THE IMPACT OF UNCERTAINTY IN MANAGING SEISMIC RISK: THE CASE OF EARTHQUAKE FREQUENCY AND STRUCTURAL VULNERABILITY[1]

Patricia Grossi[2]
Paul Kleindorfer[3]
Howard Kunreuther[4]

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[1] This paper reports on research supported by the Wharton Financial Institutions Center and the Wharton Risk Management and Decision Processes Center Project on "Managing Catastrophic Risks." This research was presented at a Sponsor's Meeting for the project held on December 15, 1998. Special thanks to Weimin Dong from Risk Management Solutions and Dennis Kuzak and Tom Larsen from EQECAT for their assistance with respect to constructing the two model cities. Also, Vivek Bantwal worked numerous hours in constructing the data analysis module, and Jaideep Hebbar, Eu Han Lee, and Mike Mulein were instrumental in creating the tables of results detailed in the paper.

[2] Doctoral Candidate, Department of Systems Engineering, University of Pennsylvania, Philadelphia, PA 19104-6315.

[3] Universal Furniture Professor of Decision Sciences and Economics, The Wharton School, University of Pennsylvania, Philadelphia, PA 19104. Co-Director of the Wharton Center for Risk Management and Decision Processes.

[4] Cecilia Yen Koo Professor of Decision Sciences and Public Policy and Management, The Wharton School, University of Pennsylvania, Philadelphia, PA 19104. Co-Director of the Wharton Center for Risk Management and Decision Processes.

ABSTRACT

In estimating economic losses from significant earthquake events, there is considerable uncertainty in the earthquake loss estimation (ELE) process. From the likelihood of future earthquake occurrences to the estimation of structural vulnerability in terms of actual dollar loss, many assumptions are made. This paper examines the impact that uncertainty in the frequency of earthquake events and the vulnerability of residential structures has on the estimated economic losses to residential insurers and homeowners from significant earthquake events with and without structural mitigation. A specific residential earthquake mitigation measure is chosen for analysis, which reduces estimated losses from earthquakes and improves the solvency of residential insurers.

First, we will discuss these analyses in the context of the Managing Catastrophic Risks project at the Wharton School, focusing on the importance of uncertainty in analyzing catastrophic losses. Next, the model cities being considered in the analysis are redefined and the specific earthquake mitigation technique used in the analysis is reviewed. Third, we will outline how uncertainty is handled within the scope of the investigation. Finally, we will present the results, form some conclusions, and outline some open questions for further analysis.

INTRODUCTION

In January of 1997, the Wharton Financial Institutions Center and the Risk Management and Decision Processes Center launched a three-year study on the ways in which individuals and institutions can manage their catastrophic risk exposure. Entitled Managing Catastrophic Risks, this on-going project has focused on how such things as mitigation, insurance, reinsurance, capital markets, and public policy can all be used to manage catastrophic risk. The analyses presented in this paper focus on two policies that can be used to reduce economic losses from earthquakes: mitigation and insurance. Further, the importance of the interaction between these tools for reducing losses with the uncertainty associated with the earthquake loss estimation process is emphasized.

In some ways, the research presented in this paper is an update to the preliminary analyses presented at the Public Private Partnership 2000 Conference in December of 1997 (Kleindorfer and Kunreuther, 1997). In the suggestions for further research, the authors note that the probability of earthquake events, damage estimation to structures before and after mitigation, and the costs of mitigation are three areas of uncertainty which need to be explored. So, using more accurate costs and benefits associated with earthquake mitigation, the analyses presented below are a more precise look at the effects of mitigation on reducing losses. And, the issue of uncertainty in estimating earthquake frequency and structural vulnerability is systematically analyzed.

THE UNCERTAINTY ISSUE

In April of 1998, there was one in a series of Sponsors' Meetings for the Managing Catastrophic Risks project. Within this meeting, there was a panel discussion on the issue of uncertainty in catastrophic risk modeling. Representatives from each of the three modeling groups involved in the project took part in the discussion, including Karen Clark from Applied Insurance Research, Dennis Kuzak from EQECAT, and Weimin Dong from Risk Management Solutions. Prior to this time, there was vague discourse on the need to incorporate uncertainty into the analyses already completed for the project, but no formal dialogue had taken place.

The need to understand the uncertainty involved in the loss estimation process is apparent when one considers the development of catastrophic risk modeling. In estimating economic losses from catastrophic events, such as earthquakes, the methodology used in the existing software models is based largely on limited information and expert opinion. The general methodology for earthquake loss estimation can be broken down into four main steps: define the earthquake hazard, define the inventory exposure characteristics, define the inventory damage, and calculate the loss. Each of these four stages is fraught with uncertainty. Limited scientific information in defining the hazard, lower quality data in defining the exposure inventory characteristics, and limited engineering information in estimating the inventory damage result in error bounds in estimating expected losses.

Why is understanding the uncertainty associated with earthquake losses so important?

Similar to other low-probability, high-consequence (LPHC) events, the problem arises when decisions need to be made. Decision-making should not be based solely on mean estimates of loss, but should consider the error bounds or confidence limits in calculating such mean values. While expected values of loss are easily determined and they clarify whether or not an individual is risk adverse or not, more information is usually needed for an individual to make a decision in the case of potential catastrophic losses. *Balanced risk management* methods (Dames and Moore, Inc., 1994), which allow explicit incorporation of error bounds into an analysis, is the preferred method by those making these types of decisions.

But, if the decision-maker does not appreciate the complexity of the problem and chooses to ignore the uncertainties involved, difficulties could ensue. For instance, an insurer can use one of the software tools developed by the modelers to analyze his insured losses in a significant earthquake event. But, if he thinks in terms of mean loss only, and does not consider the worst case scenario, he could stand to lose his business through insolvency.

With this issue in mind, one can easily recognize the need to quantify and reduce the uncertainty associated with earthquake loss estimation. But, how does one accomplish this? Specifically, how should uncertainty be defined? Uncertainty has been classified by leaders in the field of seismic hazard analysis as either **aleatory** (i.e. randomness) or **epistemic** (i.e. lack of knowledge) in nature (Budnitz et al., 1997). Furthermore, uncertainty has been categorized into **modeling** uncertainty, due to differences between the process being modeled and the simplified model used for analysis, and **parametric** uncertainty, due to differences between actual values of parameters and those estimated for analysis.

