ARE FLOODINGS PREVENTABLE UNDER MORAL HAZARD AND LIMITED LIABILITY?

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In this paper, we use a mathematical model based on the agency theory to determine the optimal level of discretion granted to a regulatory body. This model reduces the probability of an accident inflicted on the society by resolving a downstream and an upstream moral hazard problem existing in engineering with special attention to the Fukushima nuclear accident. When the regulator and the parliament have conflicting objectives under moral hazard, a pro-industry regulator imposes a cap of the fine below parliament's optimal inducing the operator to implement lower quality sea defences. This is because the liability rent left to the operator increases with lower quality sea defences. By setting an upper bound to the regulator's range of feasible decisions, the parliament can encourage the regulator to work in the interest of the broad society.

I. INTRODUCTION

The International Atomic Energy Agency's (IAEA's) International Nuclear Safety Group believes that if best practices are implemented, major releases of radiation from existing nuclear power plants should occur about fifteen times less frequently. Indeed, improvement on this scale is probably necessary for nuclear power to gain widespread social and political acceptance[1].

Regulators face upper bounds in the damages that operators should cover for the harm inflicted on third parties or on the environment[2]. The presence of limited liability enables nuclear operator's bear the cost of an accident only up to the fire set value of the net assets; beyond that point society will be responsible for the damage cost[3]. As a consequence of this, nuclear operators face wrong incentives when making decisions on safety imposing a risk of catastrophic damages on the society who do not earn a contractual return for bearing that risk. According to the Carnegie Endowment for international peace, Tokyo Electric Power Plant (TEPCO) used risk assessment methods that fall behind international standards causing flaws in the decision making process[4].

These methods did not consider serious uncertainties like earthquakes that were gigantic but rare. Furthermore, computer modelling of the tsunami threat was inadequate by evaluating tsunami run up without taking into consideration the effect of debris[3, 4, 5, 6].

The regulator's interest in relaxing international safety regulations to the operator can be understood 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[4] . In line with this, the objectives of the Japanese parliament and NISA are misaligned triggering an upstream moral hazard problem.

This article proposes a game theoretic approach in the principal and agent framework to eliminate the conflict of interest between the parliament and the nuclear regulator by restricting the potential realization of damage cost that regulator can announce according to her expertise.

The main contribution of this paper is to fully characterize the optimal delegation set that maximizes the parliament expected payoff for a lognormal distributed run up height.

I.A. Delegation theory

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[7].

In this article 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[8].

Our paper builds on, and borrows 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. In other words, the more align are the payoff functions, the more authority is granted to the regulator[9].

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[10].

II. THE MODEL

We consider the relationship between a parliament, a regulatory agency, and an operator in the implementation of a nuclear plant whose safety affects the society. Our model has six main features.

First, the operator has not sufficient solvency to cover the damage cost in case of an accident. For damages caused by an accident at a nuclear power plant (NPP), NPP's owner is liable by special statute. A plant's operator must maintain both an insurance with a private insurer and a separate contract with the government. The contract with the government will cover those disasters caused by the events like earthquakes and tsunamis[3]. However, for extremely massive natural disasters the reactor's operator is not liable, providing wrong incentives for operators to shirk her safety responsibilities.

Second, the survival of a sea defence due to an earthquake depends on how the grounds moves. That movement depends on the quake'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 can be thought as the materials in the composition of cement, the thickness of the seawall, etc. [3] 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. [11]

Third, 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 public.

Forth, the regulator is dominated by nuclear industry implementing policies that are pro-operator. This is due to the lack of independence from government.

Fifth, the regulator possesses valuable information about the parameters determining the damage cost in case of flooding.

Sixth, the parliament cannot evaluate if the policies implemented are the most appropriate in light of the information possessed by the regulator.[11] This triggers an upstream moral hazard between the regulator and the parliament.

II.A. Formulation of the model

The stakeholders involved in the project evaluate the possible stochastic damage cost outcomes inflicted by the operator's choice of the safety design parameter. Each stochastic damage cost outcome yields some payoff for the stakeholders which are determined by the following payoff functions.

The operator's payoff function is

$$\tilde{P}_0 = T - \varphi(k) - \tilde{F} \qquad (1)$$

This payoff is a function of the safety design parameter k, a transfer payment T and a fine F. To exert effort, the operator must bear a cost $\varphi(k)$. We assume that the cost $\varphi(k)$ function is strictly increasing in k, $\varphi'(k) > 0$, and convex $\varphi''(k) \geq 0$.

The society's payoff function is

$$\tilde{P}_S = S - T - \tilde{D} + \tilde{F} \qquad (2)$$

This payoff is a function of the safety design parameter k, society revenue from implementing sea defences S, a transfer payment T, a damage cost D, and a fine F. The society receives a revenue associated with non-accident related benefits to the society such as affordable electricity, energy source independence, low carbon emissions, creation of jobs, etc. The society gives a transfer payment to the operator in exchange for his protectionary measures which depends on the damage cost outcome and the sea defences. The society bears the damage cost of an accident.

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 $0 < \alpha_R < 1$ 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 it is conveniently rewritten as

$$\tilde{P}_R = S - \varphi(k) - \tilde{D} - (1 - \alpha_R)\tilde{P}_O \qquad (3)$$

The parliament's payoff function is also the weighted sum $\tilde{P}_R = \tilde{P}_S + \alpha_R \tilde{P}_O$ where parliament's weight parameter $0 < \alpha_P < \alpha_R < 1$, yielding,

$$\tilde{P}_P = S - \varphi(k) - \tilde{D} - (1 - \alpha_P)\tilde{P}_O \qquad (4)$$

III. FULL DISCRETION TO THE REGULATOR.

Let's consider the case when a parliament grants full authority to the regulator to implement optimal risk regulatory policies despite information asymmetries. We start with the full liability case when the operator has enough assets to cover the damage cost in case of an accident and then, we develop it to the case when the operator has limited resources to compensate for any harm inflicted to a third party or the environment.

