Risk Analysis, Vol. 23, No. 3, 2003

Sovereign Cat Bonds and Infrastructure Project Financing

David Croson[1]* and Andreas Richter[2]

We examine the opportunities for using catastrophe-linked securities (or equivalent forms of nondebt contingent capital) to reduce the total costs of funding infrastructure projects in emerging economies. Our objective is to elaborate on methods to reduce the necessity for unanticipated (emergency) project funding immediately after a natural disaster. We also place the existing explanations of sovereign-level contingent capital into a catastrophic risk management framework. In doing so, we address the following questions. (1) Why might catastrophe-linked securities be useful to a sovereign nation, over and above their usefulness for insurers and reinsurers? (2) Why are such financial instruments ideally suited for protecting infrastructure projects in emerging economies, under third-party sponsorship, from low-probability, high-consequence events that occur as a result of natural disasters? (3) How can the willingness to pay of a sovereign government in an emerging economy (or its external project sponsor), who values timely completion of infrastructure projects, for such instruments be calculated? To supplement our treatment of these questions, we use a multilayer spreadsheet-based model (in Microsoft Excel format) to calculate the overall cost reductions possible through the judicious use of catastrophe-based financial tools. We also report on numerical comparative statics on the value of contingent-capital financing to avoid project disruption based on varying costs of capital, probability and consequences of disasters, the feasibility of strategies for mid-stage project abandonment, and the timing of capital commitments to the infrastructure investment. We use these results to identify high-priority applications of catastrophe-linked securities so that maximal protection can be realized if the total number of catastrophe instruments is initially limited. The article concludes with potential extensions to our model and opportunities for future research.

KEY WORDS: Catastrophe-linked securities; contingent capital; natural disasters; infrastructure; project finance

1. INTRODUCTION

Insurers and reinsurers, private entities who bear risk on behalf of their clients, use catastrophe-linked securities to protect themselves against insolvency in the case of a natural catastrophe.[1,2] Although private enterprise has already begun to find catastrophe-linked securities useful in reducing the variation of its costs, this hedge against disaster comes at a price: 100% of the expected cost of these catastrophes, plus a generous premium for assuming the risk, is paid to investors.[3–5]

To our knowledge, there has been neither a theoretical analysis nor even a compendium of potential motivations for sovereign governments to use such instruments. Given this lack of analysis, it is not surprising that no sovereign governments (or third-party infrastructure project funders, such as the

1 Assistant Professor of Operations and Information Management and Senior Fellow, Financial Institutions Center; The Wharton School of the University of Pennsylvania.
2 Assistant Professor of Risk and Insurance, University of Hamburg.
* Address correspondence to David C. Croson, The Wharton School, University of Pennsylvania, 562 Jon M. Hunstman Hall, 3730 Walnut St., Philadelphia, PA 19104-6340.

World Bank) have issued such securities to protect themselves against catastrophe. We therefore address the question, "Why might the *sovereign government* of an *emerging nation* be interested in *employing catastrophe-linked instruments* to protect *infrastructure* investments, funded by a *third party*, *from low-probability, high-consequence* events such as *natural catastrophes*?"

2. GOVERNMENT CONCERN WITH CATASTROPHES

A private insurer or reinsurer worries about catastrophes because they trigger financial obligations, which may result in insolvency. It uses catastrophe-linked securities to prevent this insolvency and preserve its franchise value as a profitable ongoing concern.(6)[3]

A sovereign government worries about catastrophes because they trigger obligations to preserve the welfare of its affected citizenry, in addition to damaging infrastructure projects in progress. Catastrophes generate sudden funding requirements for emergency humanitarian aid, and at the same time they generate additional funding requirements to continue with works in progress. The consequence of omitting (or skimping on) such humanitarian aid is not insolvency, but increased suffering for the population, as well as political unpopularity, potential civil unrest, and a potentially guilty conscience for politicians. In particular, disbursing such humanitarian aid at generous levels seems incentive-compatible for government officials, who act as agents for the citizens, as well as prescribed by the charter of the government. That efforts of government officials to succor the populace will be pursued at a maximal level is practically guaranteed by political and media pressures (in addition to the force of genuine heartfelt sympathy for afflicted citizens). A government may find it worthwhile to issue state-contingent catastrophe securities to assure its ability to provide humanitarian aid at an efficient level, completely independent of any other reasons.

A relatively risk-averse government may also wish to protect its investment in wholly owned infrastructure features such as roads, schools, dams, electric utilities, and the telecommunications infrastructure, rather than self-insuring as most governments do.[4] These infrastructure investments, almost by definition, have the characteristic of offering high social benefit but diverse/scattered individual benefits, and so cannot be efficiently organized by the private market. Although the expected capital requirements for completing these projects are completely known *ex ante*, the stochastic character of the capital requirements (which we will term "emergency repair costs" in our example) requires some contingency planning to ensure that needed project funds are available. The government may in particular wish to assure liquidity immediately after a catastrophe, given that it rationally anticipates that all liquid resources will be devoted to humanitarian aid, to assure that these projects can be completed in a timely manner and without extraordinary costs caused by interruption. Such possibility of either sudden and unexpected financial distress due to catastrophe, or the adoption of inferior construction strategies because of the potential for future financial distress, leads to higher expected costs to complete such projects. The simple strategy of holding "capital inventory" to avoid these costs is, unfortunately, very costly for emerging economies.

3. BASIC STRUCTURE OF CATASTROPHE-LINKED SECURITIES

A catastrophe-linked security (or cat bond) is a contract between an issuer and an investor. The investor puts up a sum of cash at the beginning of the coverage period; this cash is held in escrow (under the control of a neutral third party) and invested in low-risk short-term securities until either a catastrophe occurs or the coverage period ends, whichever occurs sooner. The issuer offers to supplement this escrowed principal with a coupon payment, provided that no catastrophe occurs during the coverage period, at the end of the period and return both principal and interest to investors. The escrowed funds are not available for general-purpose use in the interim. In the event of a catastrophe, the investors will receive no coupon payment and some, or all, of their principal may be distributed to the issuer.[5]

The major benefit that these instruments offer to the issuer is an instantaneous inflow of cash (here, to

[3] The wish to avoid or reduce costs of financial distress and bankruptcy costs is a major rationale for a firm's demand for risk management tools. Detailed discussions of motivations for corporate risk management and, in particular, for risk-averse entrepreneurial decision making are given, e.g., by Mayers and Smith,(7) Greenwald and Stiglitz,(8) and Doherty.(9)

[4] Particularly for emerging-economy governments, high capital costs, representing large opportunity costs of future investment and consumption if the nation's capital base is depleted by a catastrophe, may make the role of "insurer of last resort" unattractive.

[5] For structures and conditions of recent cat bonds, see Reference 5.

the government) immediately following a prespecified catastrophic event (such as a flood, earthquake, or hurricane). This payment flows from an escrow account established at the time of issuance, and is not a loan or sovereign obligation—the principal need not ever be repaid by the government to any party, whether a catastrophe occurs or not. If there is no catastrophe during the coverage period, the escrowed principal is returned to the investors with the country having never had the use of it. If there is a catastrophe, the escrowed principal flows to the country free and clear of any repayment obligations. Under no circumstances does the country get the use of the capital under an obligation to repay it. This feature is likely to be quite important to an emerging economy, which already carries a substantial debt burden—particularly if the country's existing (senior) sovereign debt carries a covenant restricting the amount of additional debt that can be assumed.

Given the rather substantial premium that investors receive in return for accepting the risk to their principal, we might ask "Why might such a state-contingent catastrophe-linked security be more attractive to a sovereign government than more traditional types of financing?"

