engineering viewpoint, it would be interesting to explore model extensions with a more elaborate description of a specific project with all the technically relevant parameters.

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Table 1. Optimal effective sea defence, transfer payment, and residual damage risk under full liabiliy

	medium damage $b = 50$			very high damage $b = 100$			extreme damage $b = 200$		
	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$
Socially optimal sea defence (level of effectiveness)	7.174	7.154	7.194	7.530	7.490	7.510	7.885	7.826	7.787
Transfer payment (million €)	5.46	5.46	5.46	5.57	5.57	5.57	5.72	5.69	5.68
Residual damage risk (%)	0.739	0.765	0.709	0.366	0.399	0.382	0.177	0.201	0.218

Table 2. Regulator's optimal cap $\overline{D}^*$

Optimal cap $\overline{D}^*$ (million €)	medium damage $b = 50$			very high damage $b = 100$			extreme damage $b = 200$		
	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$
$\alpha_R = 0.2$	27.67	35.57	48.42	75.10	130.40	179.80	330.00	341.90	349.80
$\alpha_R = 0.5$	8.20	10.57	12.85	17.79	22.73	28.66	61.26	63.24	64.23
$\alpha_R = 0.8$	4.94	5.93	6.92	9.88	11.86	14.82	30.63	32.61	35.57

Table 3. Comparison of the optimal effective sea defence under full and limited liability

Optimal sea defence (Level of effectiveness) **Full vs limited liability**	medium damage $b = 50$			very high damage $b = 100$			extreme damage $b = 200$		
	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$
$\alpha_R = 0.2$	7.174	7.154	7.194	7.530	7.490	7.510	7.885	7.826	7.787
	6.996	6.937	6.917	7.431	7.431	7.451	7.866	7.806	7.767
$\alpha_R = 0.5$	7.174	7.154	7.194	7.530	7.490	7.510	7.885	7.826	7.787
	6.591	6.581	6.561	6.957	6.897	6.877	7.490	7.401	7.292
$\alpha_R = 0.8$	7.174	7.154	7.194	7.530	7.490	7.510	7.885	7.826	7.787
	6.250	6.225	6.304	6.700	6.680	6.700	7.134	7.095	7.055

Table 4. Comparison of the optimal transfer payment under full and limited liability

Transfer payment (million €) **Full vs limited liability**	medium damage $b = 50$			very high damage $b = 100$			extreme damage $b = 200$		
	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$
$\alpha_R = 0.2$	5.46 28.89	5.46 36.77	5.46 49.62	5.57 76.48	5.57 131.78	5.57 179.19	5.72 331.55	5.69 343.42	5.68 351.00
$\alpha_R = 0.5$	5.46 9.29	5.46 11.65	5.46 13.93	5.57 19.00	5.57 23.92	5.57 29.84	5.72 62.66	5.69 64.61	5.68 65.55
$\alpha_R = 0.8$	5.46 5.92	5.46 6.90	5.46 7.91	5.57 11.00	5.57 12.98	5.57 15.94	5.72 31.90	5.69 33.87	5.68 36.81

Table 5. Comparison of the residual damage risk under full and limited liability

Residual damage risk (%) **Full vs limited liability**	medium damage $b = 50$			very high damage $b = 100$			extreme damage $b = 200$		
	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$
$\alpha_R = 0.2$	0.739 1.027	0.765 1.157	0.709 1.195	0.366 0.449	0.399 0.449	0.382 0.431	0.177 0.184	0.201 0.210	0.218 0.226
$\alpha_R = 0.5$	0.739 2.137	0.765 2.215	0.709 2.294	0.366 1.110	0.399 1.239	0.382 1.289	0.177 0.399	0.201 0.485	0.218 0.591
$\alpha_R = 0.8$	0.739 4.033	0.765 4.165	0.709 3.628	0.366 1.790	0.399 1.861	0.382 1.790	0.177 0.796	0.201 0.854	0.218 0.921

Table 6. Relationship between liability protection, residual financial risk, and transfer payment under full and limited liability ($\alpha_R = 0.2$)

Weight parameter ($\alpha_R = 0.2$)	medium damage $b = 50$			very high damage $b = 100$			extreme damage $b = 200$		
	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$	$\beta = 1$	$\beta = 1.5$	$\beta = 2$
Liability protection	7.253	7.332	7.470	7.569	7.589	7.708	7.905	7.905	7.925
(up to run up heights (m))	7.549	7.727	7.885	8.182	8.617	8.775	9.407	9.229	9.071
Residual financial risk	0.632	0.540	0.411	0.335	0.323	0.253	0.170	0.170	0.162
(%)	0.359	0.245	0.175	0.094	0.037	0.025	0.005	0.008	0.012
Transfer payment	5.46	5.46	5.46	5.57	5.57	5.57	5.72	5.69	5.68
(million €)	28.89	36.77	49.62	76.48	131.78	179.19	331.55	343.42	351.00

