Optimal timing of hazardous waste clean-up under an environmental bond and a strict liability rule

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Abstract

This study compares the impacts of an environmental bond and a strict liability rule on a firm's incentives for cleaning up hazardous waste resulting from resource extraction. A stochastic optimal control problem is described by a system of HJB equations. A numerical solution is implemented for the case of a typical copper mine in Canada. The price of copper is modelled as an Ito process and bankruptcy risk as a Poisson process. The impact of the bond depends on whether the firm operates as a going concern, or instead takes account of the possibility of bankruptcy. The bond policy can provide incentives for waste abatement and site clean-up that are greater than or equal to the strict liability rule. Under realistic conditions, the bond encourages stronger abatement and earlier site restoration, while the strict liability rule motivates the firm to remain inactive as a way to delay clean-up costs.

Keywords: Environmental bond; Strict liability; Bankruptcy; Mining; Restoration; Abatement; Stochastic optimal control; HJB equation.

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1 Introduction

Hazardous waste production is a significant consequence of large natural resource projects such as mines. Such waste is often disposed of into local ecosystems and can impose high costs on the environment and society during mining operations and after a mine is abandoned. Without appropriate regulations, profit maximizing firms are likely to generate more waste than is desirable and are unlikely to undertake adequate waste clean-up. This problem is commonly dealt with through the imposition of a strict liability rule,[3] whereby the agent is held legally responsible for waste clean-up or restoration upon project termination.[4] An obligation for restoration under the strict liability rule increases the cost of mine abandonment, which may cause some firms to choose to remain inactive as a way to escape restoration costs, even when there is no hope for reactivation (Muehlenbachs 2015).

Another cause of inadequate waste clean-up is firm bankruptcy. Surveys reveal that large numbers of mining operations in the US and Canada have been abandoned due to bankruptcy resulting in significant environmental damages and clean-up costs. In the event of bankruptcy, the environmental liability may fall to government with restoration costs funded out of general tax revenue, leading to a dead-weight loss (Campbell & Bond 1997). For various reasons, the clean-up cost to government may be higher than for the firm, including the need to hire outside contractors (Ferreira et al. 2004). For governments, the potential for highly negative media coverage and public outrage is another undesirable consequence of firms avoiding their clean-up obligations.[5]

[3]Strict liability refers to the imposition of liability on a firm regardless of whether the firm has adhered to accepted standards of care. This may be contrasted with the negligence standard, where a firm is only liable if it has acted negligently.

[4]Waste clean-up costs are mine specific, can range from millions to billions of dollars for a single mine (Boyd 2002, Grant et al. 2009), and depend on the extent of activity, the expected difficulty of restoration, etc (Grant et al. 2009).

[5]Alberta, Canada, provides a good illustration of these issues where in 2017 and 2018 numerous news articles have appeared detailing the growing stock pile of oil wells that are abandoned with no site clean-up undertaken. In addition, the insolvency of firms has left many so-called "orphan wells" which no longer

In practice, environmental bonds, as a complement to the strict liability rule, have been widely used to address these issues by attempting to ensure adequate funds are available for end-of-activity restoration.[6] Under an environmental bond, a firm estimates and reports its expected future clean-up costs based on current knowledge and deposits a bond of an equivalent amount. The amount deposited for the bond may be updated over time as the firm's expected clean-up costs are revised. The government releases the funds upon successful closure and restoration; otherwise it retains them. Environmental bonds are intended to simulate all future adverse effects, consider them in present terms, and internalize the associated clean-up costs (Perrings 1989).[7] However, without a specific template for cost estimations and also in the absence of a third-party verification, firms may underestimate their clean-up costs. If the bond amount is inadequate and if a firm walks away from its obligation, clean-up costs will be transferred to the government. In 2009, over 10,000 mines operating under an environmental bonding regulation in Canada were classified as abandoned without being cleaned up and with insufficient funds for restoration (Grant et al. 2009). For instance, the Faro Mine in the Yukon Territory set aside \$93.8 million for restoration resulting in a \$356 million liability for government, and the Giant Mine in the Northwest Territories deposited only \$400,000 environmental bonds and transferred \$399 million uncompensated clean-up costs to society (Grant et al. 2009). An adequate level of environmental bond increases the likelihood that a firm will meet its obligation to clean up a contaminated site. This fact is confirmed by an empirical study for the US oil and gas producers (Boomhower 2014).

The objective of this paper is to study the impact of an environmental bond, plus liability for site clean-up, on a firm's optimal operating decisions over the life cycle of a mine. This

have owners to undertake clean-up. For example see Souza et al. (2018), Lewis & Wang (2018), and Morgan (2017).

[6] See Sasson (2009) for a survey of bonding practices in extractive industries worldwide.

[7] Peck & Sinding (2009) note that environmental bonds can be deposited through a variety of mechanisms such as cash deposited in a trust fund, letters of credit, and pledge of assets. The current practices regarding these different mechanisms are surveyed by Miller (2005), and the incentives for environmental protection by US hazardous waste managers under each mechanism are compared in Zhou (2014).

policy will be compared to a policy of strict liability with no bonding requirement. We will refer to the bond plus liability as the 'bonding policy' or just 'the bond', to contrast with the strict liability rule on its own. The goal of the bond is to fully collateralize the government against the possibility that a firm may be unable to clean up its waste.[8] The required payment to the bond in each time period is determined so that clean-up costs would be fully covered should a mine be closed immediately. The bond is in the form of a cash deposit, which is a common form of environmental bond in practice. We consider the impact of different features of the bond, such as whether interest is paid, the inclusion of extra (third-party) costs that the government would incur if it undertakes the clean-up, and the bond service charges such as a risk premium the firm must pay to finance the bond. In order to focus on the clean-up of mine waste, we abstract from any environmental damages caused by waste creation during the production process.

This paper examines two different scenarios: the solvent firm scenario and the bankruptcy scenario. The solvent firm scenario assumes that the firm operates as a going concern and does not consider the possibility of bankruptcy in its optimal choices regarding production, waste abatement, and timing of operations. This may be a reasonable assumption for an individual firm due to the high costs of declaring bankruptcy, including loss of goodwill and reputation. Nevertheless, based on past experience with the mining industry, it is further assumed that the government requires an environmental bond from all mining operations in order to be fully collateralized against any possible losses. The solvent firm may delay clean-up through mothballing, but must eventually undertake site remediation at the expiry of its lease. In the bankruptcy scenario, the firm is assumed to consider the possibility of bankruptcy in its optimal operating decisions. In this paper we consider bankruptcy as an

[8] In this study, we are not concerned about the clean-up of environmental accidents associated with a waste disposal facility, such as accidental release of chemicals. However, environmental bonds and liability rules have been widely used to control environmental risks. Torsello & Vercelli (1998) provides a critical assessment of these policies for risk control, and Poulin & Jacques (2007), Gerard & Wilson (2009), Smith (2012), and Davis (2015) highlight their practical challenges for different case studies relevant to environmental risks.

exogenous event, which depends on commodity prices, and is hence beyond the control of the firm. If the firm goes bankrupt it will no longer be responsible for waste clean-up.

We develop a stochastic optimal control model of a firm's decisions over the life cycle of the mine. An important component of the model developed in this study is that the firm can abate waste during the production process and/or let the waste accumulate to be cleaned up upon mine abandonment, similar to the model of Keohane et al. (2007). Resource prices are uncertain, which affects the optimal timing of production and abandonment, and hence waste accumulation and clean-up. The price of the mine's output is modelled as an Ito process. In the bankruptcy scenario, bankruptcy is modelled as an exogenous risk described by a Poisson process[9] that depends negatively on the price of copper. The mine owner chooses the optimal timing to build, operate, mothball, and eventually abandon the project. During operation, the mine produces waste that accumulates and by legal requirement must be cleaned up when the firm ceases operations permanently (abandonment). Abandonment can be due to low prices, reserve depletion, landfill's capacity exhaustion, or lease expiration, whichever comes first. The firm can undertake abatement during the project to reduce the waste flow. The firm chooses the amount of ore produced and the level of waste abatement to maximize the value of the mining operation. The optimal control model results in a system of Hamilton Jacobi Bellman equations, solved using a numerical approach. The results allow us to contrast the firm's optimal decisions under an environmental bond (plus liability) compared to a strict liability rule on its own.

There are several streams of literature relevant to this study. One stream examines optimal resource extraction decisions under uncertainty and the importance of mine closure costs (Brennan & Schwartz 1985, Mason 2001, Slade 2001, among others). These papers use a real options type framework assuming uncertain output prices and/or costs. Their focus is

[9] A Poisson process has been widely used by authors to model risks in different contexts. For example, this process is used by Insley & Lei (2007) to specify the risk of fire in an optimal tree harvesting model, by Nkuiya (2015) to capture jumps in climate change damage, and by Ayache et al. (2003) to model a default risk for valuing risky debts.

on the option to close temporarily, rather than costly abandonment and final site restoration. A recent study has examined optimal extraction under uncertain resource prices with a fixed abandonment cost, without modelling government policies and abatement decisions, and has shown that abandonment timing depends on the level of reserves and the profitability of the project (Insley 2017).

A second stream of literature addresses policy tools to deal with negative externalities from pollution. It is well known that an appropriate time variable tax rate can, in theory, deal with flow and stock externalities from emissions (Farzin (1996), Baumol & Oates (1988), among others). Keohane et al. (2007) recognized that some types of environmental damage can be controlled both through abatement of emissions and through clean-up and restoration of environmental quality some time after the pollution initially created. Abatement and restoration may be substitutes for each other, whereby more abatement today implies the need for less restoration in future. Keohane et al. (2007) analyze the optimal trade-off between abatement and restoration in a model in which the quality of the environment fluctuates randomly, and there are economies of scale in restoration. They showed that when site restoration is feasible, it is not optimal to depend only on abatement to improve the quality of the environment, as at some low levels of environmental quality or high social damage costs, abatement may become more expensive than restoration. In their model, the regulator sets a tax rate on waste equal to the marginal value of abatement to ensure that firms choose the optimal amount of abatement given the possibility of periodic restoration of environmental quality. Site restoration is assumed to be the responsibility of the government. The funds raised by the tax are shown to be greater than or equal to the cost of restoration, but as the variance of pollution flow goes to zero the tax raised converges to the restoration cost.

A variable tax rate on waste may be difficult to administer, particularly given the unpopularity of taxes in many jurisdictions. In addition, in most jurisdiction firms, rather than governments, are responsible for site restoration. Environmental bonds have been considered as a practical tool to encourage firms to meet their obligations. A stream of the economics literature, dating back to Solow (1971) and Perrings (1989), deals with environmental bonds as a regulatory tool with a focus on conceptualizing and explaining the mechanism of this policy instrument. Other relevant papers examining environmental bonds and liability include Shogren et al. (1993), Cornwell & Costanza (1994), Kaplow & Shavell (1996), Costanza & Perrings (1990), and Gerard & Wilson (2009), among others. Several recent studies have conducted theoretical analyses of environmental bonds and investigate their impact on mining firms' optimal extraction profiles through developing either a firm's problem or a social planner's problem (Igarashi et al. 2010, White et al. 2012, Lappi 2018).

Compared to the existing literature, our paper adds several innovations. First, we consider the full life cycle of a mining project in order to examine the impact of an environmental bond on optimal operating decisions, and in particular, on project commencement and on incentives to site idle in a mothballed stage.[10] Second, we consider the risk of bankruptcy that may occur at any instant during the project life, which in other papers is either ignored (Igarashi et al. 2010, Lappi 2018) or included as a known parameter at project termination date (White et al. 2012). Third, we compare the optimal actions of a firm with and without an environmental bond. Finally, we model the mine's output price as stochastic, in order to capture the effect of price uncertainty on optimal operations, as well as on the likelihood of bankruptcy.

To preview our results, we find that the effect of the bonding policy, relative to the strict liability rule on its own, depends whether the firm takes bankruptcy risk into account in its operation decisions. It also depends on certain key characteristics of the bond – in particular if government pays interest on the bond and whether the firm pays additional bond service charges, such as a risk premium on borrowing to fund the bond. Note that current practice

[10] Lappi (2018) has explicitly modelled production and rehabilitation stages and demonstrates an optimal time for rehabilitation, without modelling the option of temporary closure.

regarding payment of interest on environmental bonds varies across jurisdictions, with some but not all, paying some amount of interest. Also, it would normally be the case that any firm borrowing to finance bond payments would need to pay a risk premium above the risk-free rate.[11] Key results from the two scenarios are summarized as follows.

- Solvent firm scenario:
  - If the firm finances the bond out of retained earnings (or if it can borrow at the risk free rate) and if the government pays the risk-free interest rate on the bond, then the value of the mine prior to construction is the same under the bonding policy and the strict liability rule. The optimal abatement rates are also the same under the two policies, as the bond imposes no extra costs on the firm. This case is not a realistic scenario and is used as a benchmark.
  - If the government pays less than the risk free rate of interest on the bond and/or if the firm finances the bond through borrowing and pays a risk premium or incurs other bond service charges, then the value of the project is reduced compared to the strict liability rule and the firm undertakes a larger amount of waste abatement under the bond. This implies a smaller stock of waste at the termination of the project and lower final clean-up costs. Because the mine is less profitable, it is less likely that the firm will invest in this mine.
- Bankruptcy scenario:
  - When the firm takes the possibility of bankruptcy into account, it considers that in the event of bankruptcy it would no longer be responsible for waste clean-up. Therefore, the requirement of an *ex ante* payment under the bond financed from

[11] Or if the bond is funded from retained earnings or by issuing shares, the cost of capital would also exceed the risk-free rate. This is an extra cost imposed on the firm, and reflects, in part, the market's assessment of the likelihood that the firm will walk away from its obligation. Environmental bond service charges are discussed in White et al. (2012) and White (2015).

retained earnings increases the firm's compliance costs compared to the strict liability rule, resulting in a lower project value and a higher abatement rate under the bond.

– If the firm finances the bond through borrowing, bankruptcy implies the firm avoids its clean-up obligation by defaulting on its loans. In this case, the incentives provided by the bond would be similar to those under strict liability alone. The liability for site clean-up would then be transferred to the lender. However, in practice, this scenario would be less likely given monitoring and performance requirements normally imposed by lenders, which are designed to ensure a firm's actions are not to the detriment of the lender.