1. *Funds of the magnitude required to rebuild damaged infrastructure investments may not be available to emerging economies in advance*. Although substantial amounts of borrowing at the sovereign level may be desirable to support economic growth, the total amount of sovereign debt that a government can support may be sharply limited, either through explicit restrictive covenants on existing debt or by the market's unwillingness to advance additional funds for general purposes. A government nearing its total allowable-debt constraint has a substantial incentive to ensure that this constraint will not be violated in case of a catastrophe.
2. *Even if these rebuilding funds would be available during normal circumstances, they may not be available after a sufficiently severe catastrophe*. Unless provisions for emergency capital are arranged in advance, investors may be reluctant to make large new capital commitments if a catastrophe occurs that is sufficiently severe to threaten the stability of the national currency, create civil unrest, or cause default on outstanding sovereign debt. A rational response before making additional investment might be to "wait and see" whether the country's ability to repay the new debt has been compromised by the catastrophe.
3. *Portions of these funds are required immediately after the catastrophe to address catastrophe-induced difficulties*. The demand for liquid funds immediately after a catastrophe is extremely high, and the short-term opportunity cost of not having capital available immediately after a catastrophe is considerable, both for emergency humanitarian aid and for reconstruction. It is this high short-term social value of liquid assets that leads governments to divert capital flows earmarked for sponsored infrastructure projects to emergency humanitarian aid when all other sources of liquid assets have been exhausted. This short-term cash-flow problem is exacerbated when the infrastructure projects themselves suffer damage from the catastrophe and require reconstruction. A new roof for a nearly finished school may be required after a hurricane hits the area, for example; if this roof is not immediately installed, rain damage may dramatically increase the total cost of finishing the school. Delays in the availability of emergency-repair funds may therefore generate significant costs of financial distress after a disaster.
4. *The government may not desire to borrow more money in the future, even if allowed to do so at a competitive rate*. The government's overall financial strategy (prior to a catastrophe, but rationally anticipating its possibility) may be to *reduce* its overall level of borrowing, or to maintain its current optimal level, rather than potentially *increase* it if a catastrophe were to occur. The government may be willing to pay a premium to avoid disruption of the rationalizing of its financial structure on a *national* level, in much the same way we describe the gains from avoiding disruption on the *project* level in our later analysis. Furthermore, the nation's existing (senior) sovereign debt rating would benefit through a reduced anticipated default rate; lenders would presumably offer more favorable terms (or larger amounts at equivalent terms) if the risk of default due to a natural disaster (a disruptive event whose cash-outflow requirements that might contribute to default, if sufficiently severe), is lessened.

5. *The cost of capital for an emerging economy is high*. A sovereign government may be able to handle a larger deductible than a private company and still exhibit an aversion to self-insuring. Holding excess funds idle in inventory, against the possibility of unexpected cash needs, has a very high cost for an emerging economy—either an explicit cost of borrowing in the capital market, or a high opportunity cost based on depriving a socially desirable investment project of capital. It does not make sense to withhold large amounts of capital every year simply to hedge against an event that occurs only one year in ten.

3.1. Introduction to Project Disruption Costs

Funds may be diverted from infrastructure projects—even despite the sovereign government's genuine long-term commitment to the desirability of investing in these projects—to assuage short-term humanitarian and political needs immediately following a catastrophe. The timely application of these loaned funds to infrastructure development is a condition of the original loan agreement. Such diversion creates not only a technical default on the original agreement, but also a shortage of capital to be invested in the ongoing project. This unexpected lack of funds will certainly lead to increased costs over and above the damage that might have been done to the infrastructure project itself.

These costs may be explicit, through increased costs of project completion due to the disruption in a smooth flow of capital (requiring unexpected mothballing of the construction projects, relocation of construction materials, equipment, and personnel, as well as frictional hiring-and-firing costs and forced idling of capital equipment). These costs may also take the form of implicit, or opportunity, costs simply through the inevitable delay in having the completed project come online, and therefore pushing the onset of benefits from the completed project further into the future. In the special case of a durable investment (where, once paid for, the stream of benefits continues indefinitely) a one-year delay (for example, the completion of a technical institute) amounts to losing one year's worth of service (for example, one full graduating class of engineering students) forever. Sovereign governments value the stream of services from such infrastructure projects as direct contributions to social welfare, even if their returns are noncash items (a graduating class of engineers). In our cost analysis, we therefore include the opportunity losses of these foregone benefits from project completion to capture the full economic cost of project failure or delay.

Although the government's decision to divert funds to humanitarian needs is certainly a justifiable one (and may, indeed, represent the best use of available funds given that a catastrophe has occurred), it exerts an unintended negative externality on project costs. Planning for the contingency that all available liquid funds will be diverted can thus reduce the total expected costs of project completion. By assuring a ready source of capital when needed, construction progress on the infrastructure project can continue, avoiding not only project disruption costs but also delays in the project coming online.

The external sponsor of the infrastructure project may also benefit from the creation of a source of liquid capital, to be accessed only in the case of catastrophe. The sponsor is frequently forced to renegotiate the terms of the loan under unfavorable conditions, with the diversion of the original loan principal a *fait accompli*. Additional loan capital is requested to finish the partially complete project, even though the social benefits (and, thus, the potential pay-back capabilities) from the completed project have not increased. Although this unfavorable prospect (and the government's revealed history of unilateral renegotiation) would seem to discourage a lender from advancing more funds at the *beginning* of a project, the lender may feel compelled to invest additional funds in the *middle* stages of a project. Because, without additional funding, investments previously sunk into the project will amount to nothing—and the original loan principal will need to be written off as unrecoverable—the benefits from such previous investments are effectively "held hostage" to the funder's acquiescence to these terms. Borrowers' commitment to project completion may improve lenders' long-term willingness to provide funds, as we examine in Section 5.

Prearranged sources of contingent capital, such as event-triggered cat bonds, can generate cash quickly and thereby capture the benefit of immediate liquidity. On-the-spot post-catastrophe arrangements may take several weeks to accomplish, even for a creditworthy country far away from its maximal debt constraint using previously established contacts at investment banks.[10,11] A financial device, such as a catastrophe-linked security, will thus reduce the costs of financial distress and thereby generate value to a sovereign government and external project sponsors to the extent it can:

1. Eliminate the risk of project disruption due to damage to infrastructure projects in progress when emergency repair funds are not otherwise available, by supplying these emergency repair funds immediately upon damage to the project; and
2. Provide a ready source of immediate contingent capital for project completion when humanitarian aid requirements force diversion of all liquid resources, including ongoing project funding, even when the project itself is not damaged.

3.2. Enabling Commitment to Continued Project Funding

A sovereign government desires to split its current expenditures between consumption (emergency humanitarian aid after a catastrophe) and investment (continued funding for projects in progress). Its obligations extend first to the welfare of its citizenry, and only secondarily to the continued success of its investment projects (even though the fruits of these projects will determine future welfare of future citizens). Even though the optimal decision involves an intertemporal tradeoff balancing present humanitarian aid with future investment gains, there is always a strong temptation (particularly in a democracy) for the current government to overspend on present citizens. Resisting this temptation, although good for the country in the long term, may be politically infeasible (or undesirable) in the short term.

A government may therefore be able to improve its intertemporal capital management by investing in instruments that generate benefits that *cannot* be used for humanitarian aid, and that thereby commit the nation to continuing investment in infrastructure projects—a classic example of benefiting by following rules rather than discretion.(12)

This commitment benefit cannot be captured if the proceeds from catastrophe securities are paid in cash (which is, of course, fungible between investments in infrastructure and current consumption) to the government itself (which is the party caught in the invest/consume dilemma). For the government to create and capture this commitment benefit, the proceeds must be either:

1. Paid in a "currency" that advances the infrastructure investment task but cannot be readily converted to cash (e.g., bulldozers, construction labor, etc.); and/or
2. Distributed not to the central government, but rather to a party that has no temptation to spend on immediate emergency aid at the expense of investment. Whether the most effective distribution mechanism is to disburse directly to local project managers, to the third-party sponsor, or a wholly disinterested party remains a topic for future research.