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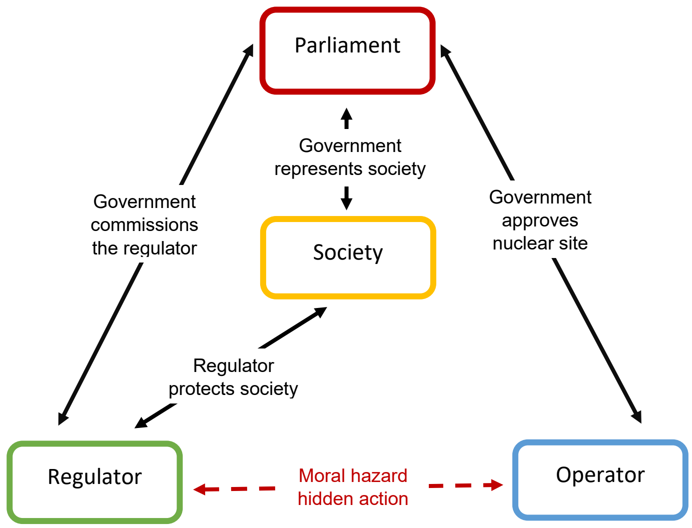

Fig. 1. Stakeholders in a flood defence project.

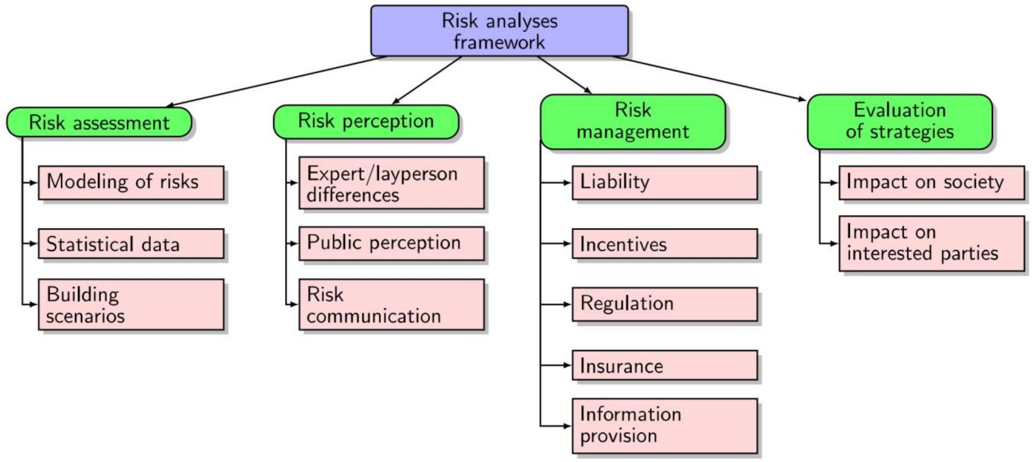

Fig. 2. Conceptual framework for risk analysis, adapted from Cohen and Kunreuther 2007.

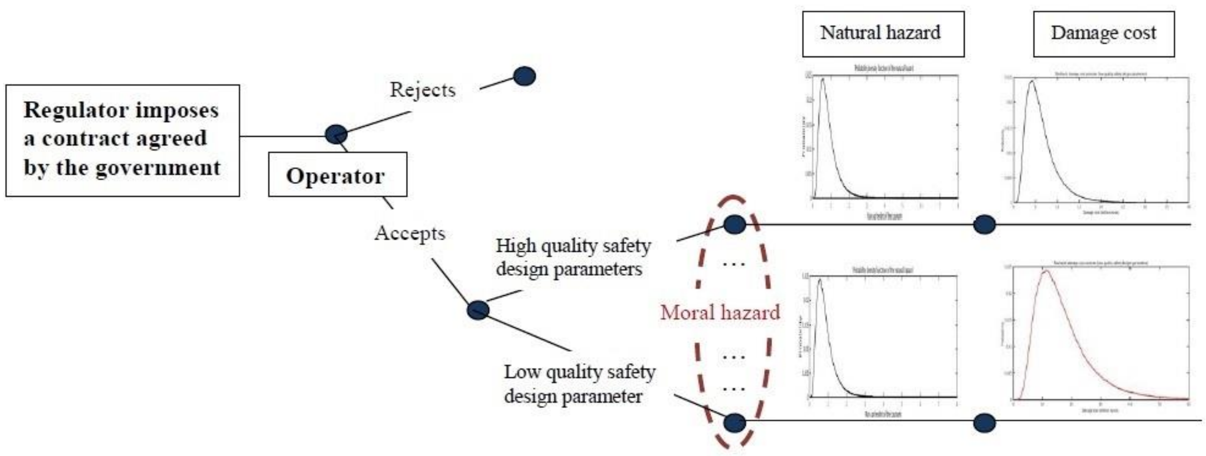

Fig. 3. Sequence of actions.