A bond sufficient to cover the full cost of immediate clean-up of mine waste ensures that the government will never have to bear these costs. However, certain characteristics of the bond noted above (i.e., bond service charges and payment of interest by the government) make the bond more costly than a strict liability rule for the firm. The bond policy may well give the socially optimal result, if these added costs are less than the extra costs incurred by governments as a result of firms failing to meet their clean up obligations. This paper does not address this question directly, but in Appendix B we provide qualitative discussion of the social planner's problem.

The next section explores the existing literature about restoration and environmental bonds. Section 2 develops the theoretical model. The dynamic programming solution of the model and optimal strategies for extraction and abatement are in Section 3. The case of borrowing to finance the bond is explained in Section 4. Section 5 presents a numerical solution approach. An application of the model to the copper industry is discussed in Section 6. An analysis of the results is provided in Section 7. The last section summarizes results and conclusions.

2 Model formulation

2.1 Description of the decision problem

Consider a firm which extracts a non-renewable resource and thereby generates hazardous waste disposed of into a landfill. A government regulator requires the waste be cleaned up when the operation is terminated. This study assumes that two policies can be implemented: (1) the strict liability rule, and (2) an environmental bond combined with liability for clean-up. We refer to the latter as the bonding policy. For simplicity, we have assumed that there is no risk of accidental release of pollution from the landfill. Therefore, the only environmental obligation is the clean-up of the landfill.

This study considers two scenarios regarding firm behaviour. In the first scenario (referred to as the solvent firm scenario), the firm chooses its optimal actions assuming it is a going concern, ignoring the possibility of bankruptcy. In the second scenario (termed the bankruptcy scenario), the firm takes into account the possibility of bankruptcy in its optimal decisions. It is assumed the firm is of medium or large size and owns a number of mines. The firm's probability of bankruptcy is modelled as an exogenous risk, negatively related to the price of copper. Hence, the probability of bankruptcy is not tied to the value of the individual mine under consideration.[12]

As also noted in the Introduction, the objective of the environmental bond is to fully collateralize the government for the clean-up cost. The bond addresses any inefficiencies that arise when the government is left to clean up a mine site, including any dead weight loss if the cost is funded by general tax revenues, as well as the extra costs involved because the government has less expertise and experience than the mining firm. In this paper, we assume that there are no damages from the flow of waste production or the build-up of the

[12] Note that we are not considering strategic bankruptcy decisions in this paper. This will be the subject of future work.

waste stock prior to a fixed date, denoted by T. By government regulation, waste clean-up must happen before or on this date. This assumption is made in order to focus on the bond, but could be relaxed through the addition of a damage function which depends on the stock of waste.

Before being allowed to develop the mine, the firm enters into an environmental contract with the government specifying the firm's clean-up obligations. Once the firm enters into the environmental contract, it can decide the optimal timing of its initial investment to develop the project, which entails significant capital costs. After the project is launched, the firm manages the level of reserve and the stock of waste by choosing the optimal rates of extraction and abatement, respectively. In addition, the firm maximizes its project value by determining the optimal timing of production, mothballing, reopening the operation, and abandoning the facility and site restoration.

The firm's optimal decisions depend on four state variables: the price of the commodity, $P(t)$, the stock of the resources, $S(t)$, the amount of waste in the land fill, $W(t)$, and the stage of operation, $\delta_i,\ i = 1, 2, 3, 4$. Stage 1 ($i = 1$) is pre-construction, Stage 2 ($i = 2$) is active extraction, Stage 3 ($i = 3$) is mothball or temporary shut down, and Stage 4 ($i = 4$) is abandonment and landfill restoration. The firm has three control variables: the rate of resource extraction, q, the rate of waste abatement, a, and the decision to move to a new stage of operation, δ. We note that δ serves as both a state variable and a control variable in the system of HJB equations. Cash flows depend on the current δ at a particular time t, but as described later, the firm makes choices at discrete times as to whether to move to a different stage.

The commodity price, $P(t)$, is assumed to be described by a simple one-factor Ito process, which is mean reverting in the drift term. As is discussed in Section 6.1, this model has been used by other researchers to describe commodity prices (Schwartz 1997). Under the risk neutral measure,

$$dP(t) = \kappa(\hat{\mu} - \ln P)P\ dt + \sigma P dz;\ P(0) = p_0\ given \tag{1}$$
$$P\ \in [p_{\min}, p_{\max}]$$

where $\kappa, \hat{\mu}, \sigma$ are parameters reflecting the speed of mean reversion, the long run mean of $\ln(P)$, and volatility, respectively. t denotes time where $t \in [0, T]$, and dz is the increment of a Wiener process. The estimation of the parameters is described in Section 6.1. Parameters are estimated for the risk-neutral world, so that the term $\kappa(\hat{\mu} - \ln P)P$ represents a risk-adjusted drift rate.

The level of resource stock, $S(t)$, falls over time at the extraction rate q. The dynamic path of resource stock is given as:

$$dS(t) = -qdt; \quad S(0) = s_0\ given. \tag{2}$$

The waste stock, $W(t)$, as a by-product of the operation, is assumed to be disposed of into a landfill with a known, maximum capacity denoted by $\bar{w}$. By assumption, $\bar{w}$ is specified by regulation and is optimal from society's point of view. During the operation phase, each unit of resource extracted adds to the stock of waste at the constant rate ϕ, and abatement at the rate a reduces the waste flow. Therefore, the rate of change in the volume of waste or in the stock of landfill is given by

$$dW(t) = (\phi q - a)dt;\ W(0) = w_0;\ W(t) \leq \bar{w} \tag{3}$$

in which w_0 represents the initial level of waste that must be cleaned up at the end of operations, where $0 \leq w_0 \leq \bar{w}$, and $\bar{w}$ is set by regulation. The abatement effort is any action, such as recycling the waste, that occurs during the operation phase. Consistent with the model of Keohane et al. (2007), the abatement rate could be higher than the waste generation rate (i.e., $\phi q < a$). It follows that waste abatement could affect the previously generated waste and reduces the waste stock. Abatement is restricted by the installed capital and cannot exceed its maximum value, $\bar{a}$, at each point of time. By assumption, this upper bound does not change over time.

We now specify admissible sets for δ, q, and a. Let Z_δ denote the admissible set for δ where

$$Z_\delta = \{\delta_1, \delta_2, \delta_3, \delta_4\}. \tag{4}$$

We define an admissible set for the extraction rate q, which depends on both the resource stock and stage of operation. Denote this admissible set as $Z_q(S, \delta)$, which is given as follows:

$$\begin{aligned} & q \in Z_q(S, \delta) \\ & Z_q = [0, \bar{q}], \quad \text{if} \;\; S > 0, \;\; \delta = \delta_2. \\ & Z_q = 0, \quad \text{if} \;\; S = 0, \;\; \delta = \delta_2. \\ & Z_q = 0, \quad \text{if} \;\; \delta = \delta_i, \;\; i = 1, 3, 4, \;\; \forall S. \end{aligned} \tag{5}$$

By assumption, the extraction rate cannot exceed its maximum rate $\bar{q}$. This upper bound is known as the capacity constraint and is assumed to remain constant during the operation.

Similarly, we define an admissible set for a, denoted $Z_a(w, q, \delta)$, as follows:

$$\begin{aligned} & a \in Z_a(w, q, \delta) \\ & Z_a = [0, \bar{a}], \quad \text{if} \quad 0 < W < \bar{w}, \;\; \delta = \delta_2 \\ & Z_a = [0, \phi q], \quad \text{if} \quad W = 0, \;\; \delta = \delta_2 \\ & Z_a = [\phi q, \bar{a}], \quad \text{if} \quad W = \bar{w}, \;\; \delta = \delta_2 \\ & Z_a = 0, \quad \text{if} \quad \delta = \delta_i, \;\; i = 1, 3, 4, \;\; \forall W. \end{aligned} \tag{6}$$

It is assumed that $\bar{a} > \phi\bar{q}$, implying that the firm can abate at a rate that exceeds the waste level generated when extraction is at the maximum $\bar{q}$. Note that Equations (2)–(6) imply that

$$0 \le W \le \bar{w} \tag{7}$$
$$0 \le S \le s_0$$

The characteristics of extraction costs are given in Assumption 1. Let $(C^q)' \equiv \frac{\partial C^q(\cdot)}{\partial q}$ and $(C^q)'' \equiv \frac{\partial^2 C^q(\cdot)}{\partial q^2}$.

Assumption 1 *The extraction cost function $C^q(q)$ is linear in the extraction rate so that $C^q(0) = 0$, $(C^q)'(\cdot) \ge 0$, and $(C^q)''(\cdot) = 0$.*

The non-renewable resource extraction literature typically assumes that extraction costs are convex with respect to extraction levels and the remaining stock of reserve.[13] For simplicity we have adopted this linear functional form, as well as an upper limit on the extraction rate. This simplified cost function has been used in some other papers such as Roan & Martin (1996), who note that it is appropriate for "mining for disseminated ore such as occurs in many gold deposits in the western states, where open pit methods of extracting the ore are used" (page 189).[14]

Assumption 2 gives the cost of abatement as a convex function of abatement, implying that removing each additional unit of pollution is increasingly difficult and more costly to the firm. Use similar notation as for Assumption 1 to denote derivatives.

[13]See the paper by Farzin (1996), for example, which assumes resource exploitation costs are convex in both extraction and remaining reserves.

[14]Mason (2001) uses a fixed extraction cost. Slade (2001) (page 207) estimates extraction cost functions for copper mines in Canada finds that "costs are higher when ore grade, capacity utilization, and remaining reserves are lower," and "reserves respond positively to higher prices but not to lower costs."

Assumption 2 *The abatement cost function, $C^a(a)$, is assumed to be twice differentiable with $C^a(\cdot) \geq 0$, $C^a(0) = 0$, $(C^a)'(\cdot) \geq 0$, $(C^a)''(\cdot) \geq 0$, and $(C^a)'''(\cdot) = 0$.*

Convexity in abatement costs is a common assumption in the literature, such as in Farzin (1996) and Keohane et al. (2007).

Restoration affects the stock of waste, rather than the flow. To ease the analysis, it is assumed that periodic restoration is not possible, and thus abatement is the only way to maintain the quality of the environment during the active life of the project.

2.1.1 An environmental bond

To model the mechanism of an environmental bond, we assume that the firm must deposit an amount with the government prior to project commencement sufficient to cover clean-up costs of waste generated during construction. The value of the environmental bond has to be adjusted periodically during the life of the project based on the firm's estimated restoration costs. Therefore, at the end of each period, the firm submits a revised cost estimate and the government adjusts the amount of deposited bonds according to these estimates. The value of the environmental bond in any period must completely cover the closure costs if the firm were to abandon the mine at the end of the current period. We assume that the appropriate level of restoration and the associated cost are correctly determined and thus the bond level is appropriate.

One important policy consideration is that the firm is required to estimate the closure costs based on the fact that a third party will do the restoration should the firm default on its clean-up obligation. It has been found in practice that it is more costly for a third party to clean up environmental damages than for the firm itself by 15% to 30% (Ferreira et al. 2004). This additional amount internalizes third-party costs such as mobilization costs (White et al. 2012, Peck & Sinding 2009). Therefore, requiring restoration cost estimates to be made on the basis of expenses to a third party ensures sufficient funds for the required clean-up should the firm walk away from its obligations (Grant et al. 2009, Otto 2010). This study assumes a convex cost function for clean-up given by Assumption 3. As the stock of waste increases, it becomes increasingly more difficult to return the land to its pristine state. Therefore, additional waste requires additional costs for removing a greater volume of waste and, depending on the degree of toxicity, requires greater safety precautions for workers during restoration. Moreover, the cost of stabilizing the waste to prevent geographical expansion can increase with waste volume (Phillips & Zeckhauser 1998). As a result, more waste requires more clean-up effort which becomes more costly at the margin.

Assumption 3

- *We define the firm's clean-up costs by $C^f(W)$ and the third party's clean-up costs by $C^{tp}(W)$, so that $C^{tp}(\cdot) = \nu C^f(\cdot)$ where $\nu > 1$ is a constant.*
- *The firm's cost of cleaning up the accumulated waste and improving the quality from the state W to zero waste is given by $C^f(W)$ with $(C^f)'(\cdot) \geq 0$, $(C^f)''(\cdot) \geq 0$, and $(C^f)'''(\cdot) = 0$.*
- *It is assumed that $C^f(W)$ is truthfully estimated and reported by the firm.*

The assumption of a convex clean-up cost is consistent with assumptions in White (2015) and White et al. (2012).

Let $B(t)$ denote the total value of the bond at each point of time. This value varies according to rate of change in the firm's restoration costs adjusted by potential expenses to the third party, $\frac{dC^{tp}(W)}{dt}$. In fact, the variation of the environmental bonds over each period (i.e., the annual cost of bonds to the firm) denoted by $\frac{dB(t)}{dt}$, is given by

$$\begin{aligned} \frac{dB}{dt} &= \frac{dC^{tp}(W)}{dt} \\ &= \frac{dC^{tp}}{dW}\frac{dW}{dt} \\ &= \theta(W)(\phi q - a) \end{aligned} \tag{8}$$

where $\frac{dC^{tp}}{dW} \equiv \theta(W)$, and $\frac{dW}{dt} = \phi q - a$ is given by Equation (3). $\theta(W)$ is defined as the marginal restoration cost or the amount that the government collects on the waste flow over a given time interval. Therefore, the firm's rate of payment on bonds to the government at each time (i.e., $\frac{dB}{dt}$) is given by $\theta(W)(\phi q - a)$, which could be positive, negative, or zero. If waste creation exceeds abatement ($\phi q > a$), the firm will have to make a deposit to the bond. If $\phi q < a$, the firm will receive a refund on the bond. If $\phi q = a$, the bond value is unchanged. Therefore, there is a trade-off between the decision to abate today to reduce the waste stock, versus posting to the bond today to be used for future clean-up at the terminal time. Note that $\theta(W)$ increases linearly in W, and is determined based on the company's estimate of the change in restoration costs to a third party as W changes.

Let $B_0 = C^{tp}(W(0))$ cover the potential clean-up cost of the initial waste. B_0 has to be deposited with the government before the operation starts. According to Peck & Sinding (2009), this mechanism provides adequate assurance for the existence of funds for future clean-up because it "raises money according to the initial footprint and [is] linked to marginal increases or decreases in mine footprint over its life". Since the estimated restoration costs are higher than the costs to the firm by an amount ν (see Assumption 3), the difference will be returned to the firm at project termination. We refer to this saving as restoration benefit defined by Assumption 4.[15]

[15]Note that in practice, a firm may go bankrupt, and would thereby forfeit the bond refund. This case is not considered in this paper.