4. MODEL OF EXPECTED COSTS OF FINANCIAL DISTRESS

As we have discussed, a multitude of costs may be avoided, and social benefit realized, by avoiding project disruption due to financial distress—whether through enabling defense of previously sunk costs against instantaneous depreciation due to the catastrophe, supporting cost-minimizing construction strategies, or accelerating the coming online of the new project. We now turn to a model of the size of these costs, and explicitly calculate values of these costs in a series of numerical examples.

We use a simple model to illustrate the magnitude of potential advantages from a sovereign cat bond or other form of state-contingent access to capital, such as a prearranged nonrecourse line of credit. We further assume that all projects currently underway are worth continuing.[6] We consider a sovereign acting as project manager for a certain project with a deferred payoff b, which is to be realized only on successful project completion. For convenience we assume two periods of required investment before the benefit occurs.

4.1. Project Cost Structure

The necessary investments are i_1 at the beginning of the first period and i_2 at the beginning of the second. Both investments must be made to achieve the benefit b at the end of Period 2.

[6] If this condition is not currently satisfied in the portfolio of funded investments, a simple supplementary method to free capital for repairs would be to discontinue those projects for which incremental future costs exceed incremental future benefits. We assume that the infrastructure investment portfolio has already been so rationalized before the decision about cat risk financing arises. If external contingent capital is available, only projects that are attractive given that contingent capital is available should be begun. As will be seen in our example, there will be situations when the initial attractiveness of the project depends critically on the availability of capital to see it through to completion.

The risk faced by this project is "catastrophic" in that (1) 100% of the value of the project is destroyed if not immediately repaired, and (2) the costs of repairs are large compared to the total amount of capital available to the project sponsor. A catastrophic event causes damage to the project with probability p in each period.[7] If a disaster occurs, all progress made on the project to date will be completely lost unless the project is "defended" by immediately carrying out an emergency repair. In the event of a disaster, the costs of emergency repair (e_1 and e_2 in Periods 1 and 2, respectively) must be invested by the end of the period in which the disaster occurred. If the emergency-repair investments are not made, the project returns to the original state and must be started over at the beginning of the next period.[8]

4.2. Information Structure

The magnitudes of e_1 and e_2 are known *ex ante*, as are other relevant parameters such as the net present value of the social benefit (b) that accrues to the country once the project is completed, the probability of a disaster (p), which is the same across all periods, and the discount rate (r). This is a single-decisionmaker problem; the probability of disaster is assumed to be independent of any model parameters, financing arrangements, or construction strategies used by the project manager.

4.3. Strategy Alternatives

The project manager chooses an investment strategy to maximize the (expected) net present value of the project opportunity. A strategy for this investment problem is thus characterized by the decisions concerning emergency repair in case of a disaster occurring in the different project stages. Assuming that no additional information can be derived during the process (e.g., on the disaster probability), and if there are no limitations to the availability of funds for emergency repair if needed, the decisions do not depend on the project history—in particular, on whether a disaster has already occurred. There are then five strategies a project manager must choose from.

- (R,R): Emergency repair will be done if a disaster occurs in the first period, the second period, or in both.
- (F,R): Emergency repair will be done only in the second period; if a catastrophe occurs in the first period, the project will be allowed to fail and restart.
- (R,F): Emergency repair will be carried out only in the first period; if a catastrophe occurs in the second period, the project will be allowed to fail and restart.
- (F,F): No emergency repair will be carried out, regardless of timing; the project will be allowed to fail and restart after any catastrophe.

Of course, the project manager also has the option of not investing at all (0), which will be chosen if the expected net present value of the result of the best strategy among (R,R), (F,R), (R,F), and (F,F) is negative.

4.4. Strategy Selection

The optimal strategy for the problem described above depends on whether it is attractive to pay for emergency repair in one or both project stages. Consider first the situation without any capital constraints, which means that there is always enough capital available to defend the project after a disaster if doing so would form a part of the optimal solution at that stage.

We want to derive explicit expressions for the net present values under the different strategies: $NV_0^{R,R}$, $NV_0^{F,R}$, $NV_0^{R,F}$, and $NV_0^{F,F}$. The discounted cash flows for these strategies and the possible scenarios are given in Table I. δ denotes the discounting factor, $\delta = \frac{1}{1+r}$. Note that since we assume that the project is restarted if a disaster happens and no emergency repair is carried out, the expected net present values themselves appear in the table as a cash-flow component whenever the project is let fail and restarted.

Considering each row of the table in turn, weighting each outcome by its probability and solving for the expected net present values of the project opportunity under the four strategies described gives

[7] Although we assume that disasters in Period 1 and Period 2 are independent, our model is easily adapted to account for serial correlation (either positive or negative) of disaster likelihood, allowing the capture of some interdependencies among events.

[8] Each time the project is allowed to fail we assume it will indeed be begun again in the next period, as the project was initially attractive and has the same (positive) expected NPV at the point immediately following the disaster, independent of its history, as it did at the initial decision point.

Table I. State-Contingent Cash Flows Resulting from Repair Strategy Choices

		Outcome			
		No Event	Event (only) in Period 1	Event (only) in Period 2	Event in Both Periods
	Probability	$(1-p)^2$	$p(1-p)$	$p(1-p)$	p^2
Repair Strategy	(R,R)	$-i_1$ $-i_2\delta$ $+b\delta^2$	$-i_1 - e_1\delta$ $-i_2\delta$ $+b\delta^2$	$-i_1$ $-i_2\delta - e_2\delta^2$ $+b\delta^2$	$-i_1 - e_1\delta$ $-i_2\delta - e_2\delta^2$ $+b\delta^2$
	(F,R)	$-i_1$ $-i_2\delta$ $+b\delta^2$	$-i_1$ $+NV_0^{F,R}\delta$	$-i_1$ $-i_2\delta - e_2\,\delta^2$ $+b\delta^2$	$-i_1$ $+NV_0^{F,R}\delta$
	(R,F)	$-i_1$ $-i_2\delta$ $+b\delta^2$	$-i_1 - e_1\delta$ $-i_2\delta$ $+b\delta^2$	$-i_1$ $-i_2\delta$ $+NV_0^{R,F}\delta^2$	$-i_1 - e_1\delta$ $-i_2\delta$ $+NV_0^{R,F}\delta^2$
	(F,F)	$-i_1$ $-i_2\delta$ $+b\delta^2$	$-i_1$ $+NV_0{}^{F,F}\delta$	$-i_1$ $-i_2\delta$ $+NV_0{}^{F,F}\delta^2$	$-i_1$ $+NV_0{}^{F,F}\delta$

$$NV_0^{R,R} = \delta^2 \cdot b - i_1 - \delta \cdot i_2 - \delta \cdot p \cdot e_1 - \delta^2 \cdot p \cdot e_2,$$

$$NV_0^{F,R} = \frac{1}{1 - p \cdot \delta} \cdot \left[\delta^2 \cdot (1-p) \cdot b - i_1 - \delta \cdot (1-p) \cdot i_2 - \delta^2 \cdot (1-p) \cdot p \cdot e_2\right],$$

$$NV_0^{R,F} = \frac{1}{1 - p \cdot \delta^2} \cdot \left[\delta^2 \cdot (1-p) \cdot b - i_1 - \delta \cdot i_2 - \delta \cdot p \cdot e_1\right],$$

and

$$NV_0^{F,F} = \frac{1}{1 - p \cdot \delta - p \cdot \delta^2 + p^2 \cdot \delta^2} \cdot \left[\delta^2 \cdot (1-p)^2 \cdot b - i_1 - \delta \cdot (1-p) \cdot i_2\right].$$

The optimal investment strategy $\langle (i^*, j^*) \,|\, i, j \in \{R, F\} \rangle = \arg\max NV_0^{i,j}$ and the value of the project is thus $V(i^*, j^*) = \max\lfloor 0, NV_0^{R,R}, NV_0^{F,R} NV_0^{R,F} NV_0^{F,F} \rfloor$. Consider the following numerical example:

$$\textit{Example}\,1: \quad r = 0.1 \quad i_1 = 10 \quad i_2 = 10 \quad e_1 = 10 \quad e_2 = 15 \quad p = 0.1 \quad b = 40$$

The values of the expected net present value (NPV) generated from the different repair strategies are shown in Table II.