III.A. Regulation under full liability

TABLE I. Notation

Parameter	Description	Value
$\tilde{h}$	Tsunami run up random variable.	$LN(4.5,0.89)$
a_0	Sea defence (meters).	$a_0 = 1.7$ m
k	Safety design parameter.	$0 \le k \le 7$
c	Marginal cost. (Million Euros)	$c = 0.3$ million
δ_f	Fine parameter.	$0 \le \delta_f \le 1$
b	Cost parameter (Million Euros)	$b = 200$ million
$\tilde{b}$	Cost parameter random variable (meters)	$N(350,150)$ $\tilde{b} = [25,700]$
T	Transfer payment (Million Euros).	$T = 200$
S	Society revenue from sea defences (Million Euros).	$S = 300$
α_R	Regulator's weight parameter	$\alpha_R = 0.80$
α_P	Parliament's weight parameter	$\alpha_P = 0.60$
p_0	Mark up (Million Euros).	p_0 =-30

General Assumptions

- The regulatory agency cannot observe the quality of the elements that form the sea defence. This is represented by the safety design parameter k exerted by the operator.

- We assume that the heights of the tsunami run up is log-normal distributed. Empirical observations of tsunamis on the coast of the Hawaiian Island 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 defined by the lognormal distribution[12] .

- The realization of damage cost $\tilde{D}$ is induced by $\tilde{h}$ and the safety design parameter k . The conditional cumulative density function $H(D,a_i)$ first order stochastically dominates the conditional cumulative density function $H(D,a_j)$. That is $H(D,a_i) \ge H(D,a_j)$ for whenever $a_i \ge a_j$.

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

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

The quadratic cost function is of the form

$$\varphi(k) = c/2\, k^2.$$

Since $\tilde{D} = \int_{a_0 k}^{\infty} b(h - a_0 k) f(h) dh$ and $\tilde{F} = \int_{a_0 k}^{\infty} \delta_f b(h - a_0 k) f(h) dh$ where $\tilde{h}$ is the height of the run up, the operator's expected payoff function takes the form

$$E[\tilde{P}_O] = T - c/2\, k^2 - \int_{a_0 k}^{\infty} \delta_f b(h - a_0 k) f(h) dh$$

We consider a risk-neutral operator who cares about the expected value of the expected damage cost but not about the magnitude of the damage cost. Thus, the operator's optimization problem is the choice of the safety design parameter $k \geq 0$ and takes the form

$$\max_{k\geq 0} T - \frac{c}{2} k^2 - \int_{a_0 k}^{\infty} \delta_f b(h - a_0 k) f(h) dh \qquad (5)$$

An optimal solution when the initial value of δ_f is 0.75.

$$k^*(0.75) = 4.15 \text{ and } a^* = a_0 k^*(0.75) = 7.055 \text{ meters.}$$

The regulator's decision problem is the choice of the optimal fine δ_f^* and the optimal transfer payment T^* that maximizes the expected payoff of the regulator.

We assume throughout 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 the operator's assets that she could sell in order to meet her payment obligations.

The regulator's choice of the fine parameter 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.

$$\max_{k\geq 0} S - \frac{c}{2} k^2 - \int_{a_0 k}^{\infty} b(h - a_0 k) f(h) dh - (1 - \alpha_R) p_0 \qquad (6)$$

Thus, the optimal solution is

$$k^{**} = 4.233 \text{ and } a_0 k^{**} = 7.196 \text{ meters}$$

We note that the operator finds optimal to implement a sea defence below the social optimum. In order to incentivize the operator to implement the socially optimal sea defence, the fine parameter δ_f is raised to 1, such that

$$k^{**} = k^*(1) = 4.233 \text{ and } a^{**} = a_0 k^{**} = 7.196 \text{ meters}$$

A numerical result of the sea defence when the optimal $\delta_f^* = 1$ is implemented is presented in figures 1 and 2.

The regulator's choice of the transfer payment takes the form

$$T^* = \frac{c}{2} k^{2**} - \int_{a_0 k}^{\infty} b(h - a_0 k^{**})^+ f(h) dh + p_0 \qquad (7)$$

The optimal transfer payment is

$$T^* = 35.05 \text{ Million euros}$$

This is the minimum payment transfer that satisfies the participation constraint, that is,

$$E[P_O(T^*, \delta_f^*)] = p_0$$

The optimal transfer payment is presented in figure 3 and 4

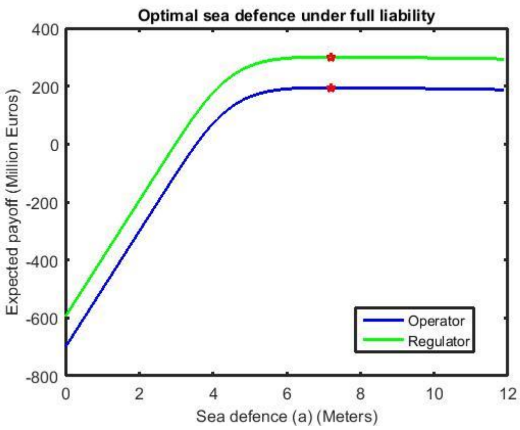

Fig. 1. Optimal sea defence of the regulator and the operator when the fine is equal to the damage cost, that is $\delta_f{}^* = 1$

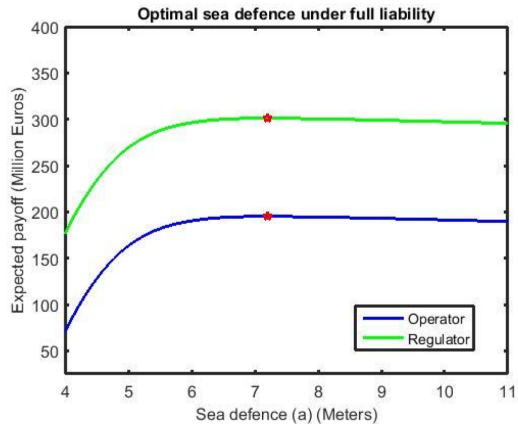

Fig. 2. The zoom of the optimal sea defence in Fig.1. shows concavity of the payoff function.