Assumption 4 *Under bonding requirements, the firm receives a refund from restoration at the project termination date equivalent to* $(\nu - 1)C^f(W)$*,*[16] *which is the difference between the firm's estimated restoration costs to a third party and its actual costs of restoration, and* $\nu > 1$*.*

We allow for the possibility that the government pays interest paid on the bond at the risk-free rate, r.[17] While the project is operating, the annual compliance cost with the environmental bond has three components: 1) the cost of abatement effort, 2) the expected bond payment, and 3) any interest paid on the bond. Therefore, the annual compliance cost is defined by

$$\Omega = C^a(a) + \mathbf{1}_{b=true}[\theta(W)(\phi q - a) - rB]. \tag{9}$$

where $\mathbf{1}$ is the indicator function and $b = true$ under the environmental bonding policy and is false otherwise.

2.1.2 The strict liability rule

Under the strict liability rule, the regulator requires the firm to clean-up the stock of waste once the project terminates, and does not require *ex ante* payments for associated costs. Moreover, termination entails sunk costs to the firm. Therefore, we can adjust Assumption 4 as follows

Assumption 5 *Under liability requirements, the firm's restoration cost at the terminal point,* T*, is* $C^f(W)$*.*

[16] According to Assumption 3, the benefit of restoration of $[C^{tp}(W) - C^f(W)] = [\nu C^f(W) - C^f(W)] = (\nu - 1)C^f(W)$ where $\nu > 1$.

[17] Note that in Section (4) we also consider the case where the firm borrows at rate $\rho > r$ to finance the bond. For clarity in describing the model, we ignore this possibility at the moment.

While the project is operating, the annual compliance cost with the strict liability rule is associated with abatement efforts. In Equation (9) the last two terms on the right hand side disappear as $b =$ false.

2.1.3 Instantaneous cash flow

The firm's objective is to choose controls to maximize the discounted sum of expected cash flows under the risk neutral measure.[18] Cash flows at any time t will depend on the firm's stage of operations, δ, rate of abatement, a, and extraction, q. Instantaneous cash flows are given as follows:

$$\pi(t) = P(t)q - C^q(q) - \left[C^a(a) + \mathbf{1}_{b=true}\theta(W)(\phi q - a) - \mathbf{1}_{b=true} rB\right] - C_i^m, \quad \text{if} \quad \delta = \delta_i, \quad i = 1, 2, 3. \tag{10}$$

$$\pi(t) = 0, \quad \text{if} \quad \delta = \delta_4.$$

in which the term in square brackets is the compliance cost, Ω, as previously given by Equation (9). C_i^m refers to fixed costs under both the bond and strict liability policies in stage i. Because the tax treatment of bonds varies across jurisdictions, we have chosen to ignore taxes in our model specification.[19]

2.2 Defining state and control variables, and the value function

The resource price, $P(t)$, resource stock $S(t)$, waste stock, $W(t)$, and stage of operation, $\delta(t)$, all represent state variables in the decision problem. The value of the firm's operations

[18] The risk neutral measure (or Q-measure) means that the risky factor (price) is modelled as a risk adjusted process, implying that the risk free rate is the appropriate discount rate. This approach is common in the real options literature and is described in Dixit & Pindyck (1994).

[19] Tax issues include whether the money paid into the bond is deductible for income taxes, whether interest paid to finance the bond is deductible, and whether the bond refund is taxable. See Sasson (2009).

is a function of these state variables and time, t, denoted as $V(P,S,W,\delta,t)$.

It is assumed that at specific fixed times, the firm makes a decision about whether to move to another stage of operation. These fixed decision times are given as follows:

$$\mathcal{T}_d \equiv \{t_0 = 0 < t_1 < ... < t_m <, ..., t_M = T - 1\} \tag{11}$$

where we assume that the optimal decision to move to another stage of operation occurs instantaneously at $t \in \mathcal{T}_d$. Note that at the end of the project life, T, the firm's only option is to terminate the operations. Therefore, time T is excluded from the firm's optimal decisions dates in the above set. Choices regarding optimal rates of abatement, a, and extraction, q, are made in continuous time at time intervals given as follows:

$$\mathcal{T}_c \equiv \{(t_0,t_1), ..., (t_{m-1},t_m), ..., (t_{M-1},t_M)\}. \tag{12}$$

Since we search for the closed loop control, we assume the controls are in feedback form, i.e., functions of the state variables.[20] Control variables can be specified as: $q(P,S,W,\delta,t)$, $a(P,S,W,\delta,t);\ t \in \mathcal{T}_c$, and $\delta^+(P,S,W,\delta,t);\ t \in \mathcal{T}_d$. Admissible sets for q, a and δ are given as Z_q, Z_a and Z_δ, specified in Equations (5) and (6), and (4). We specify a control set which contains the controls for all $t_0 \leq t \leq t_M$.

$$K = \{(\delta^+)_{t\in\mathcal{T}_d}\ ;\ (q,a)_{t\in\mathcal{T}_c}\} \tag{13}$$

Regardless of the controls chosen, the value function can be written as the expected discounted value of the integral of cash flows under the risk neutral measure, given the state

[20]Closed loop controls are, of course, superior to open loop controls, which are functions only of time.

variables, with the expectation taken over the controls:

$$V(p, s, w, \bar{\delta}, t) \; = \; \mathbb{E}_K \left[\int_{t'=t}^{t'=T} e^{-r(t'-t)} \; \pi(P(t'), S(t'), W(t'), \delta) \; dt \; + e^{-r(T-t)} V(P(T), S(T), W(T), \delta(T), T) \right. \\ \left. \middle| P(t) = p, S(t) = s, W(t) = w, \delta(t) = \bar{\delta} \right]. \tag{14}$$

where $(p, s, w, \bar{\delta})$ denote realizations of the random and path dependent variables (P, S, W, δ). r is the risk-free interest rate, and $\mathbb{E}[\cdot]$ is the expectation operator, given a filtration $\mathcal{F}_t$. The value in the final time period, T, depends on the current operating state. If the project is in the mothballed or active operations state just prior to period T, then its value in period T is the expected net benefits from closing and restoring the mine, since this is required by regulation. If the project is already abandoned then the value in period T is zero, as clean-up costs will have already been paid. If the project is pre-construction, then the value in time T is also zero. This is described in Appendix A as a boundary condition.

2.3 The solvent firm versus bankruptcy scenarios

We define two scenarios depending on whether the firm will take into account the possibility of declaring bankruptcy in its operation decisions:

- **The solvent firm scenario:** We assume that the firm operates as a going concern and ignores the possibility of bankruptcy. The firm assumes it will always be solvent. However, the government requires an environmental bond for all mining operations in order to be fully collateralized against any possible losses. This is reasonable based on the government's past experience with default of mining firms.
- **The bankruptcy scenario:** We assume that the fortunes of the mining firm are

closely tied to commodity prices, so that low commodity prices can cause bankruptcy. We specify the risk of bankruptcy, captured by $d\varphi$, as a Poisson process so that

$$d\varphi = \begin{cases} 1 & \text{with probability} \quad \lambda(P)dt \\ 0 & \text{with probability} \quad 1 - \lambda(P)dt \end{cases} \tag{15}$$

where $\lambda(P)$ represents the hazard rate over the infinitesimal interval dt and is given by

$$\lambda(P) = \frac{k_0}{P} \tag{16}$$

in which k_0 is a positive constant. Equation (15) implies that the firm is always bankrupt at very low prices (if $P \to 0$), and is never bankrupt at significantly high prices (if $P \to \infty$).

Note that if in Equation (16) we set $k_0 = 0$, we will get the solvent firm scenario. Therefore

$$\lambda(P) = \begin{cases} 0 & \text{in the solvent firm scenario} \\ k_0/P & \text{in the bankruptcy scenario,} \quad k_0 > 0 \end{cases} \tag{17}$$

The next section develops a dynamic programming solution for each scenario.

3 Dynamic Programming Solution

Equation (14) is solved backwards in time using dynamic programming. For a particular $t_m \in \mathcal{T}_d$, we define t_m^- and t_m^+ to represent the moments just before and after t_m. Specifically $t_m^- = t_m - \epsilon$ and $t_m^+ = t_m + \epsilon$, $\epsilon \to 0^+$. As a visual aid, the times around t_m and t_{m+1} are depicted below, going forward in time:

$$t_m^- \to t_m \to t_m^+ \to t_{m+1}^- \to t_{m+1} \to t_{m+1}^+ \,. \tag{18}$$

At t_m we determine the optimal control δ^+, while in the interval (t_m^+, t_{m+1}^-). We solve for the optimal controls q and a in continuous time.

3.1 Determining optimal rates of abatement, a, and extraction, q, from $t_{m+1}^- \to t_m^+$

We first start with the bankruptcy scenario as this allows us to formulate a general solution for both the solvent firm and bankruptcy scenarios. Let V represent the project value prior bankruptcy, and V_{bankrupt} be the project value after bankruptcy. Using a standard contingent claims approach,[21] we can derive a system of partial differential equations that describe the value of the resource, V, in the interval (t_m^+, t_{m+1}^-) for all operating states except for abandonment.

$$\begin{aligned}
&\frac{\partial V}{\partial t} + \frac{1}{2}\sigma^2 p^2 \, \frac{\partial^2 V}{\partial p^2} + \kappa(\hat{\mu} - \ln p)p \, \frac{\partial V}{\partial p} \\
&+ \max_{q,a} \, \Big\{ - q \, \frac{\partial V}{\partial s} + (\phi q - a) \, \frac{\partial V}{\partial w} + \pi(t) \Big\} \\
&- \lambda(p)\big(V_{\text{bankrupt}} - V\big) + rV = 0, \quad \text{for } \delta = \delta_i, \quad i = 1, 2, 3
\end{aligned} \tag{19}$$

where we maximize with respect to the control variables a and q, and $\pi(t)$ refers to net cash flows as defined in Equation (10).

Since the bankrupt firm no longer has the right to extract, the project generates no value following a bankruptcy implying $V_{\text{bankrupt}} = 0$. Therefore, the term $\lambda(p)\big(V_{\text{bankrupt}} - V\big)$ explains the net loss in the project value should a bankruptcy occur. In the solvent firm scenario, the hazard rate, $\lambda(p)$, is zero and V in Equation (19) represents the value of the project during the project life.

[21]See Oksendal & Sulèm (2005) for a detailed treatment. Dixit & Pindyck (1994) provide an excellent introduction to contingent claims analysis.

We can now define the system of partial differential equations for both scenarios as follows

$$\frac{\partial V}{\partial t} + \mathcal{L}V + \max_{q,a} \left\{ -\, q\, \frac{\partial V}{\partial s} + (\phi q - a)\, \frac{\partial V}{\partial w} + \pi(t) \right\} = 0, \quad \text{for } \delta = \delta_i, \quad i = 1, 2, 3 \tag{20}$$

in which $\mathcal{L}V$ is the differential operator as follows

$$\mathcal{L}V = \frac{1}{2}\sigma^2 p^2\, \frac{\partial^2 V}{\partial p^2} + \kappa(\hat{\mu} - \ln p)p\, \frac{\partial V}{\partial p} + \big(r + \lambda(p)\big)V \tag{21}$$

where $\lambda(p)$ is given by Equation (17).

Once the project is in Stage 4, the project value goes to zero.

$$V(p, s, w, \delta = \delta_4, t) = 0. \tag{22}$$

Note that there is a switching cost to move to Stage 4, as specified in Section 3.2.

We analyze the firm's investment decisions under the risk neutral of $\mathbb{Q}$ measure which allows us to use a risk-free interest rate as well as risk-adjusted parameters for the commodity price and for the probability of bankruptcy. The risk due to price volatility can be captured by deducting the market price of price risk from the drift rate (see Section (6.1)). This market price reflects an additional return over the risk-free interest rate that the market demands per unit of price volatility.

As is discussed in Insley & Lei (2007) and in Ayache et al. (2003), there are two approaches to hedging a jump risk due to bankruptcy (or other causes). One is to assume the risk is fully diversifiable in a portfolio of assets. In this case the asset would generate no extra return for an investor due to bankruptcy risk and it can be assumed that the real world probability of bankruptcy is equal to the risk-neutral probability. The second approach is to assume that the risk of bankruptcy can be hedged by trading another asset which faces the same risk. In this case, the market price of a jump-related risk (i.e., bankruptcy risk in our study) will be used in the valuation model instead of the actual probability (i.e., the historical probability of bankruptcy in our study). This implies that, in our study, $\lambda(p)$ in Equation (21) should be replaced by the market price of bankruptcy risk reflecting an additional return over the risk-free interest rate that the market requires to obtain per each unit of potential loss in the project value due to bankruptcy. The market price of bankruptcy risk reflects the market's perception of the bankruptcy risk and could be higher from the historical bankruptcy risk. It has been observed that the corporate bond yields exceed the risk-free rate by an amount greater than what is justified by historical default rates (Amato & Remolona December, 2003).

This study assumes that the risk from price volatility can be hedged and the risk-adjusted parameters of the commodity price including the market price for the price risk are estimated using futures prices. However, estimating the market price of bankruptcy risk is beyond the scope of this paper and instead we discuss the sensitivity of our results to the parameter of the hazard function in Section 7.2.2.

3.2 Determining optimal operating stage, δ at t_m

For $t_m \in \mathcal{T}_d$, the firm checks to determine whether it is optimal to switch to a different operating stage. The firm will choose the operating stage which yields the highest value net of any costs of switching. Let $C(\delta^-, \delta')$ denote the cost of switching from stage δ^- to δ'. Recall that $t = t^-$ represents the moment before t_m and $t = t^+$ denote the instant after t_m. Solving going backward in time, and noting the optimal stage is denoted as δ^+, the value at t_m^- is given by:

$$\begin{aligned} V(p, s, w, \delta^-, t_m^-) &= V(p, s, \delta^+, t_m^+) - C(\delta^-, \delta^+) \\ \delta^+ &= \arg\max_{\delta'} \, [V(p, s, w, \delta', t_m^+) - C(\delta^-, \delta')]. \end{aligned} \tag{23}$$

Switching costs differ under the bond and strict liability policies for project commencement as well as for mine abandonment. Opening the mine under the bond requires the investment cost and initial bond payment, whereas the latter is absent under the liability rule. Denoting the investment cost with I, the cost of opening the mine is given as

$$C(\delta_1, \delta_2) = I + \mathbf{1}_{b=true} B(w_0) \tag{24}$$

The cost to switch to Stage 4 (abandonment) from either Stage 2 (operating) or Stage 3 (mothballed) is given by

$$C(\delta_i, \delta_4) = -[\mathbf{1}_{b=true} C^{tp}(w) - C^f(w)] \qquad i = 2, 3. \tag{25}$$

Under strict liability this is just the firm's own clean-up cost $C(\delta_i, \delta_4) = C^f(w) > 0,\ i = 2, 3$. Under the bonding policy, the firm will receive a refund of the bond equal to $C^{tp}(w)$ which exceeds the expenditures required for the firm to implement the clean-up, $C^f(w)$. Hence under the bond policy $C(\delta_i, \delta_4)$ will be a negative cost, i.e., it is a restoration benefit to the firm. Switching costs between other stages are set as constants, as detailed in Section 6.