The best of these strategies would be $NV_0^{R,R}$—to carry out emergency repair each time a disaster occurs—which yields an initial expected NPV for the project opportunity of 11.82. Since $NV_0^{R,R}$ is positive, this strategy is preferred to the strategy (0), which yields a payoff of 0.

Table II. NPV of Investment Strategies with Unlimited Capital

$NV_0^{R,R} = 11.82$	$NV_0^{F,R} = 11.5$	$NV_0^{R,F} = 10.63$	$NV_0^{F,F} = 10.3$

4.5. Financial Distress

Financial distress occurs when, during the investment process, a catastrophe occurs and a shortage of capital forces the sovereign to let the project fail in a case where emergency repair would otherwise be the preferred solution. Although financial distress does not occur in the absence of a catastrophic event, the potential for the costs of financial distress must be included in the original calculation of the value of the project opportunity. The *expected cost of financial distress* (ECFD) can be measured as the reduction in the expected net present value of the project opportunity due to the constraint-induced switch of strategy.

We denote the funds available for emergency repair by f. These funds represent, conceptually, the difference between the project manager's initial capital endowment and the funds that would be earmarked for the construction of the project (i.e., i_1 and i_2) if no catastrophes were to occur. Formally,

$$ECFD = NV_0^{\infty} - NV_0^{f},$$

where NV_0^{∞} represents the value of the project opportunity if an infinite amount of capital were available for emergency repair, and NV_0^{f} represents the value of the project opportunity given that only f units of capital are available for emergency repair, and thus that strategies possibly requiring amounts greater than f are infeasible.

4.5.1. Noncontingent Repair Strategies

Consider, as an illustrative example, the extreme case of no capital being available for emergency repair (i.e., $f = 0$) in a situation when (R,R) would be the best strategy given unlimited capital. Here the only feasible strategies are (0) and (F,F). Thus the expected cost of financial distress can easily be quantified as $min\lfloor NV_0^{R,R}, NV_0^{R,R} - NV_0^{F,F}\rfloor$, the lesser of the entire project value (i.e., the difference between $NV_0^{R,R}$ and 0) or the difference between $NV_0^{R,R}$ and $NV_0^{F,F}$. This cost of financial distress is always equal to $NV_0^{R,R} - NV_0^{F,F} > 0$, assuming that the emergency repair cost is not prohibitively high and that the project is attractive to begin in the first place.

Using the numbers introduced in Example 1 and under the assumption $f = 0$, the best feasible strategy (i.e., the best strategy that does not require the availability of any emergency-repair capital) is (F,F). So the expected cost of financial distress is $ECFD = NV_0^{R,R} - NV_0^{F,F} = 1.52$ for the parameters in Example 1.[9]

4.6. Contingent Repair Strategies

To calculate the cost of financial distress for the general case we first must introduce one additional possible strategy, which allows the decision of whether to repair in the second period to depend on the outcome of the first period:

- (R, $\tilde{\text{R}}$): Emergency repair will be carried out in the first period if necessary; in case of a catastrophe in the second period, the project will be defended only if there were no disaster in the first period.

Of course, this strategy cannot be more favorable than the ones mentioned above in the case of no capital restrictions (being inferior to either (R,R) or (R,F)), but it might be a constrained-optimal (second-best) solution if the project manager has just enough capital to carry out emergency repair one time, but not twice. The cash flows associated with strategy (R, $\tilde{\text{R}}$) are shown in Table III.

The expected net present value under (R, $\tilde{\text{R}}$) is thus

$$NV_0^{R,\tilde{R}} = \frac{1}{1 - p^2 \cdot \delta^2} \cdot \left[\delta^2 \cdot (1 - p^2) \cdot b - i_1 - \delta \cdot i_2 - \delta \cdot p \cdot e_1 - \delta^2 \cdot (1 - p) \cdot p \cdot e_2\right].$$

As can be easily verified, (R, $\tilde{\text{R}}$) turns out to be the constrained-optimal strategy for Example 1 in all cases where $15 \leq f < 20$. (In particular, if $f = 15$, (R, $\tilde{\text{R}}$) is the best strategy that does not ever require more than 15 units of capital; when $f > 20$ there is enough capital to pursue strategy (R,R).) (R, $\tilde{\text{R}}$) yields an ENPV of $NV_0^{R,\tilde{R}} = 11.71$ and a substantially lower cost of financial distress (ECFD = 0.11) in comparison to the $f = 0$ case.

From this simple example, we can make two observations.

1. The optimal strategy of whether to defend the project in Period 1, Period 2, or both depends on the amount of capital available. Also, the decision of whether to begin the project at all depends, via the choice of strategy, on the amount of capital anticipated to be available to conduct emergency repairs.
2. The costs of financial distress can be greatly reduced (by 93% in our example) by holding enough capital in reserve to accommodate one disaster. For events that are individually tolerable but become catastrophic when they occur in series, this is a powerful strategy. The reduction in ECFD for insuring against the *second* disaster in the series (in our example, 0.11) is modest compared to the benefit from insuring against the first disaster (in our example, 1.41).

We will now use a series of comparative static analyses to show the effects of varying important parameters.

[9] Note that the ECFD as introduced above should be seen as a lower bound to the expected opportunity cost of financial distress. We calculate expected net present values under the assumption that, in the case where the project is destroyed and no emergency repair is done, the project can be restarted immediately. This immediate restart, however, requires the availability of funds covering the necessary initial investment i_1 and the guaranteed availability of i_2 in the following period. In a financial distress situation, these funds, even if they are lower than the emergency repair costs, might be available only later. The net present value of this restart would then, of course, need to be discounted to reflect the effect of the delayed start on the future benefits from project completion. Incorporating this aspect of the opportunity costs of financial distress caused by the delay in the project's restarting, however, would only strengthen the point being made here about the usefulness of *immediate* availability of emergency funds, such as offered by state-contingent catastrophe securities.