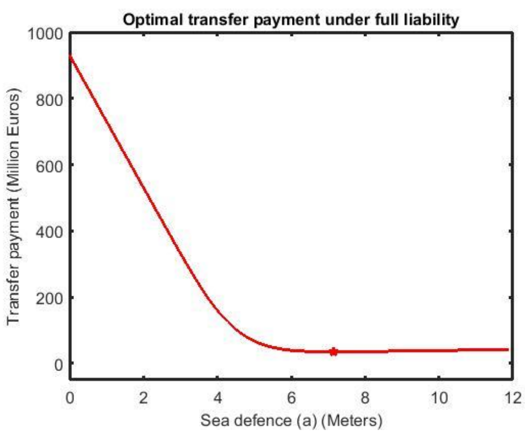

Fig. 3.The minimum transfer payment that satisfies the participation constraint of the operator.

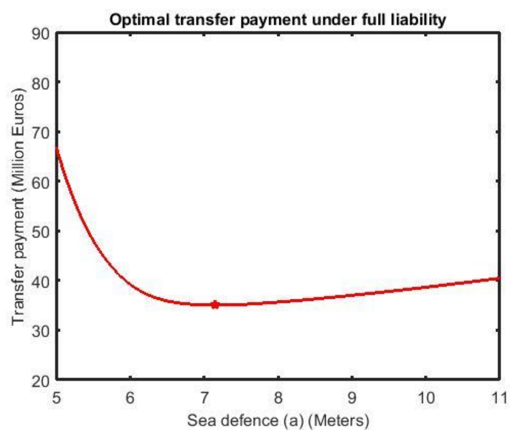

Fig. 4. The zoom of the optimal transfer payment in Fig.3. shows concavity of the transfer payment function.

Proposition 1.

The optimal regulatory policy under asymmetric information, risk neutrality and full liability is determined by the optimal fine $\delta_f{}^*$, 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 optimal to implement the socially optimal safety design parameter k^{**} that solves (5) , so that

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

The socially optimal sea defence is implemented, that is,

$$a^{**} = a_0 k^{**}$$

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 mark-up, so that

$$T^* = c/_2 \, k^{2**} - \int_{a_0 k}^{\infty} b\left(h - a_0 k^{**}\right)^+ f(h)dh + p_0$$

4. The random payoff in case of flooding is

$$\text{Operator:} \quad \tilde{P}_O(T^*,1) = p_0 + \int_{a_0 k}^{\infty} b\left(h - a_0 k^{**}\right)^+ f(h)dh - b\left(\tilde{h} - a_0 k^{**}\right)^+$$

$$\text{Society:} \quad \tilde{P}_S(T^*,1) = S - T^*$$

III.B. Regulation under 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 proposition 1 that in an optimum

$$\tilde{P}_O = p_O + \delta_f \int_{a_0 k^{**}}^{\infty} b\left(h - a_0 k^{**}\right)^+ f(h)dh - \delta_f b\left(h - a_0 k^{**}\right)^+ < 0$$

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

When the operator has not sufficient solvency to cover the damage cost in case of an extreme flooding we include 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.

Let $\tilde{F} = \min\left\{\tilde{D}, \overline{D}\right\}$ and $\tilde{D} = b(\tilde{h} - a_0 k)^+$ as before, where $\tilde{h}$ is the height of the run up. Then, the operator is fined up to the cap $\overline{D}$; beyond that point the society will bear this risk. This residual risk has possibly a very low probability but severe economic consequences. We assume that this residual risk is less than 1% in engineering projects.

The operator's expected payoff is now

$$E[P_O] = T - c/_2 \, k^2 - \int_{a_0 k}^{\infty} \min\left\{b\left(\tilde{h} - a_0 k\right), \overline{D}\right\} f(h)dh.$$

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

$$\max_{k \geq 0} T - c/_2 \, k^2 - \int_{a_0 k}^{\infty} \min\left\{b\left(\tilde{h} - a_0 k\right), \overline{D}\right\} f(h)dh. \qquad (8)$$

The optimal safety design parameter when the initial value of $\overline{D}$ is 100 million euros.

$$k_{ll}^{*}(100) = 4.110 \text{ and } a_0 k_{ll}^{*}(100) = 6.987 \text{ meters.}$$

The regulator's decision problem is the choice of the capped fine $\overline{D}^{**}$ that maximizes his payoff function.