In an uncertainty analysis, should a distinction be made between aleatory and epistemic uncertainty? Further, what confidence level should be used in determining the bounds on uncertainty? While both modeling and parametric uncertainties contain aleatory and epistemic uncertainty, "…epistemic and aleatory uncertainties are fixed neither in space…nor in time. What is aleatory uncertainty in one model can be epistemic uncertainty in another model, at least in part. And what appears to be aleatory uncertainty at the present time may be cast, at least in part, into epistemic uncertainty at a later date. As a matter of practical reality, the trick is to make sure that uncertainties are neither ignored nor double counted. The possibilities of doing so with parametrically complex models are large" (Hanks and Cornell, 1994). This is an important point to keep in mind when addressing this issue.

OBJECTIVES OF UNCERTAINTY STUDY

In October of 1998, a meeting of the Technical Advisory Committee (TAC) for the Managing Catastrophic Risks project was held at the University of Pennsylvania. This Technical Advisory Committee consists of recognized experts in the fields of engineering, seismology, statistics, meteorology, decision analysis and public policy. Each brings a demonstrated interest in our research, and the TAC was established to provide input and technical counsel to the model cities and related mitigation research initiatives. At the aforementioned TAC meeting, Professor Robert Whitman raised a very important point about any uncertainty analysis to be completed for this project. The objectives of the study need to be clearly identified before an experimental design can be implemented. In essence, the appropriateness of the design is dependent upon the study's objectives. When considering the objectives of this uncertainty analysis, there are four separate questions that could be asked:

1. How much uncertainty is there in the actual losses used to calibrate the models?
2. How much uncertainty is there in the loss predicted by the models?
3. What individual factors or parameters contribute most to the uncertainty of predicted loss?
4. Is one software model always high or low in its loss estimate? If so, why?

While all four of these questions are important, the consideration of all of them in our study is not realistic. The time and cost involved is significant. Each question deals with a major issue in software modeling of earthquake losses: calibration and scaling, loss methodology, parameter estimation, and model estimation. But, which question or questions should be the focus of the work? A discussion on this issue is warranted.

How much uncertainty is there in the actual losses used to calibrate the models?

This first question deals with the issue of scale dependencies among historic earthquakes used to calibrate and validate the models currently developed. Most of the damage statistics used in the models are based on earthquake events in California over the past 30 years or so. These events have ranged in Richter magnitude between approximately a 5.9 to a 7.3. This corresponds to ground shaking levels in the surrounding region ranging from Modified Mercalli Intensity (MMI) VI to X. What about the lower and higher magnitude or intensity levels used in a probabilistic seismic hazard analysis (PSHA)? Is it appropriate to scale damage statistics or other parameters (i.e. recurrence relationship parameters) used in the loss estimation process?

This first question also deals with the issue of the historical record of damaging earthquake events. Since the historical record of seismicity is so short, can one justify basing future estimates of expected loss on it? If a relatively minor or a large-scale earthquake were to hit California, would both events' losses agree with those estimated by the models? Would the software have to be "updated" to be consistent?

How much uncertainty is there in the loss predicted by the models?

The second issue of uncertainty questions the methodology used to predict economic losses. What do new theories on earthquake occurrence mean for the state-of-the-art in seismic hazard analysis? Recently, earthquakes have been suggested as one example of a self-organized critical (SOC) phenomenon (Bak and Tang, 1989). The Earth is described as being in a critical state everywhere, where the stress is approaching failure, and the earthquakes that occur represent small disturbances on this critical state. But, if this theory is true, what does it mean for the probabilistic seismic hazard analysis (PSHA) portion of earthquake loss estimation? Is this hypothesis in direct conflict with the Poisson model used to predict future earthquake occurrences?

Also, this second issue questions, assuming the methodology is correct, the validity of the models and parameters used to predict loss. How accurate are the seismic sources used for hazard estimation? How accurate are the vulnerability curves used for damage to various structures? If a different recurrence relationship (i.e. equation used to estimate earthquake magnitude versus frequency of earthquake event) is utilized for loss estimation, is the resulting expected loss vastly different? Also, is one recurrence relationship best? How should one define "best"?

What individual factors or parameters contribute most to the uncertainty of predicted loss?

The third question attempts to break down the loss estimation process and determine which model parameters give rise to uncertainty, how the parameters influence each other, and which ones influence the process the most. For instance, can some parameters be considered independent of others? For those that are dependent, how can this dependence be quantified? Further, how does one separate out the marginal impact of one parametric or modeling uncertainty from the rest? How does one rank the various uncertainties in the process?

Is one software model always high or low in its loss estimate? If so, why?

The fourth issue takes aim at the software being used in the project. How do the software models compare? If one of the software models always estimates expected losses on the low side, can the earthquake loss estimation process be dissected and the reason for this bias be ascertained? Is this necessary or even appropriate?

As previously stated, these four questions are all valid scientific inquiries into the uncertainty surrounding earthquake loss estimation. But, the first question seems best left to those debating the usefulness of earthquake loss modeling. The last question is left for future project analyses with the three modeling groups into the city of Charleston, South Carolina, where it is planned to undertake a comparative analysis of an earthquake hazard across the available earthquake models. So, questions two and three are the focus of the uncertainty study reported herein. With the assumption that the methodology used in the software models is justifiably correct, the amount of uncertainty predicted in the models and the parameters that contribute most to this uncertainty is investigated.

PARAMETERS CONSIDERED IN UNCERTAINTY STUDY

As mentioned, the earthquake loss estimation (ELE) process has four main steps: define the hazard, define the inventory exposure characteristics, estimate the inventory damage potential, and calculate the loss. In July of 1998, representatives of two of the modeling groups, RMS and EQECAT, and a representative of the Wharton School met to discuss which parameters and/or models of the earthquake loss estimation process should be considered in an uncertainty analysis for the Managing Catastrophic Risks project. They compiled a list of the main sources of uncertainty and discussed a procedure to incorporate uncertainty into previous analyses. In the discussion, five general areas of uncertainty emerged as possible candidates to be considered. These included:

(1) Frequency of Earthquake Events
(2) Earthquake Site Hazard
(3) Exposure Characteristics of Structures
(4) Vulnerability of Structures
(5) Costs and Benefits of Mitigation

The first two are important in defining the earthquake hazard, the third is used to define the inventory exposure characteristics, the fourth is utilized to estimate inventory damage, and the fifth aids in calculating the loss to both insurers and homeowners. It was generally agreed that the previous analyses completed for the project serve as a baseline for the study. Any or all of the five areas of uncertainty can then be incorporated one by one to see the change in results. In this way, a detailed sensitivity study could be completed.