Table III. State-Contingent Cash Flows Resulting from Repair Strategy Choices

		Outcome			
		No Event	Event (only) in Period 1	Event (only) in Period 2	Event in Both Periods
	Probability	$(1-p)^2$	$p(1-p)$	$p(1-p)$	p^2
Repair Strategy	(R,R)	$-i_1$ $-i_2\delta$ $+b\delta^2$	$-i_1 - e_1\delta$ $-i_2\delta$ $+b\delta^2$	$-i_1$ $-i_2\delta - e_2\delta^2$ $+b\delta^2$	$-i_1 - e_1\delta$ $-i_2\delta - e_2\delta^2$ $+b\delta^2$
	(F,R)	$-i_1$ $-i_2\delta$ $+b\delta^2$	$-i_1$ $+NV_0^{F,R}\delta$	$-i_1$ $-i_2\delta - e_2\,\delta^2$ $+b\delta^2$	$-i_1$ $+NV_0^{F,R}\delta$
	(R,F)	$-i_1$ $-i_2\delta$ $+b\delta^2$	$-i_1 - e_1\delta$ $-i_2\delta$ $+b\delta^2$	$-i_1$ $-i_2\delta$ $+NV_0^{R,F}\delta^2$	$-i_1 - e_1\delta$ $-i_2\delta$ $+NV_0^{R,F}\delta^2$
	(F,F)	$-i_1$ $-i_2\delta$ $+b\delta^2$	$-i_1$ $+NV_0^{F,F}\delta$	$-i_1$ $-i_2\delta$ $+NV_0^{F,F}\delta^2$	$-i_1$ $+NV_0{}^{F,F}\delta$
	(R, $\tilde{\mathbf{R}}$)	$-i_1$ $-i_2\delta$ $+b\delta^2$	$-i_1\ -e_1\delta$ $-i_2\delta$ $+b\delta^2$	$-i_1$ $-i_2\delta\ -e_2\delta^2$ $+b\delta^2$	$-i_1\ -e_1\delta$ $-i_2\delta$ $+NV_0^{R,\tilde{R}}\delta^2$

4.7. ECFD as a Function of Initial Capital

First, we consider how the expected cost of financial distress depends on the amount of capital available for emergency repair. Based on the parameters given in Example 2, Fig. 1 shows the relationship between the value of EFCD and f.

$$Example\,2: \quad r = 0.1 \quad i_1 = 10 \quad i_2 = 10 \quad e_1 = 10$$
$$e_2 = 15 \quad p = 0.1 \quad b = 40$$
$$f \text{ varies from 0 to 40}$$

Note that, in accordance with intuition, the expected cost of financial distress is very high for the case of $f = 0$ (no capital being available for emergency repair). On the other extreme, because the best strategy is (R,R) in our example, the ECFD equals 0 only when the initial capital suffices for repairs in both periods.

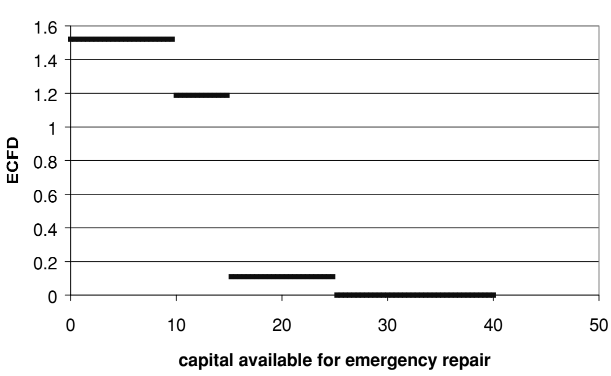

Fig. 1. ECFD and initial capital.

In this example, the emergency-repair cost in the second period is higher than in the first. In the case of amounts of available capital that allow defending the project only in the first period but not in the second, the best feasible strategy becomes (R,F) and the EFCD drops slightly from its highest level. The most dramatic incremental reduction of EFCD can be obtained by setting $f = 15$, enabling the project manager to repair in either the first or the second period, but not both—equivalent to having capital available to assuage one catastrophe but not two. This leads to the strategy (R, $\tilde{R}$) being optimal, which results in a different outcome from (R,R) only if catastrophes occur in both periods.

We thus note that the strategy (R, $\tilde{R}$), in conjunction with a limited amount of emergency capital reserves, can thus accomplish a significant portion of the benefit of the strategy (R,R) with an unlimited capital reserve. Note that this limited emergency capital reserve might be provided through a contingent financing instrument such as a cat bond, rather than representing idle funds held in inventory against the rare event of two sequential catastrophes. A cat bond designed to eliminate most of the costs of financial distress, while limiting the total amount of

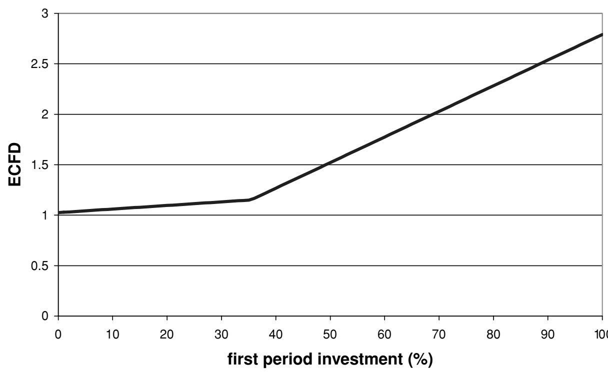

Fig. 2. ECFD vs. time structure of required investment.

investor capital at risk to that of a single disaster, ought to be constructed to pay for the *first* disaster that occurs, regardless of whether this disaster occurs in Period 1 or Period 2. A cat bond that pays for the second occurring disaster will be tapped much less often, but will also create much less reduction in ECFD.

4.8. Sensitivity of ECFD to Time Structure of Required Investment

We now consider how the expected cost of financial distress depends on the speed with which capital is committed to the project, that is, for a given project cost, what percentage of this cost must be committed during the first period, and how much may be deferred until the second.[10] Based on the parameters given in Example 3, Fig. 2 shows the relationship between the value of EFCD and this time structure of required investment.

Example 3 : $f = 0 \quad r = 0.1 \quad i_1 + i_2 = 20 \quad e_1 = 10$

$e_2 = 15 \quad p = 0.1 \quad b = 40 i_1/(i_1 + i_2)$

varies from 0 to 1

From Fig. 2, we see that ECFD rises with the percentage of the total construction costs that must be committed during the first period. The dependency is piece-wise linear, as can be seen directly from the equations governing ECFD. For a low percentage of first-period investment commitment, the project manager would tend to *choose* to let the project fail (and restart) if a disaster were to occur in Period 1, even if unlimited repair capital were available. The larger this fraction of first-period commitment, the more attractive is the strategy (R,R). The kink in the curve marks the switch from (F,R) to (R,R) as the best unconstrained strategy.

4.9. Sensitivity of ECFD to the Cost of Capital

We now consider how the expected cost of financial distress depends on the cost of capital. The same cost of capital, r, is assumed to apply both for the pure rate of discounting project benefits (effectively, the opportunity cost of not having a project's benefits sooner) and for the implied rate of return paid on borrowed funds (effectively, the explicit cash outflow for interest payments). It should be noted that we assumed that r is relatively high for sovereign project managers in emerging countries, either based on high time value of incremental infrastructure investments or based on high borrowing costs in the financial markets. Based on the parameters given in Example 4, Fig. 3 shows the relationship between the value of EFCD and this cost of capital.

Example 4 : $f = 0 \quad i_1 = 10 \quad i_2 = 10 \quad e_1 = 10$

$e_2 = 15 \quad p = 0.1 \quad b = 40$

r varies from 0% to 60% per period

For the important region, the ECFD behaves like a function concave in the cost of capital and, in addition, does not react in a highly sensitive manner to small changes in the cost of capital. It should be mentioned that ECFD first increases and then decreases, reaching a local max at approximately 0.25 in Example 4. In this example (R,R) is always the unconstrained best strategy and (F,F) is the best capital-constrained strategy as long as these strategies both

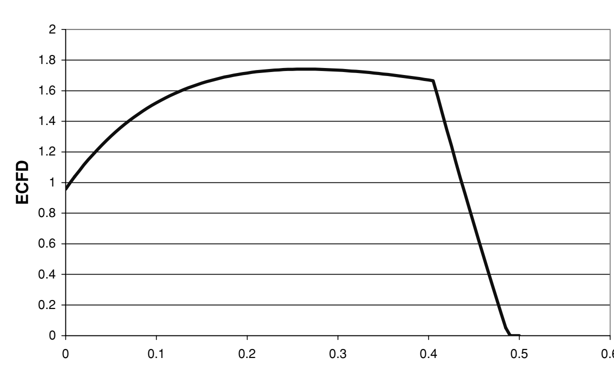

Fig. 3. ECFD vs. cost of capital.