We assume that the limited liability constraint of the operator is

$$E[\widetilde{P}_O^{\,*}] = \overline{D} - \delta_f \int_{a_0 k}^{\infty} \min\left\{b\left(h - a_0 k_{ll}^{*}\right)^{+} f(h)dh, \overline{D}\right\} + p_O .$$

Thus, the regulator has to pay a liability rent $\Re\left(\overline{D}\right)$ as a function $\overline{D}$ that guarantee no negative payoffs, that is

$$\Re\left(\overline{D}\right) = \overline{D} - \delta_f \int_{a_0 k_{ll}^{*}}^{\infty} \min\left\{b\left(h - a_0 k_{ll}^{*}\right)^{+} f(h)dh, \overline{D}\right\} + p_O . \qquad (9)$$

The optimization problem is then of the form

$$\max_{\overline{D} \geq 0} S - \frac{c}{2} k_{ll}^{2*}\left(\overline{D}\right) - \int_{a_0 k_{ll}^{*}(\overline{D})}^{\infty} b\left(h - a_0 k_{ll}^{*}\left(\overline{D}\right)\right)^{+} f(h)dh - (1-\alpha_R)\Re\left(\overline{D}\right) \qquad (10)$$

Observe that

$$k_{ll}^{**}(\alpha_R) = 4.33 \text{ and } a_{ll}^{**} = a(k_{ll}^{**}) = 7.361 \text{ meters}$$

This socially optimal sea defence $a_{ll}^{**} = 7.361$ corresponds to an optimal cap $\overline{D}^{**}$ of the fine of 115.6 million euros as presented in figure 6. Under limited liability, there is some efficiency loss as the operator will always implement a sea defence below the social optimum, that is,

$$a\left(k_{ll}^{*}(115.6)\right) < a\left(k_{ll}^{**}\right)$$
$$7.008 < 7.361$$

When the operator implements a sea defence $a\left(k_{ll}^{*}(115.6)\right) = 7.008$ meters, the probability that the run up height of the tsunami will exceed the sea defence is 0.90% as presented in figure 8. This is a residual risk and is borne by the society.

The society pays a transfer payment as a function of $\overline{D}^{**}$, that is

$$T_{ll}^{*} = \frac{c}{2} k_{ll}^{2*} + \overline{D}^{**} + p_0 = 88.147 \quad \text{Millions euros} \qquad (11)$$

This is the minimum payment that satisfies the limited liability constraint, that is,

$$E[\widetilde{P}_O(T_{ll}^{\,*}, \overline{D}^{**})] = p_0 + \overline{D}^{**} - \delta_f \int_{a_0 k}^{\infty} \min\left\{b\left(h - a_0 k^{*}\right)^{+} f(h)dh, \overline{D}\right\}$$

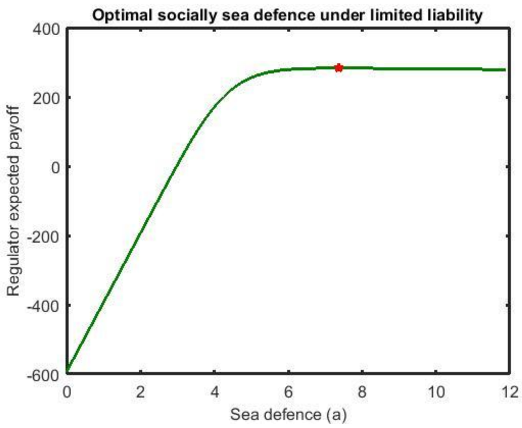

Fig. 5. Under limited liability, the socially optimum sea defence is lower with respect to the full liability case.

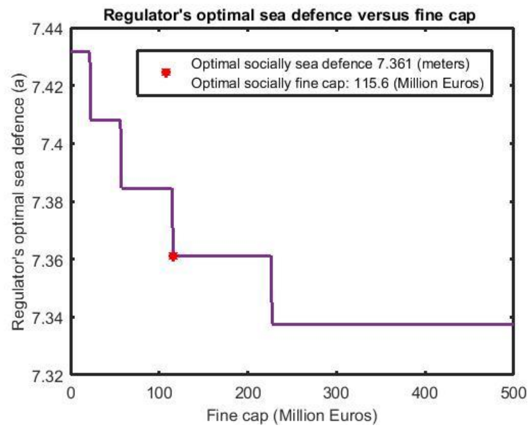

Fig.6. The optimal socially sea defence of 7.361meters induces the regulator to set an optimal cap of 115.6 million euros.

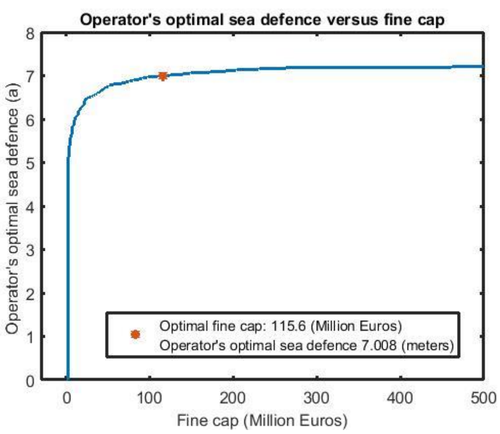

Fig. 7. The optimal cap set by the regulator induces the operator to implement a sea defence of 7.008 meters.

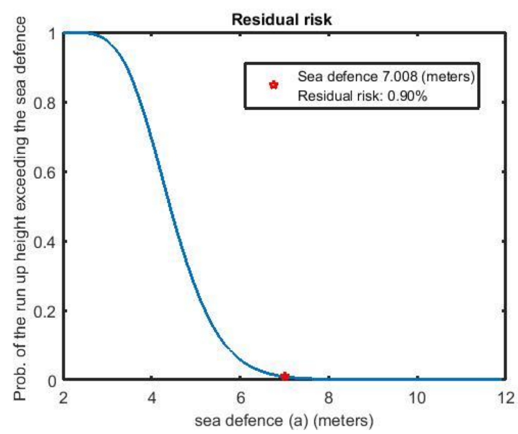

Fig. 8. The implementation of a sea defence of 7.008meters leaves to the society with a residual risk of 0.90%.

Proposition 2.

The optimal regulatory policy under asymmetric information, risk neutrality and limited liability is determined by the capped fine $\overline{D}^{**}$, the optimal payment transfer T_{ll}^{*} and the optimal safety design parameter $k_{ll}^{*}\left(\overline{D}^{**}\right)$.