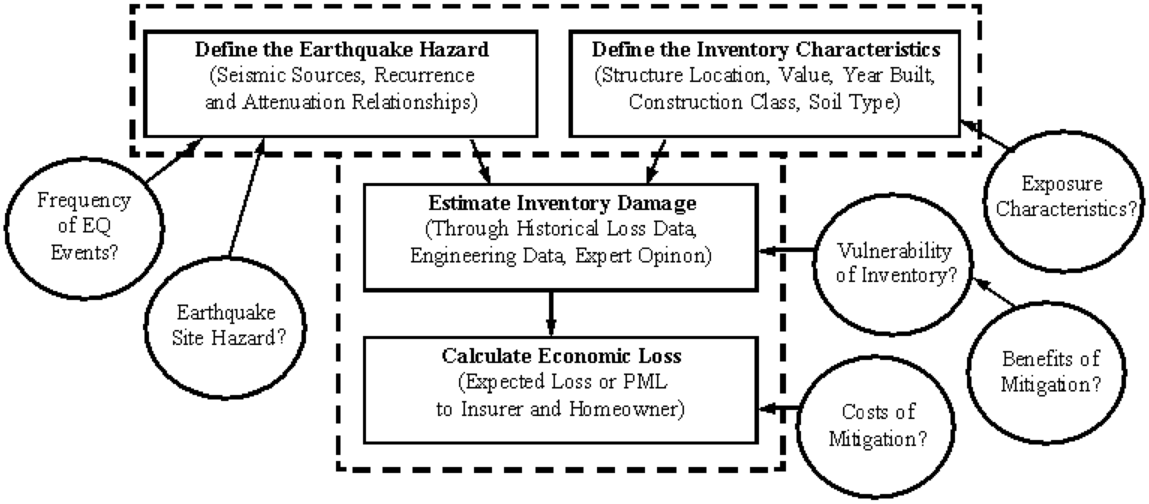

Figure 1: Scope of Uncertainty Analysis

(1) Frequency of Earthquake Events

In previous analyses, the two model cities investigated for earthquake hazard were Oakland, California and Long Beach, California. Since the seismic sources used to describe earthquake hazard in California are primarily fault sources (i.e. line sources rather than area sources), the uncertainty in the frequency of an earthquake event is unique to California. Therefore, the discussion on incorporating the recurrence of damaging earthquake events focused on this area of the country. Uncertainty in the frequency of an earthquake in California can be found in the following:

(i) the earthquake sources assumed, primarily line sources but including area sources;
(ii) the maximum magnitude event assumed for the sources;
(iii) the slip rate and assumed displacement with magnitude of fault sources;
(iv) the recurrence relationship for the sources, such as the Gutenberg-Richter model (Peterson et al., 1996) or the Characteristic Earthquake model (Dieterich et al., 1990).

Preliminary discussion led to the agreement that the recurrence relationship, including consideration of the slip rate, could be studied in an uncertainty analysis.

(2) Earthquake Site Hazard

In studying the uncertainty surrounding earthquake site hazard, the impact of assuming different attenuation relationships for ground shaking could be considered. Attenuation relationships are the equations used to estimate ground motion expected at certain distances from the source to sites with varying soil types. In the original discussion, the three attenuation relationships for shallow crustal earthquakes in the Western United States used in HAZUS were under consideration for an uncertainty study. These included:

(i) Boore, Joyner and Fumal relationship (1993);
(ii) Sadigh, Chang, Abrahamson, Chiou and Power (1993); and
(iii) Campbell and Bozorgnia (1994).

Each of these empirical relationships determines the expected ground shaking at a site due to a certain magnitude event at a certain distance from the fault. Additionally, there was a discussion about possibly incorporating the uncertainty due to soil amplification into the models, varying the factors assumed for different soil types. No resolution was made on this point, though.

(3) Exposure Characteristics of Structures

The exposure characteristics used to classify structures in an insurance portfolio include the structural class, occupancy type, year built, number of stories, structure value, contents value, etc. Typically, the exposure data quality is very uncertain. Assumptions are often made about the structure type, the replacement cost of a structure, and the undervaluation of a structure, to site a few examples. The problem lies in the fact that given the data is incomplete and/or erroneous, how does one obtain more complete and/or accurate data? This is not easily accomplished. While there are two main sources of information on portfolio exposure characteristics, specifically tax assessor’s data and insurance company data, neither is ideal. For example, insurance companies often make an assumption on structure type based on ISO fire construction information.

In an analysis, an assumption can be made on the undervaluation of insured structures, but any distribution assumed would be arbitrary unless better information could be obtained.

Since current data for the project is based on tax assessor's data, better data might be found in insurance company databases. Then, a comparison between losses based on the exposure characteristics assumed from tax assessor's data versus exposure characteristics assumed from insurance company's data could be completed.

(4) Vulnerability of Structures

The vulnerability functions used in the models are primarily based on expert opinion and previous damage statistics. In analyzing the uncertainty surrounding the vulnerability of structures, bounds on the mean estimates of damage could be determined and then used for a sensitivity study on the differences in losses. In an analysis, a lower bound and an upper bound based on the modeler's 90% confidence level in the estimates of damage could be used.

(5) Costs and Benefits of Mitigation

The final area of uncertainty under consideration is the uncertainty associated with the costs and benefits of the mitigation measures being analyzed. In an uncertainty analysis, varying assumptions on the upper and lower bounds of costs and benefits of mitigation techniques can be incorporated into the study, similar to the analysis for the vulnerability of structures.

After considering the feasibility of incorporating these various aspects of uncertainty into the sensitivity analysis, in the end, the results presented here are looking systematically at **two aspects of uncertainty**. These are the **uncertainty in the frequency of earthquake events in defining the hazard and the vulnerability of the residential structures in estimating the inventory damage**. Surveys sent to contractors on their estimates of the costs of mitigation and to structural engineers on their estimates of the benefits of mitigation (Grossi, 1998) are also incorporated into the study. But, these new estimates are to be viewed as an update to the baseline analysis only. Future analyses will look at the range of costs and benefits associated with earthquake retrofit techniques as they affect the homeowner's decision to mitigate.