[10] Note that in Example 3, $i_1 + i_2 = 20$ in all cases; only the balance between i_1 and i_2 will be changed.

have positive NPVs. The first kink of the curve is linked to the switch of the constrained best strategy from (F,F) to (0) at approximately $r = 0.4$; this occurs when the cost of capital becomes so high that the project is no longer attractive to begin (i.e., has a negative NPV). Once (0) becomes the best alternative strategy to (R,R), the ECFD decreases rapidly in the cost of capital—not because the problem of contingent capital is solved (because $f = 0$, no repairs can be made in any event), but simply because the attractiveness of the project falls rapidly in r but the constrained best outcome does not decrease any further.

An interesting extension to the model would be to incorporate the costs of borrowing the optimal amount of capital at the beginning of Period 1 with the goal of maximizing the overall expected benefit from the project including these capital costs. This optimal amount of capital to borrow would depend on the cost of capital both directly and indirectly. The direct effect of the cost of capital on the optimal amount to borrow comes about because interest payments would need to be made (and, implicitly, made from available cash) whether a disaster occurs or not—an expensive proposition when disasters are rare. The indirect effect occurs through the borrowings increasing f and thereby reducing ECFD, which itself depends on the cost of capital as shown in Fig. 3. The sensitivity analysis of the ECFD to the cost of capital if the *optimal* amount of capital were borrowed for each value of r would differ significantly from our analysis in Fig. 3, which assumes that a *fixed* amount (here, 0) is borrowed regardless of r.

4.10. Sensitivity of ECFD to the Probability of Disaster

We now consider how the expected cost of financial distress depends on the probability of a disaster occurring in any given period. The severity of the disaster is assumed to stay constant, although its probability changes. Based on the parameters given in Example 5, Fig. 4 shows the relationship between the value of EFCD and this probability that a disaster occurs.

$$\textit{Example 5}: \quad f = 0 \quad r = 0.1 \quad i_1 = 10 \quad i_2 = 10$$
$$e_1 = 10 \quad e_2 = 15 \quad b = 40$$
$$p \text{ varies from 0 to 1 per period}$$

In the left-hand portion of the curve, the net value of the constrained best strategy ((F,F) in this example) falls much more quickly than that of the unconstrained best strategy (R,R). Defending the project, especially in the second period, becomes more beneficial as p increases. One major difference between (R,R) and (F,F) as strategies is that (R,R) guarantees that the project will come online at the end of Period 2, at which time the benefit b will be realized for certain (albeit at a random cost). As p increases, the expected length of time until the project is completed increases under the (F,F) strategy. In addition, defending the project in Period 2 is particularly valuable as p increases because a completed project does not need to "run the gauntlet" of two periods of relatively frequent risks.

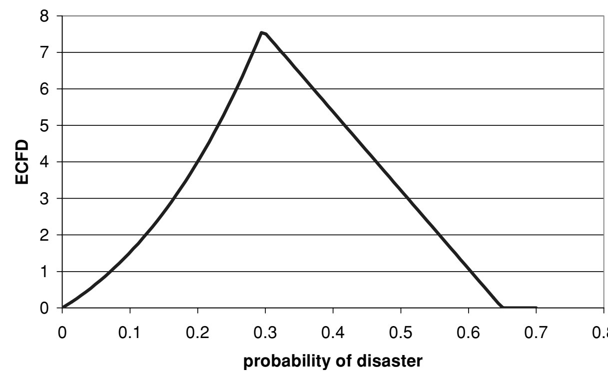

Fig. 4. ECFD vs. probability of disaster.

The kink in the curve (at around $p = 0.3$ in our example) is due to the switch from (F,F) to (0) as the optimal capital-constrained strategy. For large enough values of p, the project will suffer catastrophe so often that it should never be begun (i.e., will have negative NPV) if no emergency capital is available. In this case, the cost of financial distress (i.e., the opportunity cost of not having enough capital to defend the project, and therefore not enough to make *beginning* the project worthwhile) will thus be the same as the full project value under the unconstrained best strategy (R,R). This is the maximum possible level of ECFD, representing the loss of the entire project value for certain regardless of whether the disastrous events occur. This project value, in turn, decreases in p because the expected project completion cost is increasing (incorporating the expected costs of emergency repair) while its benefit remains constant. After a certain critical level (approximately 0.63 in our example), the likelihood of disaster is so large, and the expected damages before project completion so great, that the project manager is dissuaded from beginning the project even if an infinite amount of capital is available for emergency repairs.

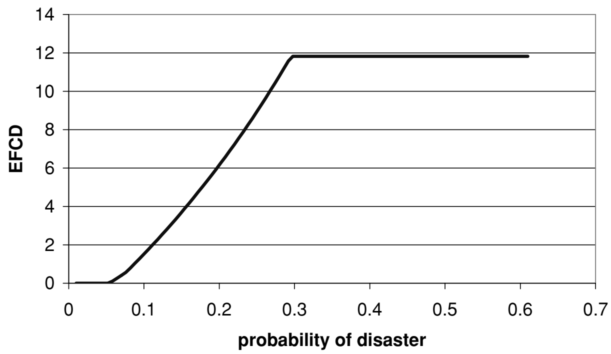

Fig. 5. ECFD vs. probability of disaster (expected loss held constant).

$$\textit{Example}\,6: \quad f = 0 \quad r = 0.1 \quad i_1 = 10 \quad i_2 = 10$$
$$p \cdot e_1 = 1 \quad p \cdot e_2 = 1.5 \quad b = 40$$
$$p \text{ varies, but } p \cdot e_1 \text{ and } p \cdot e_2 \text{ are held constant}$$

Fig. 5 shows that expected costs of financial distress caused by project disruption are higher for more frequent, less severe events than for infrequent but very severe events. The initial choice of (F,F) when severe events occur but rarely negates the impact of limited capital. If funding to repair a project is not going to be available in any event (either because the capital is not available, or because restarting the project is cheaper than repairing it), it does not matter to ECFD whether the disaster causes a \$10,000 loss that *will not* be repaired or a \$1 million loss that *cannot* be repaired. The frequency of the loss, however, increases either the expected length of time until this completion occurs (when these small losses cause the project to be restarted under the optimal repair strategy), which does not affect ECFD, or the expected costs of project completion (if these small losses would be repaired under the optimal repair strategy, but these repairs are impossible due to capital limitations). Frequent losses that cannot be repaired lead to substantial increases in ECFD; once these losses are frequent enough (which occurs at approximately $p = 0.3$ in Fig. 5), the project is no longer attractive, and ECFD achieves its maximum.

5. SUMMARY OF BENEFITS FROM PROJECT RISK MANAGEMENT

At the level of the sovereign government or the third-party sponsor, the reduction in ECFD will create three types of benefits that will increase the number of projects that can be accomplished on a given capital budget. For example, consider a capital budget of \$15 billion, \$12 billion of which is to be committed to new capital projects and \$3 billion to be kept in reserve for emergencies.

First, at the simplest level, a reduction in expected completion costs of a representative project from \$120 million to \$100 million allows 120 such projects to be funded rather than 100. Alternately, the sponsor may be able to use this incremental savings of \$200 million to fund some projects less attractive than the initial 100 that otherwise would not be in a priority position to receive capital.