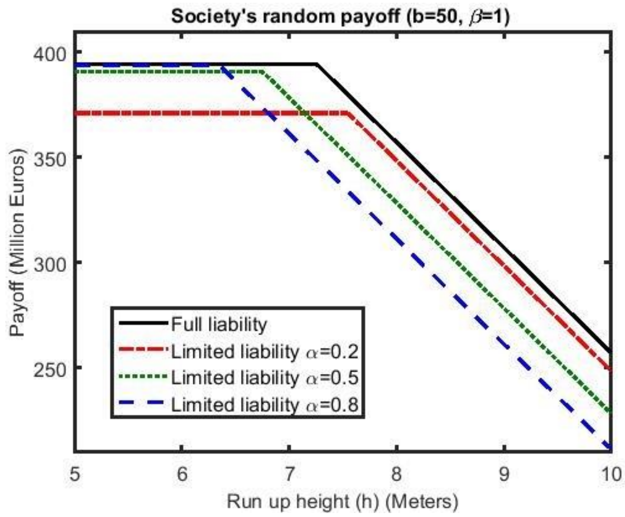

Fig. 4. Pay-offs (b=50, $\beta = 1$)

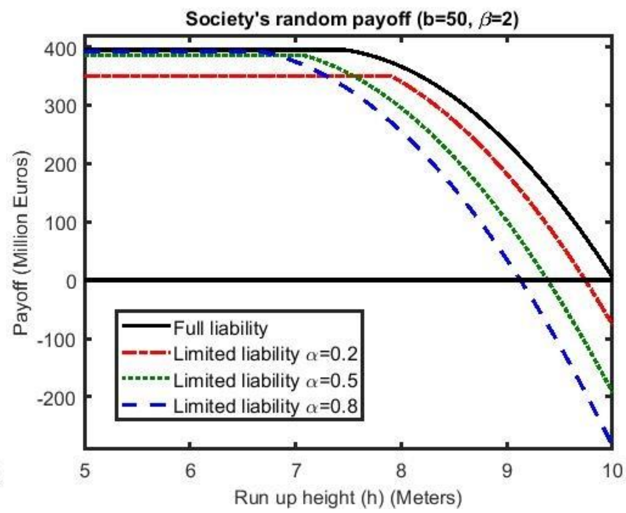

Fig. 5. Pay-offs(b=50, $\beta = 2$)

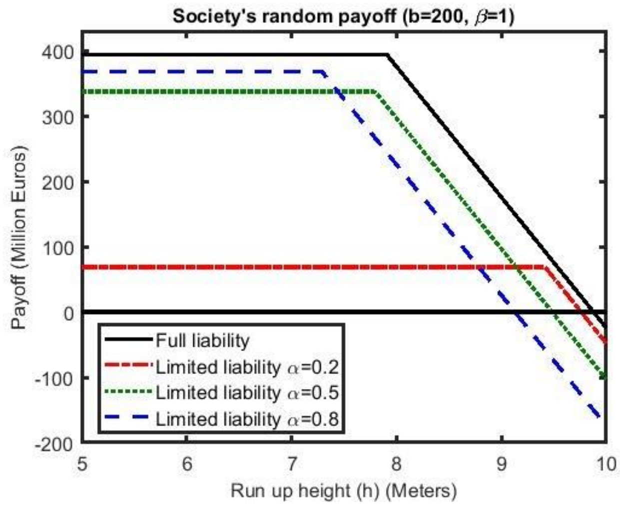

Fig. 6. Pay-offs (b=200, $\beta = 1$)

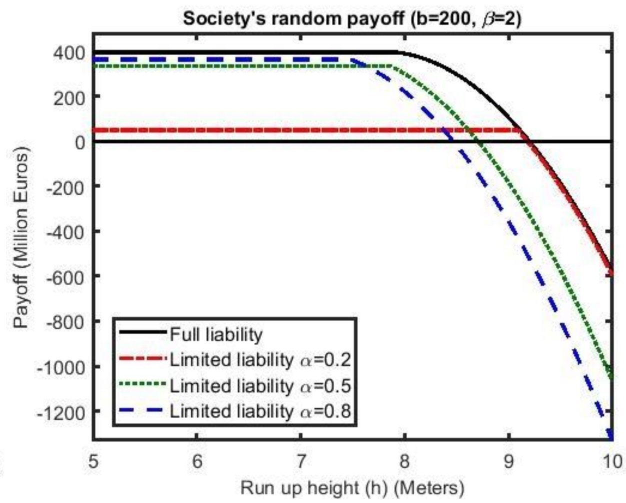

Fig. 7. Pay-offs (b=200, $\beta = 2$)