Now that we have outlined the scope of the uncertainty analysis, the next step is to redefine the model cities, the mitigation technique, and the insurer and homeowner parameters assumed in the investigation.

MODEL CITIES AND MITIGATION

In previous analyses completed for the Managing Catastrophic Risks Project, three different model cities were chosen for the examination of the effect that uncertainty has on the adoption of mitigation measures by residential property owners and the solvency of insurers. The regions included the cities of Oakland and Long Beach, California for earthquake risk and Miami/Dade County, Florida for hurricane risk. This paper presents the results for the analysis completed for managing earthquake risk in the model cities in

California. Risk Management Solutions (RMS) provided information on the residential makeup of Oakland and EQECAT provided the same information for the city of Long Beach.[5] In both regions, the tax assessor's office supplied the firms with the inventory data.

The insurance coverage is defined in terms of a homeowner's policy with varying deductible levels (i.e. 0% and 10%) and no coverage limit level. The software packages RWP and USQUAKE are being utilized for analysis. We consider two prototypical insurance companies, one in each of the model cities, which provide coverage to residential property owners. All residents would like to purchase earthquake insurance, but not everyone can obtain coverage. Specifically, if the insurer is concerned with the possibility of insolvency, then it will limit the amount of coverage it provides and some property owners will be unprotected.

It should be noted at this point that the completed analysis, using a 10% deductible level and no limit to coverage, is inconsistent with the current coverage offered in the state of California. Presently, the California Earthquake Authority (CEA) provides earthquake insurance coverage to residential property owners. The CEA is a privately financed, publicly managed state agency. The terms of the CEA homeowner's policy have not been well received by the majority of the public, being quite limited in nature. Specifically, a CEA policy covers structural damages to a residential dwelling or mobile home, paying up to $5,000 to repair or replace personal possessions and $1,500 for living expenses while the home is being repaired or rebuilt. All claims are subject to a 15% deductible.[6]

Many have noted the problems with this coverage. First, under the CEA, if damage occurs, a homeowner must pay the first 15% of the value of his home. For most homeowners, this is a catastrophic loss. For example, if a person's home were worth $300,000, he would have to pay $45,000 out of his own pocket before the insurance policy would kick in. Second, with a $5,000 cap covering personal belongings and a maximum of $1,500 for temporary living expenses, there is little incentive for a homeowner to pay for the CEA policy. If a homeowner loses all his belongings in an earthquake, he'll be given only $5,000 to replace everything. If a family must relocate while their home undergoes repairs, they would be given only $1,500. This amount does not even cover the move in costs of an apartment rental in the Los Angeles or San Francisco Bay area. Finally, every policy covers only the house itself. The policies do not cover detached garages, pools, patios, fences, driveways, landscaping, or walkways.

Because of all of these gaps in the coverage, many homeowners are opting not to have any insurance coverage at all. This is why the analyses presented in this paper are using lower deductible levels. In the on-going study, we hope to encourage discussion on the state of insurance coverage in California and the role that mitigation might play in reducing catastrophic losses.

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[5] Applied Insurance Research provided residential inventory data for Miami/Dade County.

[6] See Chapter 4 of Kunreuther and Roth (1998) for more detail on the CEA.

Based on the residential characteristic of the two study regions, the structures chosen for mitigation were pre-1940 wood-frame single family residences. From preliminary information gathered from the 1990 U.S. Census data, and subsequent information obtained from the tax assessor's office from each of these cities, it was discovered that a significant percentage of the residential structures in Oakland and Long Beach were built prior to World War II. These homes ordinarily have wood-framed cripple walls, which are the walls between the top of the foundation and the first floor diaphragm. The typical problems with homes built at this time are the lack of connection between the wood frame and the foundation and the lack of shear bracing at the cripple wall level. Therefore, the structural mitigation for pre-1940 homes in California requires bolting the structure to its foundation and bracing its cripple wall.

For both model cities, Oakland and Long Beach, we randomly picked 5,000 residential structures from the entire residential building stock to constitute the maximum books of business which the prototypical smaller-sized insurance company can write. Companies may choose to insure a smaller number of structures to protect themselves against insolvency should a major disaster occur in the region where they are providing earthquake coverage. Detailed information on the makeup of the insurance companies' maximum books of business (BOB) follow below.

<u>Oakland Model City</u>: All structures are wood frame, single-family residences. The distribution of structures for the insurance company by year of construction is given in Table 1. These were picked randomly from over 62,000 wood frame, single-family residences in the city of Oakland and all pre-1940 structures are considered appropriate for structural mitigation. Structures whose age was unknown are assumed to fall into the pre-1940 or post-1940 age with the same likelihood as for the known structures. Thus, 172 of the 259 structures in the company's "Don't Know" year built category of structures were assumed to be constructed prior to 1940. This reflects the ratio of pre-1940 to all known structures in their book of business. Thus, 3263 homes, or 65.3% of the structures, were eligible for mitigation.

Table 1: Composition of Book of Business in Oakland Model City by Year Built

Year Built	Number
Don't Know	259
Pre-1940	3,091
Post-1940	1,650
Total	5,000

<u>Long Beach Model City</u>: The properties of interest in this southern California model city are also wood frame, single-family residences. The distribution of structures in the book of business for the prototypical insurance company, shown in Table 2, is similar, but better defined, than the structure distribution in the Oakland model city. Only the "LR pre-1949 more cripple walls" structures are considered appropriate for structural mitigation. Thus, only 8.2% of the structures in the book of business can be mitigated.

Table 2: Composition of Book of Business in Long Beach Model City by Year Built

Year Built	Number
Low Rise (LR) Average	704
LR pre-1949 few cripple walls	1,448
LR 1949-1959 few cripple walls	643
LR 1960-1978 few cripple walls	973
LR Post-1979 few cripple walls	823
LR Pre-1949 more cripple walls	409
Total	5,000

Costs and Benefits of Mitigation

The earthquake mitigation measure chosen is a structural mitigation technique. It is defined as an action that reduces or eliminates the losses to individuals and their property from ground shaking due to an earthquake hazard. It involves an upfront investment cost in exchange for a stream of benefits accruing over time in the form of reduced expected losses from a catastrophic event.