1. The regulator sets an optimal maximum fine $\overline{D}^{**}$.
2. The operator implements a safety design parameter k_{ll}^{*}, that is,

$$k_{ll}^{*}\left(\overline{D}^{**}\right) < k_{ll}^{**}$$

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

$$a_{ll}^{*} = a_0 k_{ll}^{*}$$

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.

$$T_{ll}^{*} = c/2\, k_{ll}^{2*} - \overline{D}^{**} + p_0$$

4. The random payoff in case of flooding is

Operator: $$\widetilde{P}_O(T_{ll}^{\ *}, \overline{D}^{**}) = p_0 + \overline{D}^{**} - \min\left\{b\left(h - a_0 k_{ll}^{*}\right)^{+}, \overline{D}^{**}\right\}$$

Society: $$\widetilde{P}_S(T_{ll}^{*}, 1) = S - T_{ll}^{\ *} - b(\widetilde{h} - a_0 k_{ll}^{*}) + \min\left\{b\left(h - a_0 k_{ll}^{*}\right)^{+}, \overline{D}^{**}\right\}$$

IV. NO DISCRETION – FIXED POLICY.

Let's consider a better informed pro operator -regulator than the parliament with regards to the cost parameter b which determines the damage cost in case of a flooding. Due to this informational advantage the regulator can manipulate the cost parameter b to benefit the operator in detriment to the society. In order to vanish this incentive, the parliament can impose a fixed payment transfer.

As the cost parameter b is modelled as a random variable defined in the interval $\widetilde{b} = \left[\underline{b}, \overline{b}\right]$. The parliament's expected payoff is of the form

$$E[\widetilde{P}_P] = S - c/2\, k^2 - \int_{\underline{b}}^{\overline{b}} \int_{a(k)}^{\infty} b\left(h - a(k)\right) f(b) f(h)\, db\, dh - \left(1 - \alpha_P\right)\left(\overline{D} - \int_{\underline{b}}^{\overline{b}} \int_{a(k)}^{\infty} \min\left\{b\left(h - a(k)\right)^{+}, \overline{D}\right\} f(b) f(h)\, db\, dh + p_0\right)$$

In this case, a risk-neutral parliament chooses a safety design parameter k_{fix} and a capped fine $\overline{D}_{fix}$ that maximizes her expected value of the payoff.

In light of this, the parliament's optimization problem is given by

$$\max_{D \geq 0} S - c/2\, k^2 - \int_{\underline{b}}^{\overline{b}} \int_{a(k)}^{\infty} b\left(h - a(k)\right) f(b) f(h)\, db\, dh - \left(1 - \alpha_P\right)\left(\overline{D} - \int_{\underline{b}}^{\overline{b}} \int_{a(k)}^{\infty} \min\left\{b\left(h - a(k)\right)^{+}, \overline{D}\right\} f(b) f(h)\, db\, dh + p_0\right) \tag{12}$$

The parliament's optimal safety design parameter k_{fix}^{**} is

$$k_{fix}^{**} = 4.42 \text{ and } a_{fix}^{**} = a(k_{fix}^{**}) = 7.526 \text{ meters}$$

This socially optimal sea defence $a_{fix}^{**} = 7.526$ meters corresponds to an optimal cap $\overline{D}_{fix}^{**}$ of the fine of 278.7 million euros as presented in figure 10.

The parliament imposes the optimal cap $\overline{D}^{**}_{fix}$ inducing the operator to implement a sea defence of 7.455meters as shown in Figure 11. Figure 8 shows the probability that the run up height will exceed a sea defence of 7.455 that is 0.40%. However, such a low residual risk implies a high cost to the society.

The parliament chooses the payment transfer T^{*}_{fix} when the optimal safety design parameter $a^{*}_{fix} = a\left(k^{*}_{fix}\right)$ is implemented. This is because a^{*}_{fix} is independent of T^{*}_{fix}.

The fixed transfer payment is a function of $\overline{D}^{**}_{fix}$ and takes the form

$$T^{*}_{fix} = {}^{c}\!/_{2}\, k^{2*}_{fix} + \overline{D}^{**}_{fix} + p_0 = 251.58 \text{ Million euros} \qquad (13)$$

The parliament imposes an exogenous constraint on the operator's possible payment transfer that accounts for the fact that the operator will not be able to cover losses above $\overline{D}^{**}_{fix}$. The nuclear regulator will be left without discretion to use his expert information. The benefit of this fixed policy is that the rent/efficiency trade-off is evaluated in light with the parliament's choice of the safety design parameter.

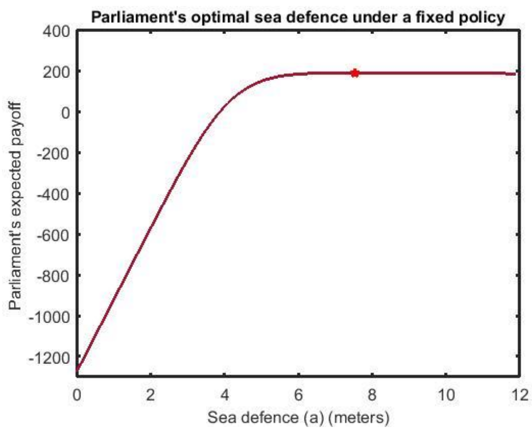

Fig. 9. Under a fixed policy, the parliament chooses an optimal sea defence of 7.526meters.