3.3 Optimal extraction and abatement policies

The decision problem specified in Equations (20)–(23) has no closed form solutions and is solved using a numerical approach, which is discussed in the next section. In this section, we examine the first order conditions for extraction and abatement which hold during in Stage 2, $\delta = \delta_2$, when the firm is actively producing the ore. These first order conditions reveal the nature of the optimal extraction and abatement rates, denoted a^* and q^*, and in particular whether the solutions are bang-bang.

3.3.1 An environmental bond

The optimal extraction rate, q^*, and the optimal abatement rate, a^*, under bonding requirements are obtained by maximizing Equation (20) with respect to the terms that contain q and a. The optimal extraction rate for a firm that actively extracts under a bonding policy satisfies

$$P - C'^{q} - \frac{\partial V}{\partial s} + \phi\Big[\frac{\partial V}{\partial w} - \mathbf{1}_{b=true}\; \theta(w)\Big] \begin{cases} \geq 0 & \Rightarrow q^* = \bar{q} \\ < 0 & \Rightarrow q^* = 0 \end{cases} \tag{26}$$

The first three terms in Equation (26) are the marginal revenue from extraction, marginal cost of extraction, and marginal value of the reserve to the firm. We have called the term in square brackets the firm's *marginal cost of waste build-up* which has two components: 1) the marginal value of the waste stock to the firm, $\frac{\partial V}{\partial w}$, and 2) the marginal restoration cost, $\mathbf{1}_{b=true}\; \theta(w)$. The total marginal cost of extracting a reserve is captured in the terms to the right of P.

Remark: Since both the profit function and the resource stock are linear in extraction rate, the optimal extraction rate, q^*, is either zero or at capacity, hence this is a bang-bang solution.

It follows that given an optimal abatement rate, the firm extracts at capacity as long as the marginal effect is positive. For zero marginal effect, the firm remains indifferent between extracting at capacity or not extracting at all, and thus it is reasonable to extract at capacity. Therefore, the firm extracts at capacity as long as the marginal revenue of extraction is not lower than its total marginal costs.

The optimal abatement under a bonding policy is given by

$$-C'^{a}(a^*) = \frac{\partial V}{\partial w} - \mathbf{1}_{b=true}\; \theta(w) \Rightarrow \begin{cases} 0 \leq a^* \leq \bar{a} & \text{if} \quad 0 < w < \bar{w} \\ 0 \leq a^* \leq \phi\bar{q} & \text{if} \quad w = 0 \\ \phi\bar{q} \leq a^* \leq \bar{a} & \text{if} \quad w = \bar{w}. \end{cases} \tag{27}$$

Along the optimal abatement path, the marginal cost of environmental degradation, $\frac{\partial V}{\partial w} - \theta(w)$, is equal to the marginal abatement cost. If abatement is costlier than environmental degradation at the margin, the polluter reduces its abatement effort and posts environmental bonds instead, until it remains indifferent between abating and polluting. In contrast, if the costs of environmental degradation are larger than the abatement costs at the margin, the optimal strategy is to increase abatement until the equality in Equation (27) holds. Thus according to the optimal policy rule, pollution should be abated up to the point that the marginal costs of abatement equal the potential marginal costs of the environmental degradation. Once the landfill capacity is reached, the lowest optimal abatement rate equals the waste build-up rate. This condition ensures that the landfill does not receive waste beyond its capacity.

A comparison between optimal criteria in Equation (26) and the optimal extraction policy with no environmental interaction in Brennan & Schwartz (1985) and the subsequent studies reveals that in our study the firm has to take into account costs of waste accumulation including the cost of clean-up (i.e., $\phi\Big[\frac{\partial V}{\partial w} \; - \; \mathbf{1}_{b=true} \; \theta(w)\Big]$) when choosing the optimal extraction rate. These terms were zero in such previous studies. Therefore, the firm may require a relatively higher price to start its operation, because accounting for costs of waste accumulation in the profit function increases the operational costs and reduces the private net benefit of extraction.

3.3.2 The strict liability rule

The optimal rules for extraction and abatement are also given in Equations (26) and (27) but the indicator function will be zero. The firm's *marginal cost of waste build-up* under the liability rule is simply the marginal value of the waste stock. Similar to the bond, the firm operating under the liability rule extracts at either zero or at capacity, because both the profit function and the resource stock are linear in extraction rate. A comparison between optimal criteria for extraction and abatement under the bond and the liability rule reveals that the payment for the marginal restoration cost, $\theta(w)$, does not appear under the latter.

4 The case of borrowing at a risk premium

As noted, in the solvent firm scenario, the value of the mine is specified in the Q-measure, which means that risk due to uncertain commodity prices is taken into account via the risk-adjusted parameters in the commodity price model. The solvent firm is assumed to operate as a going concern, and hence does not consider the possibility that it might not meet its clean-up obligation due to bankruptcy. Using standard contingent claims arguments, it is therefore appropriate to use the risk-free discount rate in our valuation model and this fully accounts for the opportunity cost of the bond to the firm.

However, in reality, the model as outlined in Section 2 for a solvent firm is unlikely to adequately reflect the true cost of the bond to the firm. As is discussed by White et al. (2012) and White (2015), a firm will typically be subject to additional costs, such as a bond service charge (largely a risk premium) assessed by a surety company. The risk premium would reflect the market's assessment that a firm might not meet its clean-up obligations, even though the firm fully intends to do so. To take account of this extra cost of the bond, we consider a case in which the solvent firm is assumed to borrow to finance the bond and must pay a premium over the risk-free rate, which accounts for the market's perception of risk and other bond service charges.

In the bankruptcy scenario, the probability of bankruptcy is under the Q-measure, which implies the risk of bankruptcy reflects the extra return demanded by the market to undertake a project with bankruptcy risk. In other words, the impact of the risk of bankruptcy is fully accounted for in the model, eliminating the need to include a risk premium for borrowing.

The model can easily be adjusted for the case where the firm borrows at rate $\rho >$

r to finance the bond. Assume that the government pays interest on the bond. Hence, Equation (9) which specifies annual compliance costs becomes:

$$\Omega = C^a(a) - \mathbf{1}_{b=true}(\rho - r)B. \tag{9b}$$

where ρB denotes the interest payments the firm makes on the loan at each period prior to abandonment.

At the time of project commencement, the firm borrows $B(w_0)$ which is deposited into the bond. Since there will be no net cash outflow associated with the bond, the cost to move from Stage 1 to Stage 2 is just the construction cost. Equation (24) is adjusted to become:

$$C(\delta_1, \delta_2) = I \tag{24b}$$

If the firm chooses to close the project (i.e., go to Stage 4), the firm receives a refund of the bond from the government which is used to pay off the loan. Hence the net cash flow at closure reflects the clean-up cost. Equation (25) becomes:

$$C(\delta_i, \delta_4) = -C^f(w) \qquad i = 2, 3. \tag{25b}$$

It is interesting to note that if $\rho = r$, the bonding policy gives the same annual compliance costs and switching costs as the strict liability rule. However, this bond fully collateralizes the government should a bankruptcy occurs, while this is not the case under the strict liability rule.

5 Numerical solution approach

Equations (20)–(23) represent a stochastic optimal control problem which must be solved using numerical methods. The computational domain of Equation (20) is $(p, s, w, \bar{\delta}, t) \in \Gamma$ where $\Gamma \equiv [0, p_{max}] \times [0, s_0] \times [0, \bar{w}] \times Z_\delta \times [0, T]$. p_{max} is chosen large enough to approximate an infinite domain. The numerical value chosen for p_{max} is \$30 per pound. As seen in Figure 1, from 1995 to 2015 copper prices fluctuated between less than U.S \$1 per pound to just under U.S. \$4.50 per pound. Increasing p_{max} to \$50 did not change the results appreciably. More details are given in Appendix A where boundary conditions are specified for the PDEs. $\mathcal{L}V$ in Equation (20) can be discretized using a standard finite difference approach. The other terms in the equation are discretized using a semi-Lagrangian scheme as described in Chen & Forsyth (2007) and will not be described further here.

Recall that the optimal control for q which we denote by q^* is bang-bang so that $q^* \in \{0, \bar{q}\}$. To determine the optimal control we search over the set $(q, a) \in \{0, \bar{q}\} \times Z_a$. We discretize the controls $a \in Z_a$ and determine the optimal control by exhaustive search at each point in the state space (p, s, w, t). Hence we make no assumption about the convexity of the value function.

6 An application to the copper industry

To illustrate the impact of an environmental bond versus the strict liability rule on optimal firm decisions, this study considers the case of investment decisions for a copper mine. A numerical example is developed based on available data from an open-pit copper mine in British Columbia, supplemented by researcher assumptions when data is lacking. The parameters of the stochastic model assumed for copper prices are estimated using copper futures contracts. We will use these estimated parameter values to solve the mine valuation

κ	0.0264 (0.001)	Root Mean Square Error	0.07
μ	2.7051 (0.079)	Mean Absolute Error	0.05
η	2.7845 (0.026)	Log-likelihood function	9652
σ^2	0.0458 (0.002)	Number of observations	937

Table 1: *Estimation results for the one-factor copper price model using Kalman Filter. RMSE, MAE, μ, and η are in terms of US \$/lb. Standard errors are in parenthesis. Weekly futures data from Aug 1st, 1997 to Jul 13th, 2015.*

problem.

6.1 Estimating the parameters of the price process

The parameters of Equation (1) are estimated in the risk-neutral world. We define the parameter $\hat{\mu} = \mu - \eta$ so that the market price of risk, η, is deducted from μ which is the long-run mean of $ln(P)$ before adjusting for the price risk. The market price of risk reflects additional returns that the market demands over the risk-free interest rate per each unit of price volatility, σ. Note that in the stochastic price process $\kappa > 0$, $\mu > 0$, $\sigma > 0$, and $\eta > 0$. These parameters are estimated using data for copper futures prices, reflecting current market expectations. Estimation results are provided in Table (1).

To obtain estimates, we have used a Discrete Kalman Filtering approach and a Maximum Likelihood Function.[22] This study uses weekly data for copper futures contracts traded on the London Metal Exchange (LME).[23] The estimation is done for six futures contracts dated from August 1997 to July 2015, with 1, 6, 11, 16, 21, and 24 months to maturity.[24] To find real copper prices, futures prices are deflated by the US Consumer Price Index. Due to the lack of data on copper spot prices, futures contracts closest to maturity proxy the market spot prices (Schwartz 1997). The Root Mean Square Error (RMSE) and Mean Absolute

[22]These methods are explained in Schwartz (1997).

[23]Data for this study were collected from Datastream.

[24]Long maturity contracts are of most interest as the goal of this study is to value a long-term investment project.

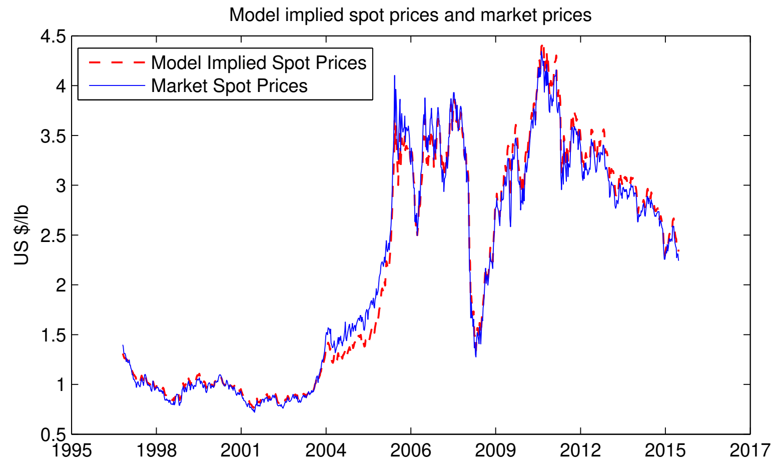

Figure 1: *Model implied copper spot prices and market copper prices. Weekly data from Aug 1st, 1997 to Jul 13th, 2015. Nominal prices are deflated by the US Consumer Price Index, base year=2007.*

Error (MAE) of the estimates of log futures prices are 7 cents per pound and 5 cents per pound, respectively. All parameter estimates are significant. These findings suggest that the one-factor model provides a good tracking of the copper market prices as shown in Figure (1).

6.2 Project specification

The numerical example is based on data from Copper Mountain which is an open-pit mine located in south-western British Columbia which had an expected mine life of 15 years when it was first proposed. In 2007, the Copper Mountain project proceeded to a feasibility study to construct an open-pit mine at the estimated cost of US $380 million. An additional US $5 million for the feasibility study, environmental testing and geological consulting increased the construction cost to US $385 million. This mine had a production target of 78.2 million pounds of copper per year, starting from June 2011, with an estimated average production cost of US $1.35 per pound of copper. The fixed cost of sustaining capital are estimated to be US $1.66 million per year. The mine's average strip ratio (i.e., waste/ore) is 1.5 pounds of waste per each pound of ore extracted.

Additional assumptions required for the numerical example are described below. By assumption, the maximum amount of waste that is allowed to be generated during the life of project is 2200 million pounds. The parameter of the clean-up cost function is calibrated based on the data provided by the Financial Assurance Guideline for determining the closure cost of a landfill provided by the Government of Ontario (2011).[25] It is further assumed that the maximum feasible rate of abatement can be twice as high as the waste build-up rate, i.e., $\bar{a} = 2\phi\bar{q}$.[26] This assumption allows for the possibility that the abatement rate may exceed the deterioration rate.