Second, reducing the variance of the capital requirements of individual projects enables the government or third-party project sponsor to more efficiently commit its limited capital. The general structure of this financial optimization problem is as follows. Normally, the government or sponsor would commit less than 100% of its available capital, withholding a portion (here, \$3 billion) to deal with extraordinary and unexpected funding requirements such as those caused by natural disasters (whether directly by damage to the ongoing infrastructure project, or indirectly due to unilateral diversion of project funds to humanitarian efforts). The optimal percentage of capital to reserve for these emergencies balances the costs of over-committing (using almost 100% of capital available at all times, maintaining only a small reserve for contingent funding, and thereby running the risk of inadvertently causing project disruption when several portfolio projects require extraordinary infusions of cash at the same time) against the costs of under-committing (allowing capital to lie fallow, which could otherwise be directed toward socially beneficial projects).

By increasing the predictability of required project financing, even if the expected amount of project funding remained unchanged, this utilization percentage could be increased without taking on additional risk of over-commitment—an increase in capital efficiency that comes at no one's expense. So, for example, availability of external contingent capital could allow the sponsor's effective \$12 billion of infrastructure budget to grow to \$14 billion of committable capital (with \$1 billion left in reserve, rather than \$3 billion). This effect combines with the reduction in project cost to enable 140 projects at the new lower cost and lower variance (again compared to 100 projects at the higher cost and higher variance) for the same \$15 billion.

Finally, this effective 40% increase in efficiency (in terms of projects completed per dollar invested) may well attract additional capital into such project financing—a demand effect.[11] If the original $15 billion total allocation for capital projects were to grow to $20 billion because of this increased efficiency, the sponsor could accomplish 200 representative projects versus the baseline of 100—a 100% increase in effective infrastructure projects, without increasing the risk to the investors, based on only a 33% increase in capital.

6. MODEL EXTENSIONS AND TOPICS FOR FUTURE RESEARCH

We have addressed the question: Why might the *sovereign government* (or third-party project sponsor) of an *emerging nation* be interested in *employing catastrophe-linked instruments* to protect *infrastructure* investments, funded by a *third-party project sponsor*, *from low-probability, high-consequence* events such as *natural catastrophes*? We conclude by presenting some additional topics—requiring analysis beyond the scope of this article—related to the questions of how the government might use these bonds, how the instruments might be designed, and to what extent the market for such securities interacts with information conditions and government policy.

6.1. Challenges and Limitations Specific to Sovereign CAT Bonds

There are many challenges to implementing catastrophe-linked securities; these challenges have been discussed elsewhere. We consider only one, a unique issue for a sovereign government possessing widely dispersed infrastructure assets.

When considering only infrastructure projects, the sovereign government is the monopoly provider of these projects, and the monopsony buyer of cat risk protection. No other party (except, perhaps, for a third-party sponsor such as the World Bank) has an obvious insurable interest in these projects. The government can thus be thought of as having 100% market share in insuring its infrastructure, even though this infrastructure may be spread out over a very large geographic region. On the one hand, this 100% market share would seem to offer an opportunity to design a countrywide cat bond with low basis risk, as catastrophe-related damage to the entire country would correlate well with catastrophe-linked damage to countrywide projects. A portfolio of similar projects (such as a highway system) spread evenly nationwide could thus be protected by a country-level index instrument. Geographical dispersion of a highway system prevents the asset from being totally destroyed by a local phenomenon (such as a flood or earthquake), a form of built-in diversification and resistance to catastrophic damages from geographically concentrated risks.

Some countries incorporate such extremely large and diverse geographic scope (e.g., China) that it may be difficult to define appropriate triggers for such catastrophe-related instruments on a national scale—paradoxically, the infrastructure projects, even though geographically widespread, are not sufficiently uniformly subjected to or affected by disaster for national coverage to be a good proxy for project coverage. Thus, the same geographical dispersion makes it a challenge to design an instrument to protect the asset without introducing massive basis risk.

Ideally, however, instruments to protect *specific* infrastructure investments would be designed project by project to incorporate customization both at the geographic level (insuring against the appropriate hazards) and at the project level (generating the appropriate cash flows for reconstruction). This project-by-project design is relatively simple to do for a project of limited geographical area (such as a dam or a nuclear power plant) but very difficult to do for an infrastructure asset that, by its very nature, is geographically dispersed (such as a fiber-optic network or a highway system). Such projects may be too widespread for customized project coverage, yet not uniform enough for country-level coverage. It is not clear how this coincidence between common ownership and geographical dispersion can be resolved.

6.2. Leveraging Investment in Project Monitoring

The structure of the project funding arrangement may offer additional opportunities to support catastrophe risk transfer. Infrastructure projects in

[11] If we consider investment in infrastructure projects as a good to be consumed, this necessary condition for the sponsor to increase the total amount of capital committed as the price of project completion falls is that the elasticity of demand for projects to sponsor exceeds unity, i.e., that abs(ε)>1. If the third-party sponsor is indeed the monopoly supplier of sponsorship, that this condition will always be satisfied follows directly from the first-order condition of optimal quantity (choosing quantity in the elastic portion of the demand curve). Thus, this demand effect will always *increase* the amount of funding devoted to these types of projects.

emerging economies generally involve a third-party sponsor, such as the World Bank, that provides capital and investment advice to the sovereign government, and may have a supervisory presence during project completion, but that does not generally control the day-to-day management of the project. Investors in project-tied CAT risk securities can rely on the project sponsor to provide at least partial monitoring—especially on large-scale infrastructure projects in emerging economies, for which the sponsor may well have an advisory team onsite during critical portions of the project. This structure allows for the investors in the catastrophe-linked instrument to take advantage of the "delegated monitoring" provided by the project sponsor,[13] reducing investors' costs of providing financing for these risks. Indeed, investments facing severe risks will likely draw *more* sponsor attention and financial commitment, rather than less (a situation analogous to that examined by Calem and Rizzo[14] in the private sector). The project sponsor may thus serve an informational role in project management, as a well as a financial role.

If investors can rely on the third-party sponsor for documentation of damage done to the project, recommendations for cost-minimizing ways to conduct emergency repairs, and similar reports—even in the event that a disaster occurs—this monitoring will presumably reduce the extent of moral hazard. Of course, to ensure that the amount of monitoring performed (and the focus of the information gathered) will be optimal, considering the interests both of the sponsor and the investors, requires that the sponsor of the project either be the investor in the catastrophe bonds or have some sort of high-powered incentives as part of a contractual agreement to act in a way consistent with being the investors' agent. Even if this alignment of incentives is only partially achieved, however, some reduction in moral hazard should ensue. Given that the barrier against constructing perfect hedges against catastrophe involves a tradeoff of moral hazard versus basis risk,[15,16] this reduction in moral hazard, in turn, allows the catastrophe-linked instruments to be constructed so as to behave more like excess-of-loss reinsurance and therefore reduce basis risk.[12] This moral hazard may already be contained by the sponsor's monitoring; quantifying this reduction, and communicating it to investors, will reduce the cost of catastrophic risk coverage provided by financial markets.

12 The optimal design of this security will thus need to trade off efficient incentives for investment in mitigation (arguing for a state-contingent payoff, statistically correlated to but causally independent of the actual losses to the project) versus incentives for accurate reporting of damages done to the project (arguing for an excess-of-loss payoff structure, which can reduce basis risk if payments are conditioned on truthfully reported actual losses).

6.3. Interaction of Project Financing and Moral Hazard

One reason catastrophe-linked securities hold such promise is that, unlike other insurance markets such as health or automobile coverage, the probability with which disasters occur, and the severity of the disaster measured purely in terms of natural forces (e.g., wind speed, flood height of a river, earthquake magnitude, etc.) cannot be affected (for good or for ill) by any actions of the government, its citizens, or any party interested in the payoff of the catastrophe-linked securities. The *damages* caused by a disaster of arbitrary magnitude may be increased, however, because of the effects of moral hazard (either through lack of effective mitigation investments before a disaster occurs, or error-prone claims adjustment techniques and lack of attention to cost-minimizing repair techniques after a disaster occurs). Determining how the costs of these *ex post* opportunities for moral hazard can be contained is an interesting subject for further research and simulation.