The proportion of structures in each model city that adopted a mitigation measure was assumed to vary from 0% to 100%. Full mitigation, at 100%, assumes that every *applicable* structure in the model city braces its cripple wall and bolts the structure to the foundation. In previous analyses, the mitigation costs were based on the engineering judgment of individuals working for the modeling companies. For the Oakland model city analysis, costs were calculated as 1.2 percent times the value of the structure. For the Long Beach analysis, costs were estimated as approximately $2.50 times the square footage of the structure.

In order to get a better understanding of the mitigation costs involved, one hundred and sixty contractors proficient in residential earthquake retrofit techniques were surveyed. Of the 33% that responded, they were, on average, between 35 and 45 years of age with 15 to 20 years of experience in structurally retrofitting homes in California. All respondents' values were weighted according to their experience in residential earthquake retrofit and their confidence in their cost estimates. Considering a 2,200 square foot, $130,000 valued residential structure, the results show that the total cost of bracing this structure's cripple wall and bolting it to its foundation can range from $2,000 to $10,000. On average, the cost is approximately $5,000. This corresponds to 3.85% times the value of the structure and $2.27 times the square footage of the structure.

Similarly, in order to estimate the benefits of mitigation (i.e. the reduction in damage to pre-1940 wood frame structures with bracing and bolting), surveys were sent to registered Structural Engineers in the state of California. Of the 24% that responded, they were, on average, between 45 and 55 years of age with 20 to 25 years of experience in post-earthquake damage assessment. All respondents' estimates were weighted according to their experience in post-earthquake damage evaluation and their confidence in their damage estimate. Again, considering a 2,200 square foot, $130,000 valued pre-1940 residential structure, an overall Mean Damage Factor (MDF) for each Modified Mercalli Intensity (MMI) level, both before and after mitigation, was generated.[7] Table 3 lists the lower, average, and upper bound on the "after mitigation" mean damage, comparing them to those obtained using ATC-13 (1985) and FEMA 227/228 (1992).[8]

Table 3: Comparison of damage after mitigation

MMI	ATC-13 and FEMA 227/228		MDF Survey Results					
			Lower		Average		Upper	
	% Reduction	MDF	% Reduction	MDF	% Reduction	MDF	% Reduction	MDF
VI	50%	2.7	34.2%	0.76	52.1%	1.14	73.4%	0.85
VII	50%	6.0	45.3%	1.14	53.4%	2.86	66.1%	3.41
VIII	43%	14.3	50.6%	2.60	59.9%	6.39	67.6%	9.48
IX	35%	19.5	43.7%	5.35	59.7%	11.93	64.0%	19.91
X	28%	29.8	40.2%	11.65	52.8%	21.71	53.0%	38.32
XI	--	--	37.8%	15.68	41.1%	34.68	32.2%	64.49
XII	--	--	37.0%	22.60	32.1%	47.37	17.1%	82.90

For each ZIP code in the two model cities, the cost effectiveness of this structural mitigation technique was determined previously by asking the following question. If every property owner, for which mitigation is applicable, actually mitigated their home, would the aggregate reduction in expected losses across the ZIP code be greater than the total annualized mitigation costs of all these properties in the ZIP code which had been mitigated? If the answer to this question were "yes", then this ZIP code would be a candidate for a building code requiring such mitigation. Based on earlier estimates of mitigation costs (i.e. 1.2% times value and $2.50 times square footage of structure), and using an interest rate of 5% and a time horizon of 20 years, we found that all ZIP codes in both Oakland and Long Beach satisfied this cost effectiveness condition.

Insurance Company Parameters

Table 4 specifies the base case parameters for the insurance companies. In contrast to previous analyses completed for the project, we expand our analysis to include the impact of reinsurance on insurance company performance. We assume that full insurance coverage against damage from the disaster is available, with a pre-specified deductible. The premium charged is proportional to the expected loss of the property covered[9] and then multiplied by a loading factor (in this case 1) to reflect the administrative costs

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[7] Mean Damage Factor (MDF) is the expected ratio of dollar loss to replacement value for the structure.

[8] See Grossi (1998) for more detail on this survey analysis.

[9] Expected loss to the insurer is defined as the probabilities of earthquakes of different magnitudes, each multiplied by the damage sustained minus the deductible and then summed.

associated with marketing and claims settlement. In other words, for this analysis, property owners are charged premiums that are twice their expected loss covered by insurance.

Table 4: Base Case Insurance Company Parameters

	Base Case Value	
Parameter	**Oakland**	**Long Beach**
Assets:	$28,000,000	$7,000,000
Deductible Level:	10%	10%
Target Ruin Probability:	0.01	0.01
Worst Case Probability:	0.01	0.01
Insurance Loading Factor:	1.0	1.0
Fixed Cost per home:	$60	$60
Reinsurance Loading:	2.0	2.0
Maximum Reinsurance (Delta):	$16,000,000	$4,000,000
Required Burden:	0.10	0.10

Insurers are concerned with insolvency and focus on worst case scenarios in determining their portfolio of risks. For this analysis, we define a worst case loss (WCL) as a disaster where the probability of exceeding this dollar amount is 0.01. Insurers are assumed to set a “target ruin probability” based on this definition of a WCL as shown in Table 4. This implies that they would like to limit their BOB so they have at least a 99 percent chance that they could pay insured losses from assets and premiums to avoid insolvency. If they have sufficient assets and/or premiums, then their actual probability of insolvency may be less than the target 1% level.

Homeowner Parameters

Table 5 specifies the homeowner parameters. In analyzing homeowner’s decision to mitigate or not to mitigate and to insure or not to insure, the time horizon was set at thirty years with a discount rate of seven percent. Benefit-cost ratios were computed as the ratio between the expected annual reduction in loss over the expected mitigation costs annualized over the life of the structure. The assumption is that homeowners will mitigate if their benefit-cost ratio is greater than or equal to one. Total expected costs as well as worst case losses for insured and uninsured homeowners are also computed for the average homeowner in each of the model cities.

Table 5: Homeowner Parameters

Parameter	**Value**
Insurance Loading:	1.0
Insurance Fixed Cost per home:	$60
Deductible Level:	10%
Length of Life of Home:	30 years
Discount Rate:	7%
Average Cost of Mitigation per Home:	$5032

INCORPORATING UNCERTAINTY INTO ANALYSIS

For each of the model cities, we begin with a base case analysis, B, which will be the best estimate for all the parameters used in the loss estimation process. The assumption is that the base case analysis utilizes parameter values incorporated into previous analyses completed for the project. The base case is defined as the most likely scenario of events.

