

# *Playing against nature: formulating cost-effective natural hazard policy given uncertainty*

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*Tohoku, Japan 3/2011*



*New Orleans 8/2005*

<http://www.earth.northwestern.edu/people/seth/research/eqrec.html>

*Developing strategies to mitigate risks posed by natural hazards depends on estimating the hazard and the balance between the costs and benefits of mitigation.*

*The major uncertainty is the probabilities of the rare, extreme, and most damaging “black swan” events.*

*Often these probabilities are difficult to estimate because the physics is not adequately understood and the short geologic record provides only a few observations.*

*Mitigation policies typically made without rational analysis of costs & benefits*

*How to do better is complex challenge at the intersection of geoscience, mathematics, and economics.*

# *Tohoku, Japan March 11, 2011 M 9.1*



NY Times

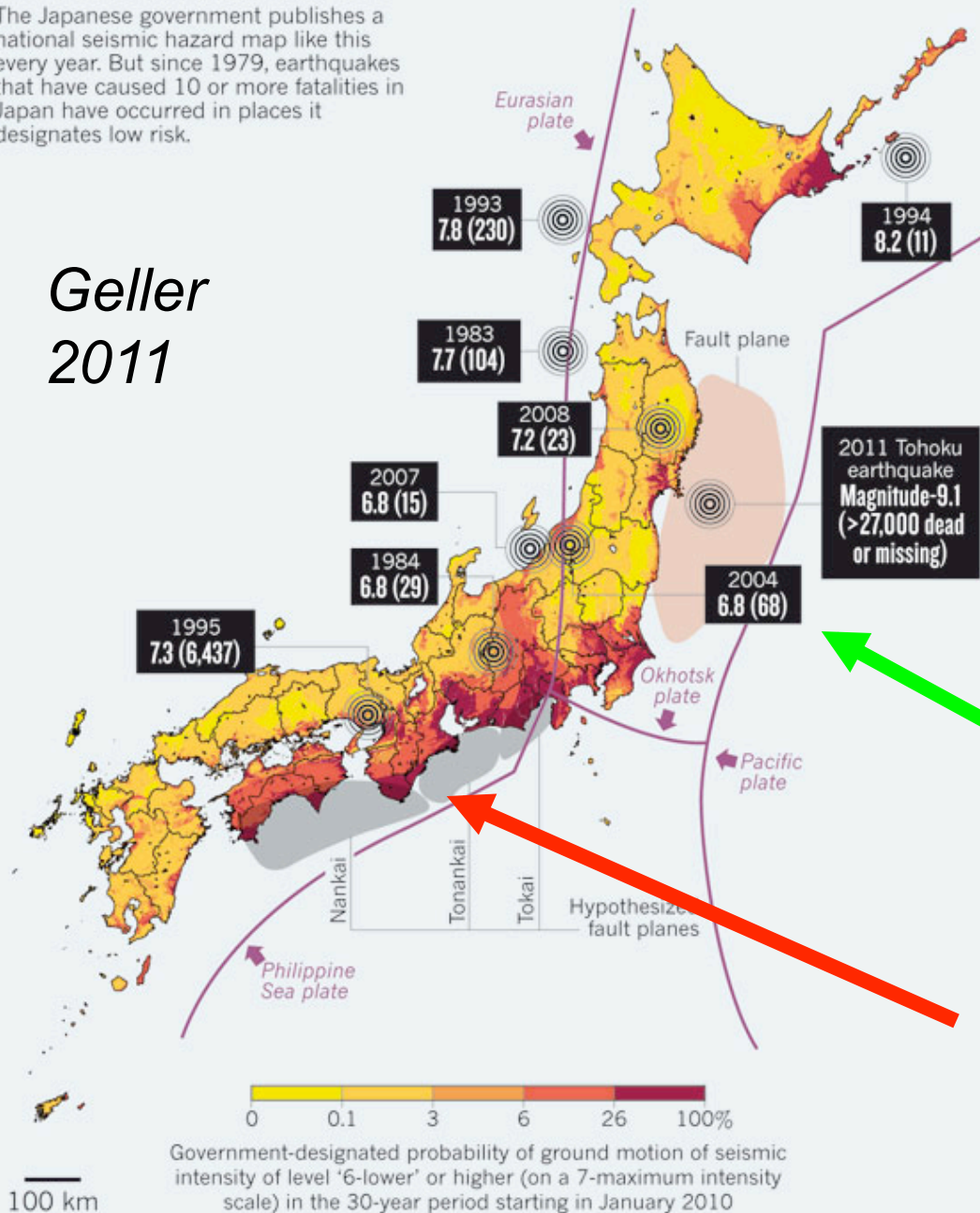
CNN

*Rare, extreme event illustrates challenge  
Hazard was underestimated  
Mitigation largely ineffective  
What to do not obvious even in hindsight*

## REALITY CHECK

The Japanese government publishes a national seismic hazard map like this every year. But since 1979, earthquakes that have caused 10 or more fatalities in Japan have occurred in places it designates low risk.