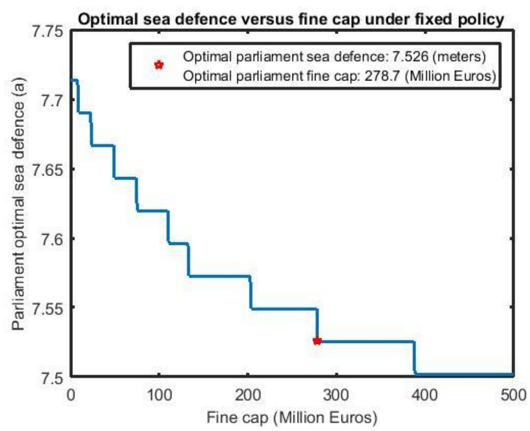

Fig.10. The parliament's optimal sea defence of 7.526meters induces the regulator to set an optimal cap of 278.7 million euros.

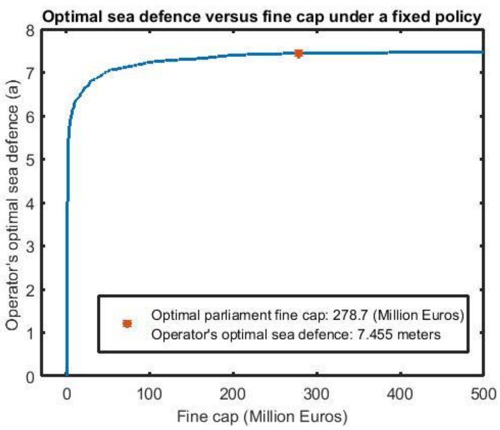

Fig. 11. The optimal cap induces the operator to implement a sea defence of 7.455meters.

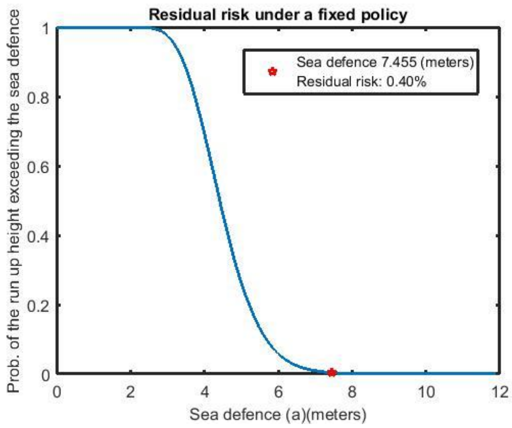

Fig. 12. The implementation of a sea defence of 7.455meters decreases the residual risk left to the society to 0.90% at a cost for the society.

Summarising, we obtain the following result.

Proposition 3.

This fixed policy would be chosen by the parliament without any expert information of the true value of cost parameter b and is determined by the parliament's optimal capped fine $\overline{D}_{fix}^{**}$, the optimal payment transfer T_{fix}^{*} and the optimal safety design parameter k_{fix}^{*}.

1. The parliament sets a capped fine $\overline{D}_{fix}^{**}$.

2. The operator finds optimal to implement the safety design parameter $k_{ll}^{*}(\overline{D}_{fix}^{**})$, that is,

$$k_{ll}^{*}(\overline{D}_{fix}^{**}) < k_{fix}^{**}$$

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

$$a_{fix}^{*} = a\left(k_{fix}^{*}\right)$$

3. The parliament imposes a fixed transfer payment that is a function of $\overline{D}_{fix}^{**}$ and is equivalent to the cost of exerting a safety design parameter, the capped fine, and a mark-up.

$$T_{fix}^{*} = {}^{c}\!/_{2}\, k_{fix}^{*} + \overline{D}_{fix}^{**} + p_0$$

V. LIMITED DISCRETION TO THE REGULATOR.

Imposing a fixed transfer payment prevents the parliament from benefiting from the regulator's expertise with respect to the accurate value of the cost parameter b . Nevertheless, the parliament can take advantage of the regulator's knowledge to some extent by encouraging the regulator to reveal the true value of the cost parameter b through restricting the range of payments that the regulator can transfer to the operator.

In order to carry out this, the parliament specifies the cost parameter space of the regulator $\mathrm{B} = \left[\underline{b}, \bar{b}\right]$ and the payoff function that maps the regulator's announcement of the cost parameter $\hat{b} \in \mathrm{B}$ into an optimal safety design parameter $k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}}$ and an optimal transfer payment $T_{llp}^{*}\left(k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}}\right)$.

This specification enables the parliament to evaluate how the transfer payment to the operator is determined by the regulator's announcement of the cost parameter $\hat{b} \in \mathrm{B}$ and is given by

1. an allocation rule that maps the regulator's announcement $\hat{b}$ of the cost parameter to an optimal safety design parameter $k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}}$.

$$k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}} : \mathrm{B} \Rightarrow \max_{k(\hat{b})\geq 0} S - \frac{c}{2} k^{2}\left(\hat{b}\right) - \int_{a_0 k(\hat{b})}^{\infty} \hat{b}\left(h - a_0 k\left(\hat{b}\right)\right)^{+} f(h)dh - (1-\alpha_P)\left(\overline{D} - \int_{a_0 k(\hat{b})}^{\alpha} \min\left\{\hat{b}\left(\tilde{h} - a_0 k\left(\hat{b}\right)\right), \overline{D}\right\} f(h)dh - p_0\right) \qquad (14a)$$

where the optimal design parameter k_{llp}^{*} increases with $\hat{b}$.

2. a transfer function that maps optimal safety design parameters $k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}}$ to transfer payments $T_{llp}^{*}\left(k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}}\right)$.

$$T_{llp}^{*}\left(k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}}\right) : k_{llp}^{**}(\mathrm{B}) \Rightarrow \frac{c}{2} k_{llp}^{*}\left(\hat{b}\right) - \overline{D}_{llp}^{**} + p_0 \qquad (14b)$$

where the optimal transfer payment T_{llp}^{*} increases with $\hat{b}$.

This specification defines a mechanism. This mechanism stipulates the range of possible transfer payments $T_{llp}^{*}\left(k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}}\right)$ available to the regulator. Equally, this mechanism stipulates the safety design parameters $k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}}$ that the regulator induces the operator to implement in response to the announcement of the cost parameter.