The two parameters, frequency (F) and vulnerability (V), are varied in two ways relative to the base case, either high (H) or low (L). These high and low estimates are evaluated to yield a 90% confidence interval on the parameter in question. In this way, these estimates will cover the true estimate of the model parameter(s) with probability 0.90. The high case is a conservative estimate of more damage and the low estimate is an optimistic estimate of less damage. For example, in estimating the high and low frequency bounds, one could use reports published by the United States Geological Survey (USGS) and the California Division of Mines and Geology (CDMB) on fault sources in California (i.e. Peterson et al., 1996), assume a normal or log-normal distribution for frequency, and estimate the 5% and 95% confidence level. Similarly, in estimating high and low vulnerability bounds, one could use the guidelines on earthquake damage in California (i.e. ATC-13, 1985), assume a beta distribution for damage, and estimate the 5% and 95% confidence interval. In order to implement this type of sensitivity analysis using the software, both modeling groups provided the Wharton team with their estimates of the confidence bounds.

Based on the assumption that the two curves for F and V are on the high side and the two curves for F and V are on the low side with the other parameters at their base case, two more 90% confidence intervals using the joint distribution for F and V were generated. The actual parameters for F and V are intuitively less extreme than the earlier ones to yield this joint confidence interval. This combined high value is designated h and the low value is designated l, where we expect L < l < h < H for both F and V.

Specifically, for the combination of parameters F and V, the 5% level of F and V are a pair of values of the relevant parameters, (f_{05}, v_{05}), such that there is only a 5% chance that the true value of both parameters will be less than (f_{05}, v_{05}). Assuming that F and V are independently distributed, the required joint probability is:

$$P\{F < f_{05} \text{ and } V < v_{05}\} = P\{F < f_{05}\} \times P\{V < v_{05}\} = 0.05 \qquad (1)$$

There are, of course, an infinite number of ways to pick f_{05} and v_{05} to make this equality true. So, arbitrarily, we picked f_{05} and v_{05} so that, roughly, the same marginal probability would hold in (1).[10] Obviously, the same logic applies to the 95% level. Again, both modeling groups provided the Wharton team with these estimates.

The first set of runs varied just one parameter, frequency (F) or vulnerability (V), keeping all the remaining parameters at their base case condition, B. For both the 0% and 100%

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[10] This means that f_{05} and v_{05} would be set so that, $P\{F < f_{05}\} = P\{V < v_{05}\} = 0.2236$.

mitigation cases, this corresponds to 10 cases. Additionally, four more runs were completed, varying both parameters at once for the 0% and 100% mitigation cases. Additionally, the following assumptions were made in the analysis.

Insurer Assumptions:

- The premiums for the insurer are based on the base (B) or mean exceedance probability (EP) curve. In this way, the insurer's income from charged premiums are always based on twice the homeowner's mean expected loss, whether the actual loss is higher or lower.
- The amount of coverage for a given level of insolvency is based on the high exceedance probability curve. In this way, the percentage of the book of business that the insurer will cover in order to satisfy his 1% target level of insolvency is based on larger than average losses. This is the most conservative course of action (i.e. the insurer is risk averse).

Homeowner Assumptions:

- The benefit-cost analysis (BCA) for a homeowner is based on the average mitigation-eligible home in a model city, and individuals do not give special attention to the worst case scenario events. In this way, the robustness of the mitigation measure can be viewed in terms of an average homeowner's decision process (i.e. length of time horizon, discount rate).

ANALYSIS RESULTS

The analysis was completed in two parts. First, the impact of uncertainty and mitigation on insurers' book of business, insolvency, and profitability with both reinsurance and no reinsurance in place was estimated. Second, the impact of uncertainty and mitigation on homeowners' decision processes to mitigate and to insure their homes was examined.

Insurer Results

The results are presented in Tables 6 and 7 for the Oakland Model City and the Long Beach Model City, respectively. Note that the results are given in four sections:

A. **Expected Losses**. These are the expected losses to the insurer for a full book of business and no reinsurance in place. Note that expected losses decrease with 100% mitigation and a higher deductible level. Also, mitigation is less effective in the Model City of Long Beach. This is due, in part, to the fact that a small percentage of structures in this city are eligible for mitigation.
B. **Insolvency Probability**. These are the expected probabilities of insolvency if the insurer covered the entire book of business (i.e. 5,000 structures) and there was no reinsurance in place. Again, there is a reduction in insolvency with 100% mitigation and a higher deductible level. Insolvency probabilities are estimated higher in the

Long Beach Model City.

C. **Book of Business**. These are the estimated percentages of the full book of business (BOB) that the insurer would cover, given a 1% target probability of insolvency and reinsurance in place. In both model cities, at low estimates of frequency, vulnerability, and a combination of the two, the insurer will choose to cover the full 5,000 structures.

D. **Profitability**. These are estimates of profits seen by the company if premiums are based on the base case (B) and reinsurance is in place.[11] Note that the profits are negative (i.e. there is a loss) in certain cases of high frequency and vulnerability. This is due to the fact that the premiums generated are twice the expected base case or mean loss.

Table 6: Insurer Results for the Oakland Model City

A. Expected Losses for full Book of Business

Frequency	Vulnerability	0 % Deductible		10% Deductible	
		0% Mitigation	100% Mitigation	0% Mitigation	100% Mitigation
B	**B**	$4,541,355	$3,160,063	$1,697,036	$962,187
H	**B**	$8,222,346	$5,656,809	$3,163,382	$1,798,139
L	**B**	$2,478,834	$1,704,916	$909,371	$514,511
B	**H**	$8,556,138	$5,712,804	$3,784,418	$2,071,727
B	**L**	$1,969,944	$1,726,149	$662,073	$412,646
h	**H**	$7,763,153	$5,345,308	$3,141,958	$1,743,863
l	**L**	$2,170,320	$1,542,638	$777,091	$465,924