Launching the project with liability requirements entails fixed costs of US \$385 million, whereas the bonding policy imposes an additional cost on the firm that is the initial amount of the bond adjusted by the third-party expenses. The third-party cost that reflects administrative costs, mobilization costs, etc is assumed to be 30% of the firm's restoration cost. Either mothballing the mine or resuming operations after mothballing are assumed to entail an up-front cost of \$5 million. It is further assumed that remaining in the mothballed stage costs \$1 million per year for environmental monitoring and maintenance. Note that in Equation (10) in the production phase, C_2^m equals the fixed costs of sustaining capital, while at the mothballed stage C_3^m is the summation of costs for sustaining capital, $C_3^{m_1}$, as well as for environmental monitoring and maintenance, $C_3^{m_2}$. Table (2) summarizes the parameter values used for the numerical example. Recall that taxes are not included in the analysis.

[25]In this guideline, the estimated closure cost of a landfill with $60,000$ tonnes capacity is around US \$3 million. After transforming tonnes to pounds, we have calculated the total closure cost of a landfill with 2200 capacity equivalent to US \$49.895 million, i.e., $C^f(\bar{w}) = 49.895$. Then, $\beta = 49.895/\bar{w}^2 \simeq 10^{-5}$. This estimate is intended to provide a rough order of magnitude for clean-up costs. This guideline is available at https://www.ontario.ca/document/f-15-financial-assurance-guideline-0.

[26]This study sets the abatement ceiling high enough so that the likelihood it binds is small, because abating at high rates is prohibitively expensive.

Life of project		$T = 15$	years
Risk-free rate*		$r = 0.02$	per year
Bond service charges*		$\rho = 0.05$	per year
Max. price in computational domain*		$p_{max} = 30$	\$/lb
Initial reserve		$s_0 = 1173$	million lb
Strip ratio (waste:ore)		$\phi = 1.5 : 1$	
Production capacity		$\bar{q} = 78.2$	million lb/year
Abatement ceiling*		$\bar{a} = 2\phi\bar{q}$	million lb/year
Landfill capacity*		$\bar{w} = 2200$	million lb
Extraction cost parameter	$C^q(q) = \gamma q$	$\gamma = 1.35$	\$/lb
Abatement cost parameter*	$C^a(a) = \alpha a^2$	$\alpha = 10^{-3}$	
Firm's clean-up cost parameter**	$C^f(w) = \beta w^2$	$\beta = 10^{-5}$	
3rd party cost adjustment factor***		$\nu = 1.30$	
Hazard function*	$\lambda(p, w) = k_0/p$	$k_0 = 10^{-1}$	
Project stages		$\delta_1,\ \delta_2,\ \delta_3,\ \delta_4$	
Fixed decision time*		τ_d	every year
Construction cost	I	\$385	million
Cost to mothball and reactivate*	$C(\delta_2, \delta_3), C(\delta_3, \delta_2)$	\$5	million
Fixed costs of sustaining capital	$C_2^m,\ C_3^{m_1}$	\$1.66	million/year
Fixed monitoring costs while mothballed*	$C_3^{m_2}$	\$1	million/year

Table 2: *Parameter values and functional forms for the prototype open-pit copper mine. All dollar values are based on 2007 US dollars.* **Assumed by the authors.* **β *is calibrated based on landfill closure costs provided by the Government of Ontario 2011.* ****From Ferreira et al. (2004).* Other values are from 2007 feasibility study conducted by the Copper Mountain Mining Corporation.

7 Results analysis

This section compares the impacts of the environmental bond and the strict liability rule on the firm's optimal investment decisions as indicated by critical prices. In addition, we compare the project value and optimal abatement decisions, under each policy and each scenario. Results are presented first for the the solvent firm scenario and next for the bankruptcy scenario. Note that the quantitative results at each stage of the project are dependent on the current values of the state variables – the resource stock, resource price, level of the waste stock, and time. To depict the results graphically, we must choose representative values for the state variables. However, the numerical solution is available over the full ranges of the state variables.

The results for the bonding policy depend on the particular characteristics of the bond. In this paper, we focus on whether government pays interest on the bond and whether the firm pays a premium on loans to finance the bond. Regarding the interest paid by the government, we contrast cases when the bond pays either zero interest or the risk-free interest rate. In the analysis, we examine the case where the bond must cover the full costs of clean-up to the government, which are assumed to be 30% higher than if the firm did the clean-up itself (i.e., $\nu = 1.3$ in Assumption 3). We do not show the results for cases where the bond is set at the firm's own estimated clean-up costs (i.e., $\nu = 1$) as these results are quantitatively close to $\nu = 1.3$, but the government is not fully collateralized for the cost of clean-up, which is the objective of the bond.

This paper focuses on the impact of these policies on the firm's optimal behaviour. In Appendix B, we briefly discuss the bonding polices in terms of the social planner's problem.

7.1 The solvent firm scenario

7.1.1 Valuation results

We begin by showing how the value of the mining project varies with the price of copper, the stock of waste, and the level of copper reserves. This is depicted in Figure (2) for the case of strict liability. Diagrams for the bond paying the risk-free interest rate are similar, and are not shown. The value of the investment project is depicted prior to construction at the initial time, $t = 0$. The left-hand panel of Figure (2) shows the value of the project across different starting prices and different levels of reserve prior to initial investment, when the

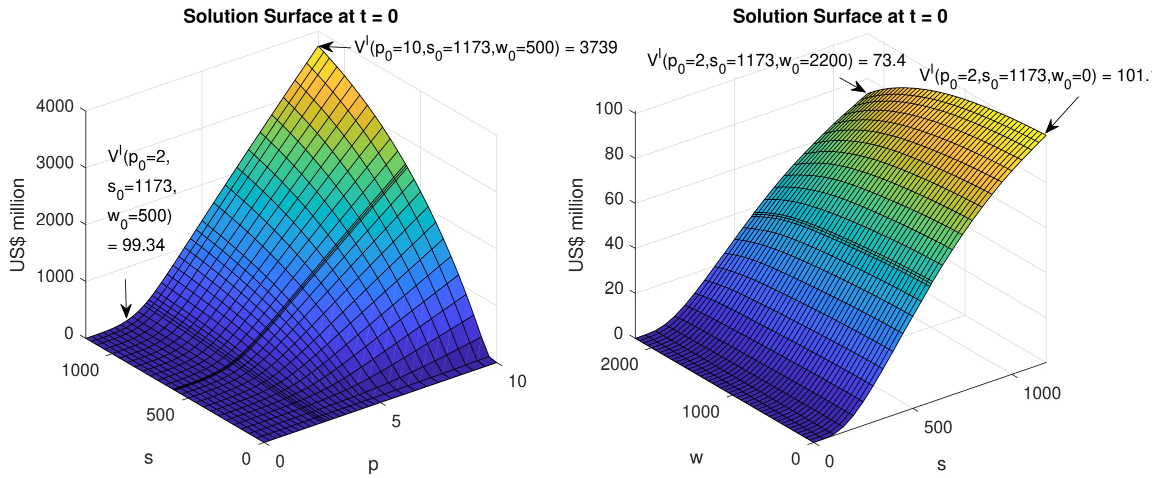

Figure 2: *Project value prior to construction under the strict liability rule. In the left-hand panel, the level of waste is fixed at* $w_0 = 500$ *million pounds, and in the right-hand panel, the price is fixed at \$2/pounds.* s_0 : *million pounds,* p : *US\$/pound,* w : *million pounds.*

starting level of waste is at 500 million pounds.[27] We observe, as expected, that there is an increasing trend in the value of the project with respect to prices and reserve levels.

The right-hand panel in Figure (2) represents the value of the project across different resource stock levels and different levels for the starting value of waste as a result of construction, when the price of copper is \$2/pound. Recall that the initial level of waste refers to the waste that would be created immediately, should the firm begin construction. At a given level of initial reserve, generating a larger amount of waste during the construction phase reduces the project value by increasing the firm's cost of complying with the strict liability rule during the extraction phase and at project termination. A larger initial waste implies that the landfill capacity will bind faster during the operation, and thus once the construction is completed, the operating firm will have to exercise more abatement to maintain space in the landfill. In addition, the firm's liability costs at project termination date rise as more waste builds up. For the prototype project with $s_0 = 1173$ million pounds, the

[27]The 500 million pounds of waste is chosen for the purpose of illustration only. Changing the initial level of waste changes the project value but the intuition remains the same.

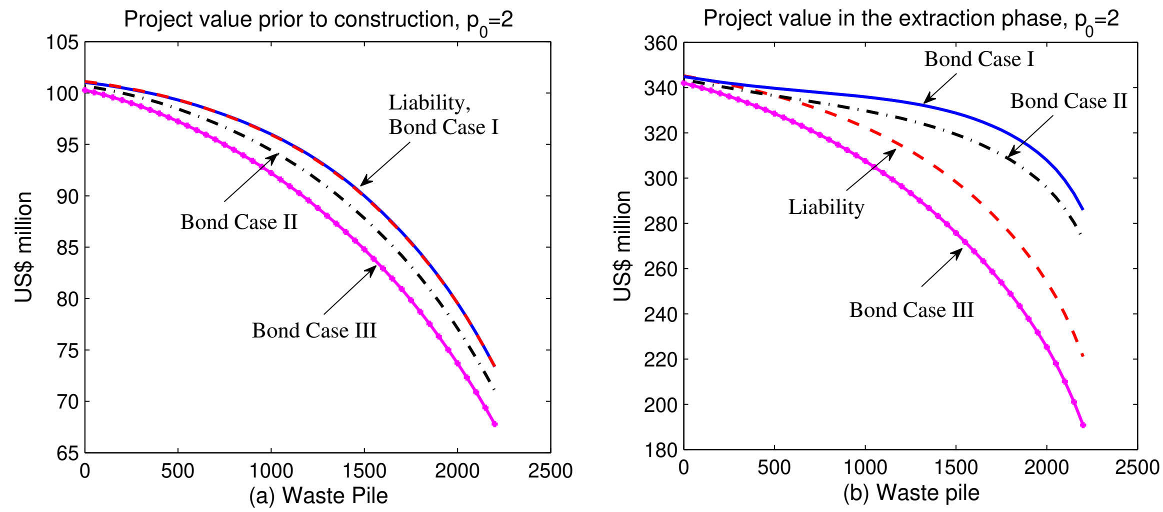

Figure 3: *A comparison of project value (a) prior to construction and (b) during the active extraction under the strict liability rule and the three bond cases, for* p_0 *=$2/pound and* $s_0 = 1173$ *million pounds.*

project value prior to construction ranges from \$73.4 million to \$101.1 million depending on the severity of damage during the initial construction.

Figure (3) compares the project value prior to construction and during the extraction phase under the strict liability rule and the bonding policy. This figure is shown for one realization of the copper price and full reserves at the initial time $t = 0$. Three cases are analyzed for the bond:

- **Case I:** The bond is financed from retained earnings and the firm receives the risk-free rate of interest on the bond ($r = 2\%$).
- **Case II:** The bond is financed from retained earnings and the government pays no interest on the bond.
- **Case III:** The firm borrows at a premium over the risk-free rate ($\rho = 5\%$) and the government pays no interest on the bond.

Panel (a) of Figure (3) shows that the value of the project under the bond for Case I is identical to the strict liability rule.[28] This follows because the interest paid on the bond is the same as the discount rate, with the implicit assumption that the firm can borrow or lend at the risk-free rate.As long as the solvent firm receives the risk-free rate on the bond, it will be indifferent between paying clean-up costs via the bond as waste accumulates, or delaying payment of clean-up costs to the end of the project. If no interest is paid on the bond (Case II), the bond is more burdensome to the firm, reducing the value of project compared to Case I. Under the realistic assumption in Case III that the firm can only borrow at rate ρ, which is higher than the risk-free rate, the project value is reduced even further.

Panel (b) of Figure (3) compares the values of project in the production phase (Stage 2) when operations have commenced. To reach Stage 2, the firm must pay an initial amount into the bond, which reflects the waste stock generated to initiate operations. For a firm in Stage 2, this initial payment is a sunk cost, and thus does not influence the project value in the extraction phase. It follows that the value of the project under the Case I bond will be higher than for the strict liability rule, where all clean-up costs will be paid at project termination. Hence, we see in panel (b) that the curve reflecting the bond in Case I lies above the liability curve. If the firm is paid no interest on the bond as in Case II , the value of the project is reduced compared to Case I, but still higher than the liability. Under Case III, when the firm must borrow at a risk premium, the value of the project is reduced even further and falls below that of the strict liability rule.

7.1.2 Optimal abatement rates

The left-hand panel of Figure (4) compares the optimal abatement rate in the production phase (Stage 2) versus the waste stock at time zero, for the strict liability rule and the three different bond cases. Note that the optimal abatement rates are all the same when

[28]Note that this identical result holds only when the risk of bankruptcy is ignored, as will make clear in Section (7.2).

the landfill is at capacity, because at this point the only way that the firm can continue production is to abate all of the waste as it is created.

For intuition about abatement rates, it is helpful to consider the optimal abatement condition expressed in Equation (27), whereby the marginal cost of increasing abatement by one unit on the left hand side is set equal to the marginal cost of waste build-up on the right hand side. The marginal cost of waste build-up to the firm differs across the different cases. For the strict liability rule, the marginal cost of waste build-up consists solely of $\frac{\partial V}{\partial w}$, which reflects the cost of using up capacity in the landfill as well as adding to future clean-up costs. For the bond in Case I, the marginal cost of waste build-up includes $\frac{\partial V}{\partial w}$ as well as the marginal cost of posting the bond, $\theta(w)$. Since costs of clean-up are paid immediately by posting the bond, $\frac{\partial V}{\partial w}$ in Case I reflects only the cost of using up landfill capacity net of the marginal restoration benefit and any interest paid on the bond. As long as the firm receives the risk-free interest rate on the bond, it will be indifferent between posting the bond when the waste is created or paying for clean-up at project termination. Hence, the abatement rates for Case I and the liability rule are identical.

If there is no interest paid on the bond (Case II), $\frac{\partial V}{\partial w}$ becomes more negative relative to Case I, because the foregone interest represents an additional cost of paying clean-up costs up-front. Hence the marginal cost of waste build-up is higher in Case II than Case I. This motivates the firm to abate at a higher rate than under strict liability (or the bond in Case I) over all waste levels, as can be seen in panel (a) of Figure (4). The marginal cost of waste build-up for the firm in Case III is even higher than in Case II. The requirement to borrow to finance the bond at a risky interest rate, combined with the fact that no interest is paid by government on the bond, means that increasing the waste stock becomes even more costly for the firm. $\frac{\partial V}{\partial w}$ is more negative as a result, motivating additional abatement compared to the strict liability rule or the other bond cases.