This mechanism, designed by the parliament, can be regarded as incentive compatible if the regulator finds optimal to announce the true value of the cost parameter b . An incentive compatible mechanism has to satisfy two conditions:

1. The truth telling condition implies that the regulator will announce the true cost parameter, that is $\hat{b} = b$, because she will yield a higher payoff than any other announcement.
   The implementation of the safety design parameter $k_{llp}^{*}\left(\hat{b}\right)_{\hat{b}\in \mathrm{B}}$ induced by the regulator's announcement of $\hat{b}$ yields the following payoff.

$$E\left[\widetilde{P}_R\left(\hat{b},b\right)\right]=S-\frac{c}{2}k^*_{llp}\left(\hat{b}\right)-\int_{a_0k^{**}_{llr}\left(\hat{b}\right)}^{\infty}b\left(h-a_0k^*_{llp}\left(\hat{b}\right)\right)^+f(h)dh-$$
$$(1-\alpha_R)\left(\overline{D}^{**}_{llp}-\int_{a_0k^*_{llp}\left(\hat{b}\right)}^{\alpha}\min\left\{b\left(\widetilde{h}-a_0k^*_{llp}\left(\hat{b}\right)\right),\overline{D}^{**}_{llp}\right\}f(h)dh-p_0\right)$$

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

$$b\in\arg\max_{\hat{b}\in B}E\left[\widetilde{P}_R\left(\hat{b},b\right)\right] \qquad (15)$$

2. Monotonicity condition implies that, as the cost parameter increases, the operator's safety design parameter also increases.
The local second order sufficient condition for truth telling becomes:

$$\frac{dk(b)}{d\hat{b}}\geq 0 \qquad (16)$$

As the difference in the weight parameters of the regulator α_R and parliament α_P allocated to the operator's payoff is positive, that is, $\alpha_R-\alpha_P\geq 0$, the regulator can yield higher payoffs by inducing higher sea defences. Therefore, the true telling condition is not satisfied.

As a result of this, the parliament can restrict the level of discretion of the regulator. This restriction takes the form of a cap in the range of cost parameters that the regulator can announce. The optimal cap of the cost parameter limits from above the number of feasible heights of sea defences that the regulator can induce the operator to implement.

In line with this, the characterization of the continuous mechanism takes the form

$$k(b)=\min\left\{k^*_{llr}\left(\underline{b}\right),k^*_{llr}\left(\overline{b}^*\right)\right\}, \qquad (17)$$

where

$$k^*_{llr}\left(\hat{b}\right)_{\hat{b}\in B}$$

is continuous implementable policy fully characterized by an upper threshold $\overline{b}^*$ such that $\underline{b}\leq\overline{b}^*\leq\overline{b}$. Within this interval, the regulator has full discretion in setting up incentive rewards according to its own announcement of the safety design parameter.

The parliament's decision problem is the choice of the cap of the cost parameter that maximizes her payoff. This is given by

$$\max_{\left(\overline{b}^*\in B\right)}S-\frac{c}{2}k^2(b)-\int_{\underline{b}}^{\overline{b}}\int_{a_0k}^{\infty}\min\left\{\underline{b}\left(\widetilde{h}-a_0k(b)\right)^+,\overline{b}^*\left(\widetilde{h}-a_0k(b)\right)^+\right\}f(b)f(h)dbdh-$$
$$(1-\alpha_P)\left(\overline{D}-\int_{\underline{b}}^{\overline{b}}\int_{a_0k(b)}^{a_0k(b)+\frac{D}{b}}\min\left\{\underline{b}\left(\widetilde{h}-a_0k(b)\right)^+,\overline{b}^*\left(\widetilde{h}-a_0k(b)\right)^+\right\}f(b)f(h)dbdh+p_0\right) \qquad (18)$$

where

$$k(b)=\min\left\{k^*_{llr}\left(\underline{b}\right),k^*_{llr}\left(\overline{b}^*\right)\right\}.$$

The regulator's optimal sea defence a^*_{llr} from the parliament point of view is presented in figure 13.

$$k_{llr}^{*} = 4.482 \text{ and } a_{llr}^{*} = a(k_{llr}^{*}) = 7.620 \text{ meters.}$$

The parliament observes that the regulator would choose a higher sea defence a_{llr}^{*} due to a higher weight parameter than the parliament's optimal a_{llp}^{*}.

$$a_{llp}^{*} < a_{llr}^{*}$$
$$7.526 < 7.620$$

As we observe from figure 14, a higher sea defence implies that the regulator sets a lower optimal cap $\overline{D}_{llr}^{**}$ than parliament's optimal, that is

$$\overline{D}_{llp}^{**} > \overline{D}_{llr}^{**}$$
$$278.7 > 177.9$$

As a result of imposing a lower cap to the operator's fine, the operator will find optimal to implement a lower sea defence a_{llp}^{*} as shown in figure 15.

$$a_{ll}^{*}\left(\overline{D}_{llp}^{**}\right) = 7.455 \text{ meters}$$
$$a_{ll}^{*}\left(\overline{D}_{llr}^{**}\right) = 7.385 \text{ meters}$$

The parliament can restore efficiency by setting an upper bound on the cost parameter $\overline{b}^{*} = 445.2$ million euros as presented in figure 16. As we observe from figure 14, setting a cost parameter cap of 445.2 million euros induces the regulator to impose a cap fine equal to parliament's optimal cap fine, such that,

$$\overline{D}_{llr}^{**}(445.2) = \overline{D}_{llp}^{**}(700)$$

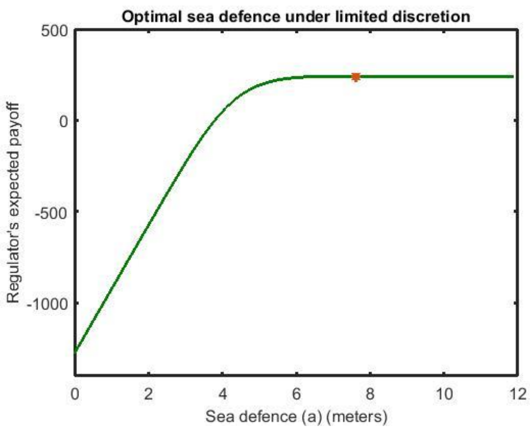

Fig. 13. The regulator's optimal sea defence from the parliament's point view is 7.62 meters which are above the parliament's optimal of 7.596 meters.