B. Insolvency Probabilities for full BOB and no Reinsurance

Frequency	Vulnerability	0 % Deductible		10% Deductible	
		0% Mitigation	100% Mitigation	0% Mitigation	100% Mitigation
B	**B**	2.44%	1.94%	1.82%	1.32%
H	**B**	4.49%	3.62%	3.36%	2.45%
L	**B**	1.32%	1.05%	0.98%	0.70%
B	**H**	5.18%	3.61%	2.04%	1.84%
B	**L**	1.81%	1.05%	1.22%	0.89%
h	**h**	4.69%	2.74%	2.53%	1.84%
l	**l**	1.46%	1.36%	1.03%	0.90%

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[11] Profits = % Book of Business * (Premiums – Loss)

C. Scope of Book of Business

Frequency	Vulnerability	10% Deductible	
		0% Mitigation	100% Mitigation
B	**B**	45.08%	74.35%
H	**B**	39.42%	63.19%
L	**B**	100.00%	100.00%
B	**H**	24.66%	42.13%
B	**L**	100.00%	100.00%
h	**h**	31.77%	53.22%
l	**l**	100.00%	100.00%

D. Profitability Table

Frequency	Vulnerability	0 % Deductible (a)		10% Deductible	
		0% Mitigation	100% Mitigation	0% Mitigation	100% Mitigation
B	**B**	$939,708	$992,431	$900,303	$938,415
H	**B**	$293,254	$352,808	$203,696	$262,825
L	**B**	$5,510,634	$4,915,264	$2,784,703	$1,709,866
B	**H**	$141,227	$336,749	-$21,754	$62,947
B	**L**	$4,554,541	$4,894,031	$3,063,810	$1,811,731
h	**h**	$346,150	$409,064	$171,744	$250,928
l	**l**	$5,009,182	$5,077,541	$2,916,983	$1,758,453

(a) For 0% Deductible and base case (BB), this profit calculation is based on no reinsurance.

Table 7: Results for the Long Beach Model City

A. Expected Loss Table for full Book of Business

Frequency	Vulnerability	0 % Deductible		10% Deductible	
		0% Mitigation	100% Mitigation	0% Mitigation	100% Mitigation
B	B	$1,269,699	$1,245,817	$681,361	$658,850
H	B	$2,632,923	$2,586,488	$1,429,264	$1,387,273
L	B	$482,681	$473,533	$255,344	$246,856
B	H	$3,727,544	$3,643,704	$2,932,775	$2,857,612
B	L	$397,374	$391,076	$110,661	$106,939
h	h	$3,052,097	$2,991,856	$2,108,008	$2,039,413
l	l	$483,071	$474,782	$193,402	$187,224

B. Insolvency Probabilities for full BOB and no Reinsurance

Frequency	Vulnerability	0 % Deductible		10% Deductible	
		0% Mitigation	100% Mitigation	0% Mitigation	100% Mitigation
B	B	3.24%	3.22%	2.17%	2.11%
H	B	6.38%	6.33%	3.84%	3.80%
L	B	1.50%	1.48%	0.95%	0.92%
B	H	6.51%	6.43%	4.99%	4.96%
B	L	1.51%	1.49%	0.52%	0.50%
h	h	6.59%	6.51%	4.73%	4.62%
l	l	1.63%	1.62%	0.89%	0.86%

C. Scope of Book of Business

Frequency	Vulnerability	10% Deductible	
		0% Mitigation	100% Mitigation
B	B	97.52%	97.52%
H	B	26.79%	27.64%
L	B	100.00%	100.00%
B	H	13.30%	13.58%
B	L	100.00%	100.00%
h	h	19.28%	19.52%
l	l	100.00%	100.00%

D. Profitability Table

Frequency	**Vulnerability**	**0 % Deductible**		**10% Deductible**	
		0% Mitigation	**100% Mitigation**	**0% Mitigation**	**100% Mitigation**
B	**B**	$281,585	$280,922	$957,053	$935,099
H	**B**	$30,795	$31,162	$60,242	$61,340
L	**B**	$2,063,779	$2,099,229	$1,407,378	$1,370,843
B	**H**	-$85,362	-$83,448	-$160,187	-$159,661
B	**L**	$2,404,690	$2,389,594	$1,552,060	$1,510,761
H	**h**	-$26,048	-$24,991	-$81,620	-$78,291
L	**l**	$1,849,607	$1,838,029	$1,469,320	$1,430,475

Homeowner Results

The results are presented in Tables 8 and 9 for the Oakland Model City and the Long Beach Model City, respectively. Note that the results are given in four sections:

A. **Insured Homeowner's Total Expected Cost (HTEC)**. These are the expected losses to the insured homeowner for various levels of uncertainty and mitigation. For the insured, this is calculated as [Expected Loss + Premiums + Cost of Mitigation (if applicable)]. Note that expected costs clearly decrease with mitigation and insurance for the Oakland Model City.

B. **Uninsured Homeowner's Total Expected Cost (HTEC)**. These are the expected losses to the uninsured homeowner. This is the Expected Loss + Cost of Mitigation (if applicable). From 0% to 100% mitigation, note that the uninsured homeowner's total expected cost decreases for the Oakland Model City but increases slightly for the Long Beach Model City.

C. **Homeowner's Total Worst Case Loss (HTWCL) versus Homeowner's Total Expected Cost (HTEC)**. This is a comparison between the worst case and expected losses that the insured and uninsured homeowners would face for various levels of mitigation. In both model cities, at high estimates of frequency and vulnerability, the homeowner will have a significant worst case loss.

D. **Impact of Uncertainty on Homeowner's Decision to Mitigate.** This is a benefit-cost analysis (BCA) using a 7% discount rate and a 30-year time horizon for the average homeowner. In the Oakland Model City, the number of homes mitigated is 3,263 for a total cost of $1,323,182. In the Long Beach Model City, there are 409 homes mitigated, costing $165,854. In the low estimates of frequency and vulnerability, a much longer time horizon will be needed for a homeowner to be willing to mitigate.