The right-hand panel of Figure (4) shows the marginal waste build-up cost of the strict

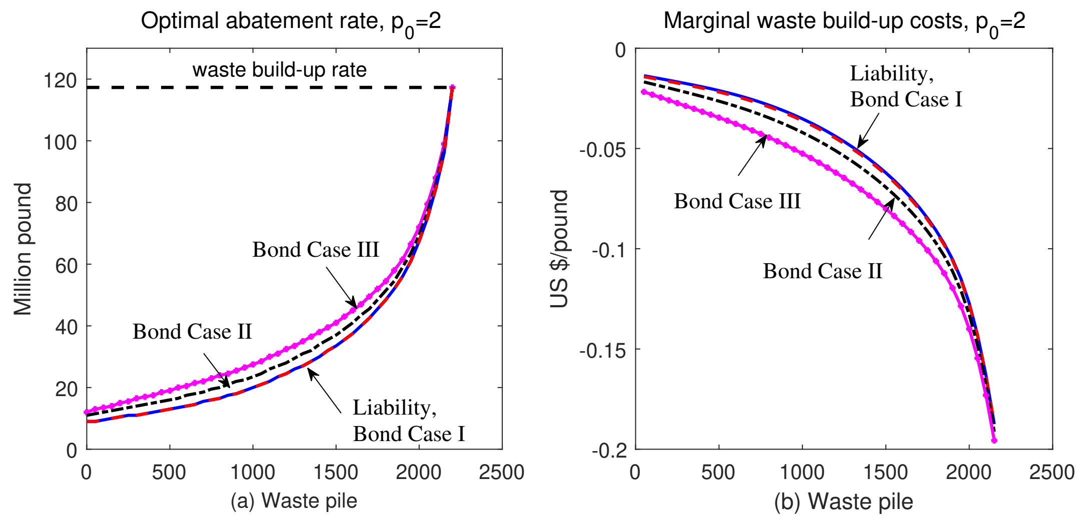

Figure 4: *A comparison of (a) optimal abatement incentives and (b) marginal waste build-up costs, at each level of initial waste under the strict liability rule versus three bond cases, at* p_0 *=\$2/pound and* $s_0 = 1173$ *million pounds.*

liability rule and the three bond cases. A more negative marginal waste build-up cost at a given level of waste implies a higher optimal abatement rate. Therefore, this diagram is the mirror image of the left-hand panel of Figure (4).

Another interesting result is the trade-off between abatement and the bond payment in Stage 2, as shown in Figure (5) for the Case I bond. Panel (a) in the figure shows the optimal abatement rate versus the waste stock for two different copper prices. Panel (b) shows the corresponding payments into the bond. At low levels of waste, the optimal abatement rate increases as more waste accumulates but is not high enough to create a significant change in the stock of waste. Consequently, the firm's payment to the bond increases with waste accumulation. At higher levels of waste, when the landfill is reaching its capacity, the firm's optimal abatement effort progressively increases. As a result, waste accumulates at a slower rate and thus the payments to the bond gradually diminish. Once the landfill capacity is reached, the only way to continue operations is to abate at least at the deterioration rate. If abatement fully offsets the deterioration rate so that the level of waste does not change,

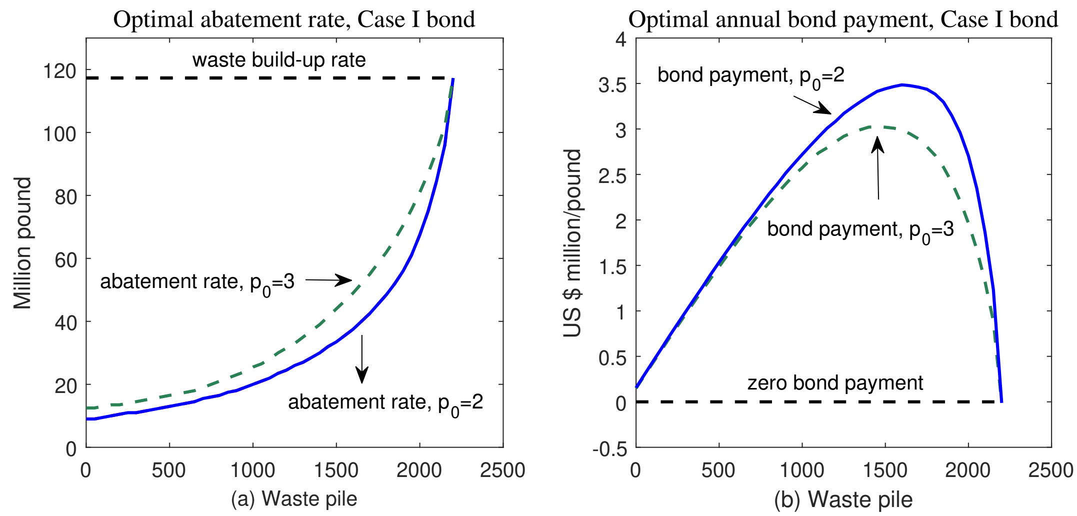

Figure 5: *Optimal rate of abatement and optimal expected bond payment across waste accumulation at the operating stage under the bond in Case I, for two price levels and* $s_0 = 1173$ *million pounds, at time zero.*

the expected bond payment is zero. This trade-off does not exist under the liability rule, because restoration costs are not required until the project terminates. At the higher price, the project is more profitable which motivates the firm to maintain more capacity in landfill by abating at a higher rate compared to the lower copper price. Note that at a zero level of initial waste, the firm still exercises a positive abatement rate because the extraction activity is creating a flow of waste (see Equation (27)). We have not shown Cases II and III, as the intuition is the same. However, the expected bond payments for Case II and Case III are lower than Case I, due to higher abatement.

7.1.3 Optimal choice of project stages

We examine the lowest copper prices at which it is optimal to switch from one stage to another, which we refer to as critical prices. Critical prices are optimally determined based on Equation (23) and change with the level of reserve, size of waste stock, and time. For example, for $s_0 = 1173$ and $w_0 = 500$ million pounds, Figure (6) illustrates the value of the

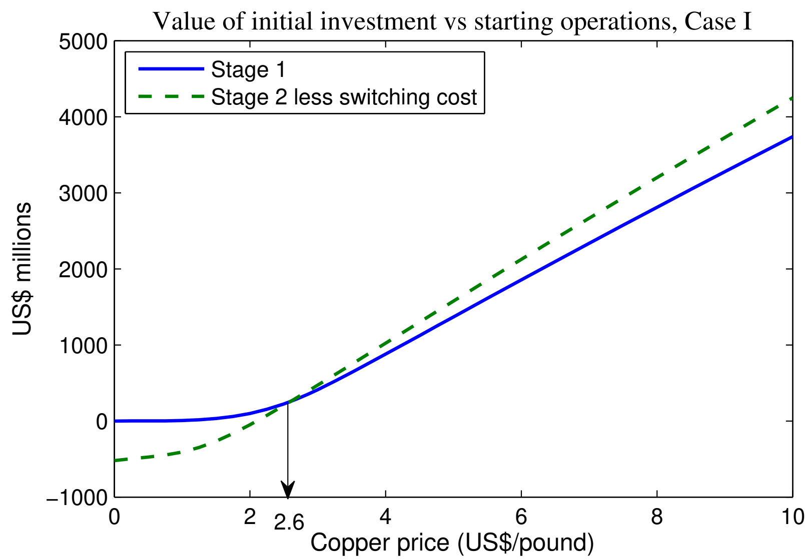

Figure 6: *Value of initial investment and beginning production (Stage 1 to 2) under the bond in Case I (identical to the strict liability rule), given* $s_0 = 1173$ *and* $w_0 = 500$ *million pounds.*

project in Case I prior to the initial investment (Stage 1) and once the operation has started (Stage 2) net of the up-front costs of construction and initial bond payment. These values are plotted across copper prices up to US$10 per pound. It is optimal to start extraction activities once the value in Stage 2 less switching costs exceeds the value in Stage 1. Therefore, it is not optimal to incur the construction cost until copper prices increase to US$2.6 per pound. Before this threshold, the net present value prior to incurring switching costs is positive and higher than the net present value of the operating option. Thus, there is an opportunity benefit to waiting for a higher price before beginning operations.

The first column of Table (3) shows the critical prices to move from one stage to another stage at time zero when switching entails up-front costs, given $s_0 = 1173$ and $w_0 = 500$ million pounds, for the bond in Case I. If per pound copper prices become as low as US$1.39, the optimal strategy is to mothball current activity and to remain idle until the prices increase to US$1.51. This is the lowest price that encourages reactivation. The inactive firm can also choose to terminate the project and carry out the restoration work. Critical prices that

Transition from:	$s_0 = 1173$	$s_0 = 587$
Stages 1 to 2: Begin production	2.60	3.00
Stages 2 to 3: Mothball	1.39	1.48
Stages 3 to 2: Reactivate	1.51	1.63
Stages 2 to 4: Abandon	1.09	1.17
Stage 3 to 4: Abandon	0.71	0.77

Table 3: *Critical prices (US\$/lb) at time zero under the bond in Case I (identical to the strict liability rule), for $s_0 = 1173$ and $s_0 = 587$ million lb, given $w_0 = 500$ million lb.*

trigger termination from the mothballed stage tend to be as low as US\$0.71 per pound.

The critical prices in Table (3) shown for $t = 0$ imply that the firm would not directly abandon the project from the operating stage at the early life of the project. This can be seen by noting that the critical prices to mothball from Stage 2 are above the prices for abandonment from Stage 2. This means that the firm will always go through the mothballed stage first before abandoning. However these critical prices reflect optimal decisions for an operating project at time zero. We would expect that if the time left in the life of the project is small and mothballing costs are non-negligible, it may be optimal to abandon directly from the operating stage. In this numerical example, we find that when there are two years left in the life of the project, it is optimal to abandon without first mothballing over all levels of waste.[29]

Critical prices are sensitive to the level of reserve, which has previously been described by Insley (2017). The second column of Table (3) shows that critical prices, under the bond that pays interest, are higher at all stages if half of the reserve is used up, assuming $w_0 = 500$ million pounds. The initial investment occurs at higher prices for lower initial reserves due to the sizable fixed construction costs. After the project is launched, as the reserve depletes and becomes more scarce, its shadow value increases (i.e., a larger $\partial V/\partial s$ in Equation (20)). Thus, the firm needs to obtain higher prices to reopen or mothball the activity. Finally, the

[29]Recall that the firm that is actively extracting has an obligation to terminate the project at $T = 15$ directly from the extraction phase regardless of prices.

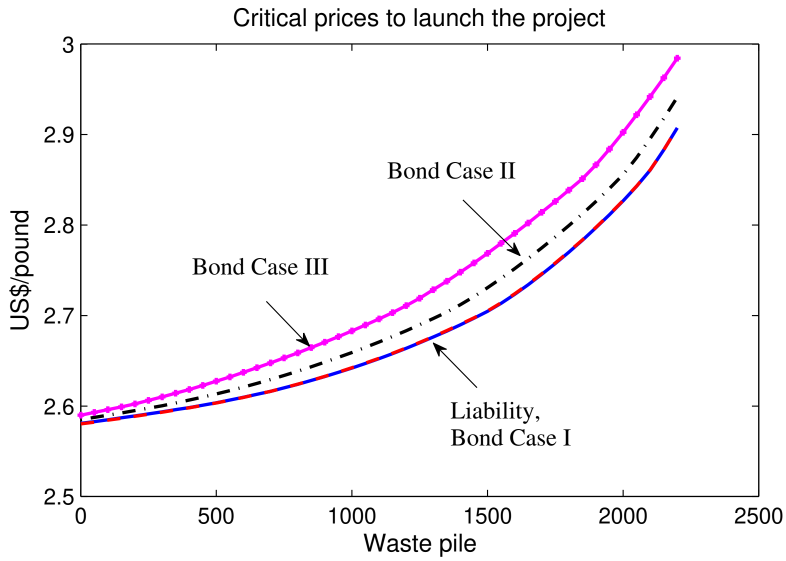

Figure 7: *Critical prices to launch the project versus the waste stock under the strict liability rule and the three bond cases, at time zero, given* $s_0 = 1173$ *million pounds.*

abandonment of the mine when half of the reserve is depleted will happen at a higher price, which indicates that the mine with the lower reserve is more likely to be abandoned.

What is interesting in the current study is how the critical prices vary in response to changes in the size of the waste stock under each policy, at a given level of reserve. We examine the extent to which each policy affects critical prices, in particular, to launch the project and to abandon the mine. The decision to move from Stage 1 to Stage 2 depends on the benefits of delaying the up-front investment costs versus the costs of delay in gaining the value of the project commencement. In Figure (7), we observe that critical prices to commence operations are identical for the strict liability policy and the Case I bond. Referring to Equation (23), recall that the cost of moving to Stage 2 is higher under the bond policy than the strict liability rule by the amount that must be paid into the bond. As noted earlier, the value of the project in Stage 2 is higher under the bond than under the strict liability rule. These two differences offset each other and result in the same critical prices for the Case I bond and the strict liability rule to move from Stage 1 to Stage 2.

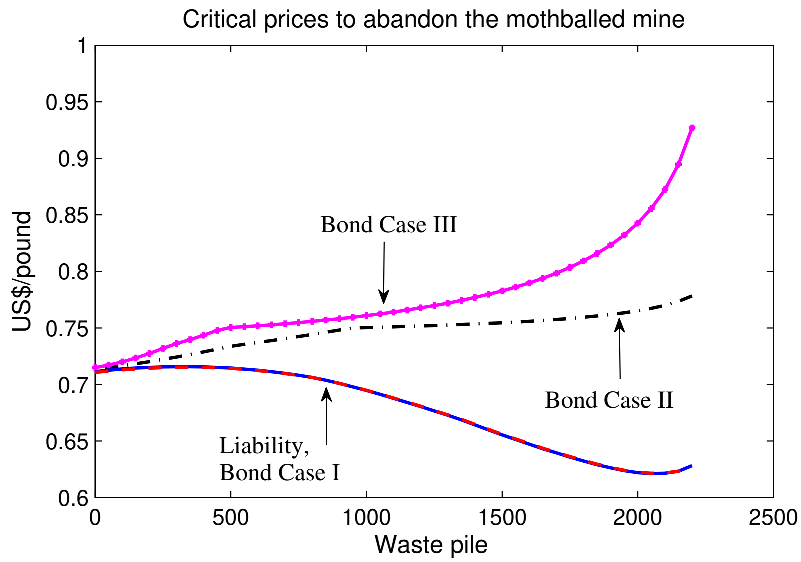

Figure 8: *Critical prices to abandon the mothballed project versus the waste stock under the strict liability rule and the three bond cases, at time zero, given* $s_0 = 1173$ *million pounds.*

The bond without interest income in Case II raises the critical prices to start extraction activities compared to the strict liability rule and thus fewer projects will be undertaken. Clearly, critical prices to begin the project are even higher for Case III, when the firm borrows at a risk premium. These results are also shown in Figure (7). Note that more waste accumulation raises the critical prices to begin operations due to higher costs of complying with both policies, making project commencement less likely under both policies.