6.4. Comparing Sovereign and Private Corporate Capital Structures

The sovereign position of the project sponsor for infrastructure projects has both benefits and drawbacks. In addition to the politically motivated commitment problem noted above, sovereign governments operate under capital constraints that private companies do not. A corporation can finance its operations, investments, and expansions through issuing equity, issuing debt, or retaining earnings from operations. Sovereign governments cannot issue equity and typically do not retain earnings; their financing is, by necessity, primarily debt. Therefore, all else equal, governments will have less flexibility in (and, presumably, higher costs of) financing than would an otherwise similar large corporation who had the choice to issue either debt or equity. Furthermore, governments value smooth growth in gross domestic product (the equivalent of return on equity for private ventures) but are restricted in their ability to diversify; they are limited to investing in infrastructure projects inside their own borders, unlike private investors who can diversify their portfolios as a first line of defense against catastrophe. A government's cost of capital will also rise faster than an equivalent company's in case of losses that would lead to insolvency (default on traditional sovereign debt) because an emergency equity recapitalization is not possible. Incorporating catastrophe-linked securities into the expansion path that a government desiring economic growth might pursue will require additional analysis, to integrate the risk-hedging abilities of the cat risk securities with the lower (but still significant, for emerging economies) costs of traditional sovereign debt.

6.5. Optimal Construction Technique—Embedding Efficient Levels of Flexibility

The correct method of organizing projects—in terms of materials used, completion schedules, and tradeoffs among amounts of capital, labor, energy, and materials to be committed to the project—will also depend on how project risk is to be handled. Catastrophe-linked instruments expand the choice set for how project managers can handle such future risks. As we have seen, risk management techniques that eliminate costs of financial distress can lead to reductions in expected completion costs. The main alternative to contingent capital availability for creating resilience to unforeseen project risks is embedded real options. Even optimally organized projects suffering from capital-availability risk may incorporate such real options as a hedge that increase production costs in high-probability scenarios to reduce production costs in disaster scenarios.[(17)] Inasmuch as such real options are costly to embed in the project, there may be gains from changing the organization of projects, if risk can be hedged using financial instruments, through substituting external sources of capital for the most costly of these embedded real options.[13]

Either embedded options or contingent capital may produce reduced total expected cost of completion, as argued analogously by Simon.[(18)] cat bonds will reduce total cost when these real options are expensive to embed and where their removal or omission will reduce project completion costs when the cat bonds assume their risk-bearing function.

[13] Of course, if these embedded options *reduce* the expected costs, even absent their benefits of reducing uncertainty and the cost-increasing effects of uncertainty, they should be left in—even if contingent capital is also used to further reduce costs.

6.6. Interactions Between Catastrophe and Fiscal Policy

A natural catastrophe leads to an instantaneous depreciation of a nation's capital stock. The optimal speed of replacing this stock depends on many macroeconomic variables. Questions for macroeconomic theory analysis include: Is there any difference, in terms of fiscal stimulus, between a macroeconomic shock caused by disaster versus the traditional multiplier on government spending? and How should government fiscal policy be adjusted both immediately after the disaster, in terms of trading off present consumption and future investment (especially the optimal speed of rebuilding the destroyed capital)?

6.7. Hidden Benefits of Catastrophe Through Forced Modernization

In this article, we have focused on completing projects in process, rather than protecting existing capital in place. Not all capital in place, however, is created equal. Some capital in place is particularly productive and carries high opportunity costs of destruction; some is obsolete. What completed projects may incorporate an implicit *advantage* of having obsolete capital destroyed and replaced with newer vintage capital, funded by cat bond payments? What implications follow for evaluating various types of infrastructure assets' economic vulnerability to disaster? In particular, which completed-project assets should be so insured, and at what level of coverage? To what extent are there additional benefits from using a state-contingent risk-transfer instrument to protect such complete-project assets by providing one large reimbursement at the national level, rather than purchasing traditional "replacement cost" coverage for each asset individually? These questions can be addressed through a model similar to ours, emphasizing the true opportunity cost of foregone project benefits rather than the "book value" of completed projects.

ACKNOWLEDGMENTS

We are grateful to Paul Kleindorfer for several discussions about the underlying motivations for this work. All errors and omissions remain the responsibility of the authors. Project support from the Wharton "Managing Catastrophic Risk" Project and from the Wharton Risk Analysis and Decision Processes Research Center, as well as financial support from the

International Institute for Applied Systems Analysis (Croson and Richter) and from an academic fellowship granted by the German Academic Exchange Service (DAAD) under the *Gemeinsames Hochschulsonderprogramm III von Bund und Ländern* (Richter) is gratefully acknowledged.

REFERENCES

1. Lewis, C. M., & Murdock, K. (1996). The role of government contracts in discretionary reinsurance markets for natural disasters. *Journal of Risk and Insurance*, *63*, 567–597.
2. Croson, D. C., & Kunreuther, H. C. (2000). Customizing indemnity contracts and indexed cat bonds for natural hazard risks. *Journal of Risk Finance*, *1*, 24–41.
3. Froot, K. A., & Seasholes, M. S. (1997). *USAA*: *Catastrophic risk financing* (Case 9, 298-007). Boston, MA: Harvard Graduate School of Business Administration.
4. Canabarro, E., Finkemeier, M., Anderson, R. R., & Bendimerad, F. (1998). *Analyzing insurance linked securities*. New York: Goldman Sachs & Co.
5. Bantwal, V. J., & Kunreuther, H. C. (2000). A cat bond premium puzzle. *Journal of Psychology and Financial Markets*, *1*, 76–91.
6. Cummins, J. D., Doherty, N. A., & Lo, A. (1999). *Can insurers pay for the "big one"? Measuring the capacity of an insurance market to respond to catastrophic losses* (Working Paper 98-11-B). Philadelphia, PA: Financial Institutions Center. The Wharton School, University of Pennsylvania.
7. Mayers, D., & Smith Jr., C. W. (1982). On the corporate demand for insurance. *Journal of Business*, *55*, 281–296.
8. Greenwald, B. C., & Stiglitz, J. E. (1990). Asymmetric information and the new theory of the firm: Financial constraints and risk behavior. *American Economic Review* (Papers and Proceedings), *80*, 160–165.
9. Doherty, N. A. (2000). *Integrated risk management—Techniques and strategies for managing corporate risk*. New York: McGraw-Hill.
10. Eccles, R. G., & Crane, D. B. (1988). *Doing deals: Investment banks at work*. Boston, MA: Harvard University Press.
11. Bhide, A. (1986). Hustle as strategy. *Harvard Business Review*, *64*, 59–66.
12. Kydland, F. E., & Prescott, E. C. (1977). Rules rather than discretion: The inconsistency of optimal plans. *Journal of Political Economy*, *85*, 473–491.
13. Diamond, D. W. (1984). Financial intermediation and delegated monitoring. *Review of Economic Studies*, *51*, 393–414.
14. Calem, P. S., & Rizzo, J. A. (1992). Banks as information specialists: The case of hospital lending. *Journal of Banking & Finance*, *16*, 1123–1141.
15. Doherty, N. A. (1997). Financial innovation for financing and hedging catastrophe risk. In N. R. Britton & O. John (Eds.), *Financial risk management for natural catastrophes* (pp. 191–209) (Proceedings of a Conference sponsored by Aon Group Australia Limited). Brisbane: Griffith University.
16. Doherty, N. A. (1997). Innovations in managing catastrophe risk. *Journal of Risk and Insurance*, *64*, 713–718.
17. Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton, NJ: Princeton University Press.
18. Simon, H. A. (1996). *The sciences of the artificial*. Cambridge, MA: MIT Press.