Table 8: Homeowner Results for the Oakland Model City

A. Insured Homeowner's Total Expected Cost

Frequency	Vulnerability	0% Mitigation		100% Mitigation	
		0% Deductible	10% Deductible	0% Deductible	10% Deductible
B	B	$1,877	$1,308	$1,589	$1,149
H	B	$1,877	$1,751	$1,589	$1,481
L	B	$1,877	$1,053	$1,589	$948
B	H	$1,877	$1,693	$1,589	$1,438
B	L	$1,877	$978	$1,589	$972
h	h	$1,877	$1,663	$1,589	$1,430
l	l	$1,877	$1,017	$1,589	$925

B. Uninsured Homeowner's Total Expected Cost

Frequency	Vulnerability	0% Mitigation	100% Mitigation
B	B	$908	$897
H	B	$1,644	$1,396
L	B	$496	$606
B	H	$1,711	$1,407
B	L	$372	$610
h	h	$1,553	$1,334
l	l	$434	$573

C. Comparing Homeowner's Total Worst Case Loss (HTWCL) to Homeowner's Total Expected Cost (HTEC)

HTWCL at Standard 10% Deductible

Frequency	Vulnerability	Insured		Uninsured	
		Mitigated	Unmitigated	Mitigated	Unmitigated
l	l	$6,534	$8,162	$9,847	$14,171
B	B	$9,467	$11,509	$21,113	$30,728
h	h	$10,790	$13,125	$27,436	$40,703

HTEC at Standard 10% Deductible

Frequency	Vulnerability	Insured		Uninsured	
		Mitigated	Unmitigated	Mitigated	Unmitigated
l	l	$925	$1,017	$573	$434
B	B	$1,149	$1,308	$897	$908
h	h	$1,430	$1,663	$1,334	$1,553

D. Impact of Uncertainty on Homeowner's Decision to Mitigate

Annual Benefits

	$192	**$423**	**$741**	**$547**	**$649**	**$763**
	Benefit-Cost Ratio (Uninsured)			**Benefit-Cost Ratio (Insured)**		
Time	**ll**	**BB**	**hh**	**ll**	**BB**	**hh**
1	0.036	0.079	0.138	0.102	0.120	0.142
5	0.157	0.345	0.604	0.446	0.528	0.622
10	0.268	0.591	1.034	0.764	0.905	1.065
15	0.348	0.766	1.341	0.991	1.174	1.381
20	0.405	0.891	1.560	1.152	1.365	1.606
25	0.445	0.980	1.716	1.268	1.502	1.767
30	0.474	1.044	1.827	1.350	1.599	1.881

Table 9: Homeowner Results for the Long Beach Model City

A. Insured Homeowner's Total Expected Cost

Frequency	Vulnerability	0% Mitigation		100% Mitigation	
		0% Deductible	10% Deductible	0% Deductible	10% Deductible
B	B	$568	$450	$591	$474
H	B	$568	$573	$591	$597
L	B	$568	$378	$591	$402
B	H	$568	$491	$591	$514
B	L	$568	$390	$591	$414
h	h	$568	$521	$591	$547
l	l	$568	$390	$591	$414

B. Uninsured Homeowner's Total Expected Cost

Frequency	Vulnerability	0% Mitigation	100% Mitigation
B	B	$254	$282
H	B	$527	$550
L	B	$97	$128
B	H	$746	$762
B	L	$79	$111
h	h	$610	$632
l	l	$97	$128

C. Comparing Homeowner's Total Worst Case Loss (HTWCL) to Homeowner's Total Expected Cost (HTEC)

HTWCL at Standard 10% Deductible

Frequency	Vulnerability	Insured		Uninsured	
		Mitigated	Unmitigated	Mitigated	Unmitigated
l	l	$2,346	$2,327	$3,334	$3,339
B	B	$4,332	$4,262	$8,295	$8,372
h	h	$6,050	$5,962	$17,319	$17,597

HTEC at Standard 10% Deductible

Frequency	Vulnerability	Insured		Uninsured	
		Mitigated	Unmitigated	Mitigated	Unmitigated
l	l	$414	$390	$128	$97
B	B	$474	$450	$282	$254
h	h	$547	$521	$632	$610

D. Impact of Uncertainty on Homeowner's Decision to Mitigate

Annual Benefits

	$20	$58	$147	$115	$113	$90
	Benefit-Cost Ratio (Uninsured)			**Benefit-Cost Ratio (Insured)**		
Time	**ll**	**BB**	**hh**	**ll**	**BB**	**hh**
1	0.004	0.011	0.027	0.021	0.021	0.017
5	0.017	0.048	0.120	0.094	0.092	0.073
10	0.028	0.082	0.206	0.161	0.158	0.125
15	0.037	0.106	0.267	0.209	0.205	0.162
20	0.043	0.123	0.310	0.243	0.239	0.189
25	0.047	0.135	0.341	0.267	0.263	0.208
30	0.050	0.144	0.363	0.284	0.280	0.221

CONCLUSIONS

For the insurers, in both model cities, there is a significant impact of uncertainty on insolvency probability, book of business and profitability. There are potentially large benefits to reducing sources of uncertainty through improved risk assessment. Further, mitigation can be of significant benefit to insurers. In particular, if uncertainty is high, there is a lower insolvency probability and a higher book of business, profitability may be increased due to lower capacity restrictions, and reinsurers may benefit through reduction in catastrophic losses.

For the homeowners, uncertainty can strongly affect the expected losses and the worst case losses to homeowners. More specifically, varying the frequency of earthquake events and vulnerability of structures has a large impact on the benefits of mitigation. The outcomes of homeowners' decision processes (decision to insure, decision to mitigate) can be strongly affected by uncertainty. Whether a homeowner will perceive mitigation to be worthwhile depends on how a set of interacting factors are used in the homeowner's decision process. Specifically, these factors include the assumed discount rate, the expected and worst case losses (which may be affected by uncertainty), the time horizon for computing benefits, and insurance pricing and coverage limits.

SUGGESTIONS FOR FUTURE RESEARCH

The following areas will be examined in our future work with the modeling groups and other private and public sector groups concerned with more effective management of catastrophic risk.

Commercial Structures. Future analyses will include the impact of uncertainty and mitigation on commercial structures. This will be a challenge, though. Although there is much qualitative information, there has been limited quantitative research done on the effectiveness of earthquake mitigation on commercial structures. Open questions include whether or not a structural or a nonstructural mitigation technique will be employed and which types of losses (i.e. building damage, contents or inventory damage, business interruption, relocation expenses) will be analyzed.

Charleston, South Carolina Analysis. Future analyses will also include a study on the uncertainty across software models in estimating catastrophic losses in the city of Charleston, SC. Open questions include which residential and/or commercial mitigation techniques will be analyzed and whether earthquake, hurricane, or both natural hazards will be modeled. Also, the portfolio of structures to be used in the analysis must be obtained.

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