Decisions to abandon the mine are compared in Figure (8) and some interesting results emerge. First, both the bond and liability policies lead to the same optimal abandoning decisions from the mothballed stage if the bond pays interest (Case I). This follows from similar logic as described above for moving from Stage 1 to Stage 2.[30] As already noted, the

[30]The relevant equations are $V(p, s_0, w_0, \delta_3) = V(p, s_0, w_0, \delta_4) + [\mathbf{1}_{b=true} C^{tp}(w_0) - C^f(w_0)]$ with $V(p, s_0, w_0, \delta_4) = 0$. With simple algebra we can derive $V^b(p^b, s_0, w_0, \delta_3) - V^l(p^l, s_0, w_0, \delta_3) = C^{tp}(w_0)$ in which p^b and p^l denote critical prices under the bond and the liability, respectively. If the gap between the two values at a given level of reserve and waste are equal to $C^{tp}(\cdot)$, the same critical prices satisfy $V^b(p^b, s_0, w_0, \delta_3) - V^l(p^l, s_0, w_0, \delta_3) = C^{tp}(w_0)$, and thus $p^b = p^l$. The Case II bond yields a relatively lower value in Stage 3 compared to Case I, and thus a higher p^b eliminates the gap, resulting in $p^b > p^l$.

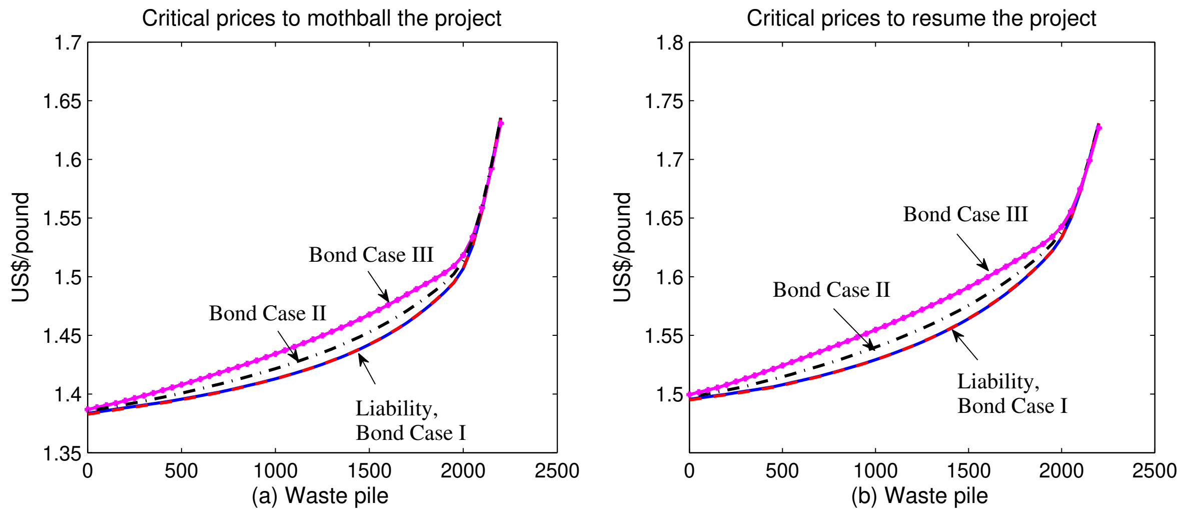

Figure 9: *Critical mothballing and resuming prices versus the waste stock under the strict liability rule and the three bond cases, at time zero, given* $s_0 = 1173$ *million pounds.*

Case II and Case III bonds are more burdensome to the firm, yielding lower project values. Hence we observe it is optimal to abandon the project at higher prices than for the Case I bond or strict liability rule.

Under the Case I bond and strict liability rule, there is a decreasing pattern for critical abandoning prices, which implies that the firm's motivation to abandon the site becomes weaker as more waste builds up. Under the strict liability rule, the sizable restoration cost at large quantities of waste provides incentives for the firm to delay paying for such costs by remaining at the mothballed stage. In contrast, with bonding requirements in Case I, the higher interest income on the deposited money at larger waste stock motivates the firm to sit idle longer. However, if the bond does not generate interest income (Case II), the longer the firm sits idle the higher the opportunity cost of the bond. Consequently, increasing critical prices are observed in Figure (8) for the Case II bond, indicating that as waste accumulates and the amount of bond grows, the firm's motivation to abandon the mine becomes stronger. For the Case III bond, as the waste stock grows the firm will have to repay a large loan at termination. Because the cost of the loan exceeds the risk-free rate, the larger is the waste stock, the more costly it is to the firm to delay clean-up. This results in an increasing trend in critical prices with a higher waste stock, and critical prices are higher than in the other cases, implying mine abandonment is more likely.

Critical prices to mothball and reactivate operations are also higher for the mine with greater waste as shown in Figure (9) under both policies and for all bond cases. More waste accumulation results in a lower project profitability due to a higher cost of compliance during operations with both policies. Therefore, the project with larger quantity of waste is more likely to be mothballed following a decrease in copper price. Similarly, the idle firm facing more waste is less likely to reopen its mine as the anticipated profits are smaller.

7.2 The bankruptcy scenario

7.2.1 Valuation results

Figure (10) shows the impact of bankruptcy on the value of the project prior to construction across different levels of initial waste, for bond in Case I and liability rule. We observe that when the bond is financed from retained earnings and the government pays interest at the risk-free rate, the two policies no longer give the same result. With no bankruptcy risk, the expected clean-up cost is the same under the either policy. Introducing the risk of bankruptcy reduces the project value under the Case I bond compared to the liability rule. This result follows because under the Case I bond the firm must pay the clean-up costs up-front. If bankruptcy occurs, the firm will not receive a refund on the bond. In contrast, under the strict liability rule, bankruptcy would allow the firm to avoid paying the clean-up costs. Under the possibility of bankruptcy, the Case I bond is much more costly to the firm. If interest is not paid on the bond financed from retained earnings, the bond in Case II is more burdensome to the firm, increasing the gap even further.

The Case III bond includes an extra cost reflecting a bond service charge, which as noted

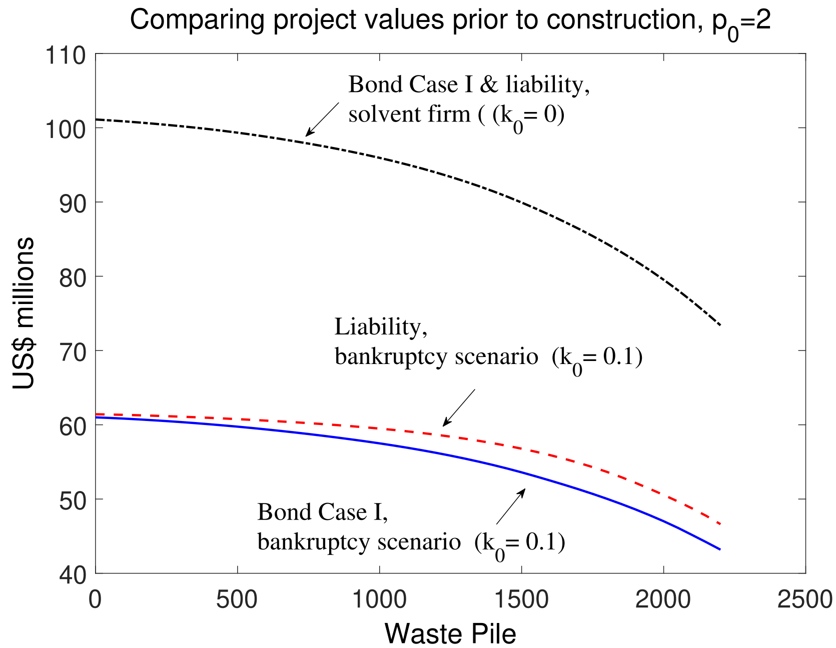

Figure 10: *Project values prior to construction across waste pile (million pounds) under Case I bond and the liability rule, for bankruptcy versus the solvent firm scenario, at* $p_0 =$ *US\$2/pound and* $s_0 = 1173$ *million pounds.*

is largely a risk premium. As discussed in Section (4), since the probability of bankruptcy is under the Q-measure, the model fully accounts for the impact of the risk of bankruptcy through incorporating the market price of bankruptcy risk. Therefore, there is no need to include a risk premium for borrowing.[31] In our model, in Case III, provided the government pays interest on the bond, the bond policy has the same outcome as the liability policy, because the firm would default on the borrowed funds in the event of bankruptcy and avoid all the clean-up costs at the project termination date, similar to the strict liability rule. Similarly, the firm's abatement rates and optimal choices of project stages in the case of borrowing under the bankruptcy scenario are identical to the liability rule. In the case of bankruptcy the responsibility for clean up would be transferred to the lender. It is therefore

[31] To the extent that the bond service charges reflect other costs, such as monitoring costs, in addition to the risk premium, then these would need to be included. For simplicity we have not included these potential extra costs in the bankruptcy case.

to the detriment of the lender, if the firm takes account of the possibility of bankruptcy in its optimal decisions regarding production and abatement. It would be expected that lending agencies would monitor the firm's actions to ensure these are consistent with the interests of the lender.[32] This case will not be considered further here.

We have also observed that the risk of bankruptcy reduces the project value markedly compared to the no bankruptcy scenario over all values of the waste stock. Such lower values are to be expected since the exogenous bankruptcy risk may cause early termination of the project, and may increase the duration of inactivity under the liability. This behaviour is discussed in Section (7.2.3).

7.2.2 Optimal abatement rates

Figure (11) shows optimal abatement rates for bankruptcy versus the solvent firm scenarios, under the bonding and liability policies. The figure is plotted for p =\$2 and full reserves at time zero. There is an obvious gap between such rates with the solvent firm having the highest abatement rates, followed by the Case I bonding policy and then the strict liability rule under the bankruptcy scenario. Recall that for the solvent firm, the Case I bond and liability policies give identical abatement incentives.

As discussed, the abatement rate is determined by the marginal cost of waste build-up. When bankruptcy is possible, $\frac{dV}{dw}$ reflects the cost of using up capacity in the landfill as well as the impacts of bankruptcy on the eventual clean-up cost (or bond refund) under each policy. The value of having spare capacity in the landfill is reduced as the firm might go bankrupt and be unable to use this capacity. It follows that abatement is less valuable to

[32]This issue has some parallels with the reforms made by the Basel Committee on Banking Supervision in 2009 in response to the financial crash of 2008. One principle of these reforms is that a bank should not be allowed to include gains and losses arising from changes in the bank's own credit risk in the calculation of its fair market valuation. This principle avoids an increase in the value of a bank's capital when its own credit worthiness declines. See BIS (2011).

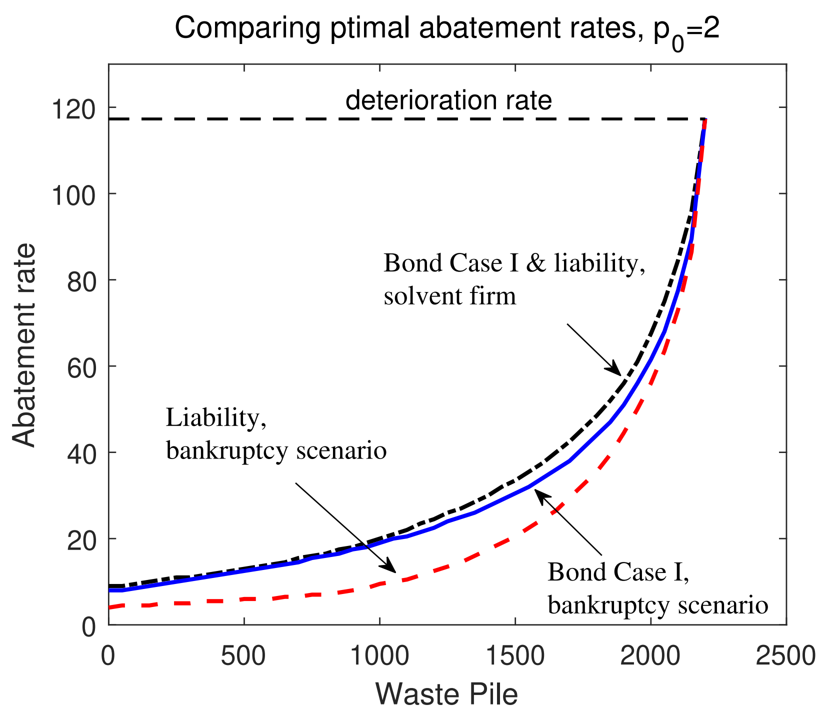

Figure 11: *Optimal abatement rates under Case I bond and the liability rule, for bankruptcy versus the solvent firm scenarios, at time zero,* $p_0 = \$2$*, and* $s_0 = 1173$ *million pounds.*

the firm, and optimal abatement rates are reduced compared to a solvent firm. The lowest abatement rates are for the strict liability rule, because under bankruptcy the firm would avoid its eventual clean-up costs altogether.