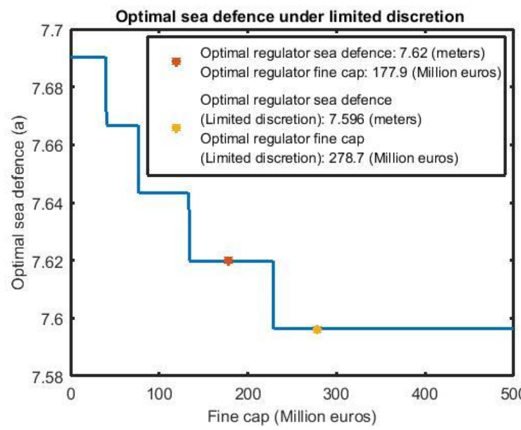

Fig. 14. The regulator would set an optimal fine cap of 177.9 million euros induced by a sea defence of 7.62. By setting an optimal cap of the cost parameter $\overline{b}^{*}$ (limited discretion), the cap fine is raised to 278.7 million euros.

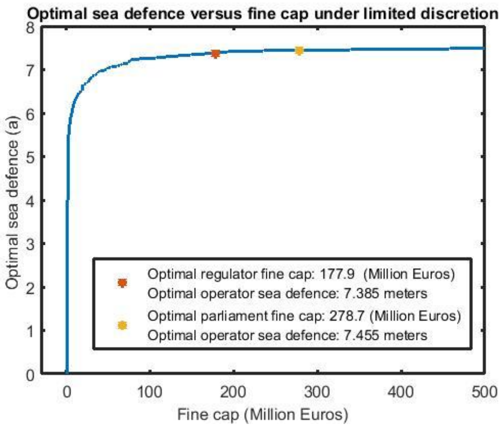

Fig. 15. Setting a cap of the cost parameter $\overline{b}^*$ induces the operator to raise the sea defence from 7.385 to 7.455 due to a raise in the cap fine to 278.7 million euros.

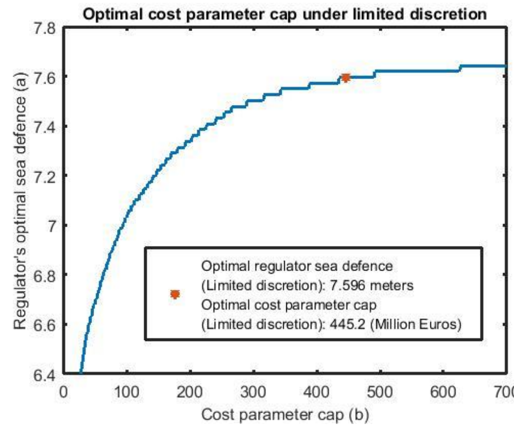

Fig. 16. Setting a cap of the cost parameter $\overline{b}^*$ of 445.2 million euros induces the regulator to choose a sea defence of 7.596 which corresponds to a fine cap of 278.7 million euros.

Proposition 4.

The optimal discretion can be characterized as follows:

1. If $a_{llr}^{**}(\alpha_{R,}\underline{b}) \geq a_{fix}^{**}$, the regulator has no discretion and implements the sea defence a_{fix}^{**} under a fixed policy.

2. if $a_{llr}^{**}(\alpha_{R,}\underline{b}) \geq a_{fix}^{**}$, the regulator has some discretion but no full discretion.

3. The parliament sets a cap to the feasible range of cost parameters $\overline{b}^*$ that the regulator can announce , so that,

$$\overline{D}_{llr}^{**}\left(\overline{b}^*\right) = \overline{D}_{llp}^{**}\left(\overline{b}\right)$$

VI. CONCLUSIONS

This paper 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. However, in the more realistic case where the operator lacks of sufficient assets to cover the damage cost in case of flooding, the risk sharing approach will incur in high costs to the society to compensate the operator for bearing the risk. This cost is also determined by the level of residual risk that the society is willing to accept.

The society demands that critical infrastructures such as chemical plants or nuclear power plants to be safe. Nevertheless, if we want to implement protectionary measures to account for the possibility of a rare event, most projects would be economically unviable. 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 a following dilemma; how much residual risk the society is 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.

Undoubtedly, the risk sharing incentive mechanism has proven useful to vanish the negative incentives in both the downstream and upstream moral hazard. In particular, the regulator's wrong incentives arisen in the presence of regulatory capture can be eliminated to enhance the implementation of protectionary 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 asymmetrical information between the regulator and the parliament with respect to certain parameters determining the damage cost outcome makes this, a non-trivial problem. As a consequence of this, the parliament faces a trade-off problem between how much discretion should be given up and how much expert information should be used up from the regulator.

This paper can be extended to explore how an optimal risk sharing and an optimal cap of the fine would look like under risk aversion. This means that the society and the operator are not only concern about the expected value of the damage cost but also for the magnitude of the damage cost. Another area of work is to include more dimensions to the model by adding more complex safety design parameters and establishing technical relationships between them.

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