Another way to interpret the optimal abatement decisions when bankruptcy is possible is to observe that the hazard rate, $\lambda(p)$, increases the effective discount rate in Equation (21). This implies that the firm cares less about future benefits and costs, in the bankruptcy scenario. Under both policies, the firm generates more waste today as it puts less weight on the future impact of the loss in landfill capacity. In addition, for the liability (bond) case, it also puts less weight on the future restoration costs (benefits) triggered by project termination. Note that higher values for $\lambda(\cdot)$ due to a higher k_0 in Equation (17) increase the effective discount rate and further reduces the optimal abatement rates, as future benefits

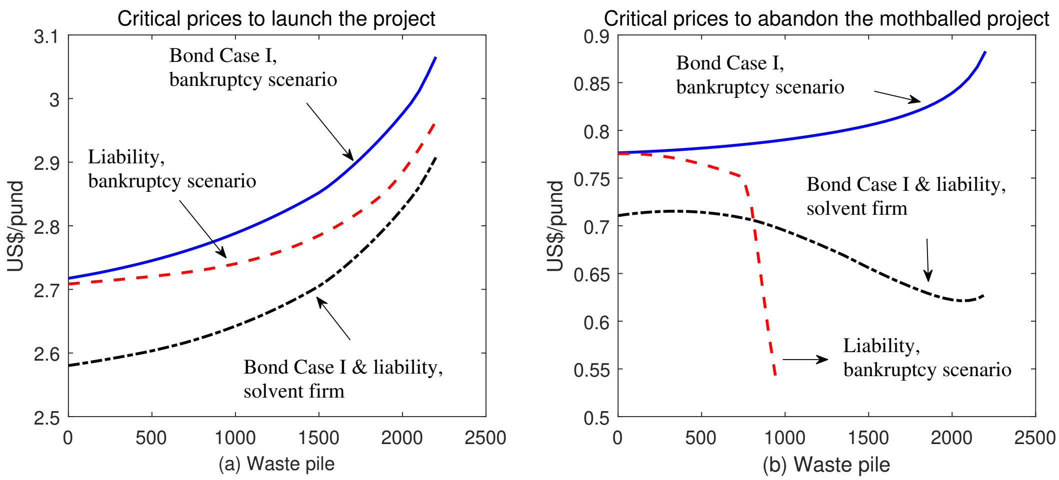

Figure 12: *Critical prices to launch the project (the left-hand panel) and critical abandoning prices from the mothballed stage (the right-hand panel) across the waste pile (million pounds) under the Case I bond and the liability rule, for bankruptcy versus the solvent firm scenarios, given* $s_0 = 1173$ *million pounds.*

and costs become less important under both policies.

7.2.3 Optimal choice of project stages

The possibility of bankruptcy creates a gap between the critical starting prices under the two policies, as shown in the left-hand panel of Figure (12). The Case I bond requires an upfront payment as well as subsequent payments during operations, whereas the clean-up costs under the liability might be avoided through bankruptcy. It follows that the increased compliance cost and thus the reduced profitability of the project under this bond compared to the liability rule increase critical prices to begin the project under the former. The gap becomes more significant for a higher stock of waste. Critical prices to launch the project are higher under bankruptcy risk than for the solvent firm.

The right-hand panel of Figure (12) shows that critical prices to abandon the mothballed mine across the waste pile have an increasing trend under the Case I bond and a decreasing trend under the liability, for the bankruptcy scenario. This follows because project termination and site clean-up under the bond yield restoration benefits that increase with waste, motivating the firm to carry out restoration projects rather than sitting idle in the mothballed stage. In contrast, under the liability, the last stage of operation entails restoration costs to the firm that rise with waste accumulation, motivating the firm to remain idle as a way to escape paying for such costs. Interestingly, with liability requirements under the bankruptcy scenario, no critical prices are found for abandoning the mothballed project for waste accumulation beyond 950. Beyond such waste thresholds, the idle firm facing low prices either goes bankrupt or remains inactive for an extended periods of time.[33]

Under the bonding policy in Case I, higher critical abandonment prices compared to the solvent firm scenario imply that the project will terminate sooner when bankruptcy is possible. As noted, the possibility of bankruptcy reduces the project value, making the project termination more probable. Under the strict liability rule, the critical prices under the bankruptcy scenario falls below the solvent firm scenario at large levels of waste, implying a longer duration for inactivity when there is an exogenous risk for bankruptcy.

8 Conclusions

This paper is motivated by the observation that many resource extraction projects leave behind a toxic legacy and taxpayers are left to fund the clean-up. Firms may walk away from their clean-up obligations or may simply let projects sit idle, even when there is no intent to restart operations. If designed appropriately, an environmental bond is one mechanism to ensure that adequate funds are set aside by private firms to undertake site clean-up. In practice, it has been observed that funds set aside in environmental bonds are often less than needed to cover actual clean-up costs.

[33]We have observed that this threshold increase as time passes so that after 14 years such a waste level increases to 1450 million pounds. This implies that the firm will have to clean up the site at time $T = 15$, regardless of waste and price levels, only if it has not declared bankruptcy at an instant prior to T.

This study formulates a stochastic optimal control problem to examine the incentives for waste creation and clean-up with and without an environmental bond designed to fully cover estimated clean-up costs. The firm is obliged to clean up any waste left at the termination of a project (strict liability), but under the bonding policy, the firm must deposit funds up-front equal to estimated clean-up costs of a third party. These funds are reimbursed to the firm as waste reduction or abatement occurs. The optimal control model is analyzed for a representative copper mine in Canada. We compare the strict liability rule (liability for clean-up) versus the bonding policy, which also includes liability for final clean-up.

Under both the strict liability and environmental bonding policies, there is no requirement for waste clean-up until the termination of the project. However, two factors, other than the bond, may give an incentive for waste abatement during the life of the project. First, there is an upper limit on the permitted size of the waste stock and when that limit is reached, firms must abate their waste in order to maintain production. Second, abatement costs and eventual clean-up costs are convex with respect to waste. Depending on the specifics of the cost functions, firms may find it beneficial to do some waste abatement during project operations rather than leave it all to the end. In this paper, we do not delve into the impact of different cost function assumptions as this is not our focus. The environmental bond may provide a third incentive to abate waste during the life of the project and also may provide a greater incentive to abandon the project early (before T), which triggers final restoration of the accumulated waste. The incentives provided by the bond depend on its particular characteristics, as well as whether the firm considers the possibility of bankruptcy in its optimal decision making.

The bond requires the firm to deposit funds to pay clean-up costs as the waste is generated, rather than delay until project termination. For a firm that acts as a going concern, (i.e., ignoring bankruptcy risk), if the government pays the risk-free rate on the bond deposit, and if it is assumed that the firm finances the bond out of retained earnings (or can borrow at the risk-free rate) (Case I bond), the bonding policy is not detrimental to the firm. However, markets would normally demand a risk premium from firms to finance bond payments, which increases the cost of the bond to the firm. Further, if the government does not pay interest on the bond deposit, this imposes an additional cost on the firm. In our numerical example, our main findings are as follows for the Case III bond in the solvent firm scenario, in which the firm must pay a risk premium and receives no interest income on the bond.

- The bond has a significant effect on the operations of a prototype copper mine. The required up-front bond payment, equal to third-party restoration costs, increases the threshold price needed for the project to go ahead, making the project commencement less likely.
- Paying a risk premium on the bond at each period makes it costly for the firm to delay clean-up and thus the firm is more likely to abandon the mine and undertake the required restoration. In the absence of a bond (strict liability rule), the firm is more likely to leave the mine inactive, rather than abandoning and cleaning up the mine.
- The bond also causes the firm to abate more during the life of the mine, and the final accumulated wasted is reduced.

If the firm takes account of possible bankruptcy, then the bond policy and strict liability policy are no longer equivalent in the Case I bond, assuming the bond is financed out of retained earnings. The bond policy now imposes significant costs on the firm compared to the strict liability policy alone.

- Whereas in the event of bankruptcy, the firm would avoid clean-up costs under strict liability, under the bond the firm cannot avoid these costs as they have been prepaid (assuming the firm finances the bond out of retained earnings). The value of the firm under the bonding policy (Case I) is lower than under strict liability rule and the firm carries out more abatement under the bond. The project is also less likely to be undertaken under the bonding policy and once undertaken, it is more likely to be abandoned and the site cleaned up.

- If the firm borrows to finance the bond, there is a possibility that the firm would default on the loan, and thereby avoid clean-up costs. This possibility makes the bond similar in outcome to the strict liability policy. However, in reality, lenders would be expected to monitor firm's behaviour to ensure it is not detrimental to lender.

The bonding policy we have analyzed is demanding of the firm in that the full cost of clean-up must be deposited with the government and this cost must be updated over time as the waste stock changes. This policy avoids any risk to the government of being left to clean up mine waste. This is more demanding than many bond policies in practice, which are not regularly updated. Imposing a costly bonding policy will reduce the number of resource extraction projects that are developed. Whether the additional costs imposed on firms are worthwhile depends on the extent of avoided costs from firms not fulfilling clean-up obligations. However, given the number of orphan waste sites in North American and elsewhere, a more stringent bonding policy seems long overdue.

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A Boundary Conditions

Boundary conditions at upper and lower bounds of p, r, w, and t are described in this section.

- Evaluation of Equation (20) as the commodity price $\boldsymbol{p \rightarrow 0}$ implies that

$$0 = \frac{\partial V}{\partial t} + \big(r + \lambda(p)\big)V + \max_{q,a}\left\{\pi - q\,\frac{\partial V}{\partial s} + (\phi q - a)\,\frac{\partial V}{\partial w}\right\} \tag{28}$$

  in which $\lambda(p \rightarrow 0) \rightarrow \infty$ for the bankruptcy scenario, while this term is absent under the solvent firm scenario (see Equation (17)). No special boundary condition is needed as there is no term involving p.

- As the $\boldsymbol{p \rightarrow p_{max}}$, we assume $\frac{\partial^2 V}{\partial p^2} \rightarrow 0$, which from Equation (20) implies:

$$0 = \frac{\partial V}{\partial t} + \kappa(\hat{\mu} - \ln p)p\,\frac{\partial V}{\partial p} + rV + \max_{q,a}\left\{\pi - q\,\frac{\partial V}{\partial s} + (\phi q - a)\,\frac{\partial V}{\partial w}\right\} \tag{29}$$

  The assumption that V is linear in p is common in the literature (In't Hout 2017). The value chosen for p_{max} is intended to approximate an infinite upper limit. Note that for the bankruptcy scenario $\lambda(p \rightarrow p_{max}) \rightarrow 0$, while this term is absent under the solvent firm scenario (see Equation (17)).

- As $\boldsymbol{s \rightarrow 0}$, the admissible set of q collapses to zero as shown in Equation (5). No boundary condition is needed.

- As $\boldsymbol{s \rightarrow s_{max}}$, no special boundary conditions is required as Equation (20) has outgoing characteristics in the s direction.

- For the boundary $\boldsymbol{w = 0}$, no boundary condition is required as Equation (20) has outgoing characteristics in the w direction.

- At the boundary $\boldsymbol{w = \bar{w}}$, Equation (6) implies that Equation (20) has outgoing or zero characteristics in the w direction. Hence no special boundary condition is needed.

- At $\boldsymbol{(t = T)}$, the obligation to clean up the site from Stages 2 and 3, under the liability rule and the bond in Cases I and II, implies that

$$\begin{aligned} V(p,s,w,\delta_i,T) &= 0 & i=1,4 \\ V(p,s,w,\delta_i,T) &= \mathbf{1}_{b=true}C^{tp}(W) - C^f(W) & i=2,3. \end{aligned} \tag{30}$$

As noted, in the bankruptcy scenario, the firm receives the restoration benefit under the bond or pays the clean-up cost under the liability if it reaches time T.

If the bond is borrowed (Case III), the firm will have to repay the loan at T, and thus the second line of the above equation becomes

$$V(p,s,w,\delta_i,T) = -C^f(W) \quad i=2,3. \tag{31}$$

Note that in the bankruptcy scenario, the firm will have to repay the loan at T only if it reaches that time.

B The social planner's problem

In this paper, we have focused on the effect of an environmental bond on a firm's optimal decisions, but have not described the socially optimal policy. This appendix provides a qualitative description of the components of a social planner's problem. A well established economics principle (Tinbergen 1952) is that the number of policy instruments should equal the number of objectives. The objective of the bond analyzed in this paper is to collateralize the government against the risk that firms will not meet clean up obligations. Other objectives, such as internalizing damages from pollution flow, would require other policy instruments, such as a pollution tax or regulatory limit.

The benefit of the bond to society derives from the assurance that government will not be faced with the cost of cleaning up a mine site. The avoided costs include:

- any additional costs incurred when the government undertakes site clean-up, rather than the firm - referred to as third party costs in the paper
- dead-weight loss from government financing site clean-up out of general tax revenues
- less tangible costs such as damage to public confidence in government oversight of resource projects if private firms are seen to be shirking clean-up obligations.

The cost of the bond to the firm is determined by:

- the opportunity cost of the capital tied up in the bond, which is reduced if government pays interest on the bond,
- bond service charges such as the required risk premium if the firm finances the bond through borrowing

In addition to these costs to the firm, included in the social cost of the bond would be any reduction in investment in mining projects, with consequent loss of jobs and income. The cost would need to be included in the social planner's problem.

Another important component of the social planner's problem is the regulation of damages from the production of waste (i.e., the waste flow), as well as build-up of the waste stock. In the paper it is assumed that the waste flow and stock buildup cause no damages prior to the mandatory clean-up date of T. In reality, damages may be on-going through the life of a mining project, as a result of surface and groundwater contamination, loss of enjoyment of the mine site for recreational or other uses, or potential harm to wildlife of degraded landscapes, to name a few examples.[34] A social planner would need an additional policy tool to address damage from the waste. In particular, a variable rate tax per unit could be imposed on the waste production. The efficient tax would reflect the damage caused

[34] Syncrude paid a $3 million penalty for the death of 1600 ducks which landed on one of its tailing ponds in Alberta, Canada, in 2008.

by a particular unit of waste created and added to the waste stock, and may be positively related to the existing size of the waste stock. The efficient tax would affect the firm's choices of abatement, production, as well as the timing of opening, mothballing, or abandoning the mine. Hence the tax would also affect the required bond posting. Consideration of a damage function from waste and the appropriate policy tool is left for future work.

The complete social planner's problem would also include the risk of accidents. In this paper, the bond reflects the cost of clean-up when the project is abandoned. However, in the event of an environmental accident, such as a tailings pond breach, the environmental damages may be significant and the cost of clean-up increased accordingly. The social planner would choose the maximum size of the allowed waste stock when the possibility of accidents is considered. To fully describe the social planners problem, a stochastic process modelling the likelihood of environmental accidents would be included, with the probability of accidents dependent on the size of the waste stock. Consideration of environmental accidents is also left for future work.

The social planners problem would also consider the moral hazard present when firms are left to monitor and report their own waste creation. The possible use of bankruptcy as a strategic tool by firms is another interesting topic for future research.