Geller  
2011

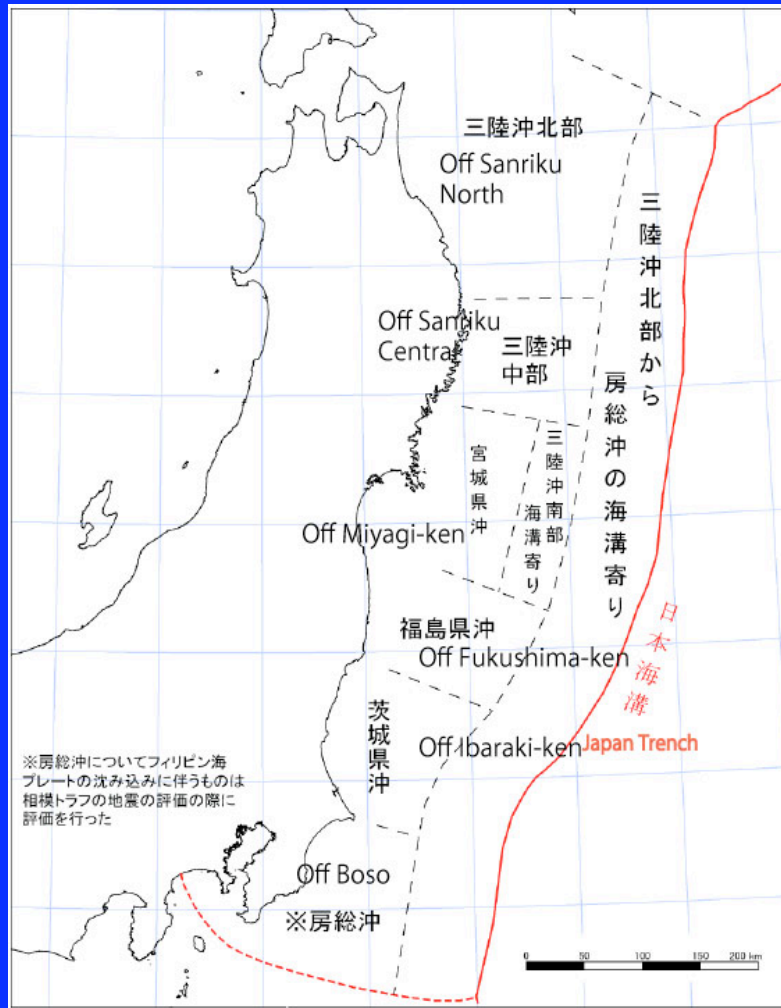


*Japan spent lots of effort on national hazard map, but*

*2011 M 9.1  
Tohoku, 1995 Kobe  
M 7.3 & others in  
areas mapped as  
low hazard*

*In contrast: map  
assumed high  
hazard in Tokai  
"gap"*

# Detailed model of segments with 30 year probabilities



Off Sanriku-oki North  
~M8 0.2 to 10%

Off Sanriku-oki Central  
~M7.7 80 to 90%

Off Miyagi  
~M7.5 > 90%

Off Fukushima  
~M7.4 7%

Off Ibaraki  
~M6.7 – M7.2 90%

Sanriku to Boso M8.2 (plate boundary)  
20%

Sanriku to Boso M8.2 (Intraplate)  
4-7%

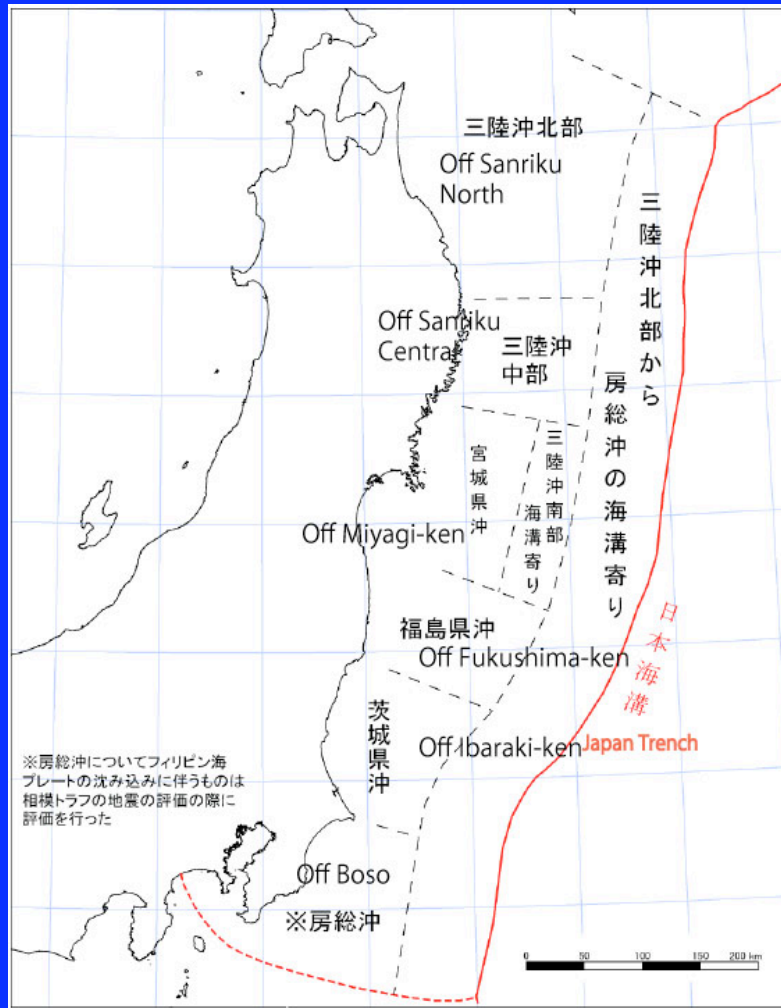
**Assumption:  
No M > 8.2**

Expected Earthquake Sources  
50 to 150 km segments  
M7.5 to 8.2

(Headquarters for Earthquake Research Promotion)

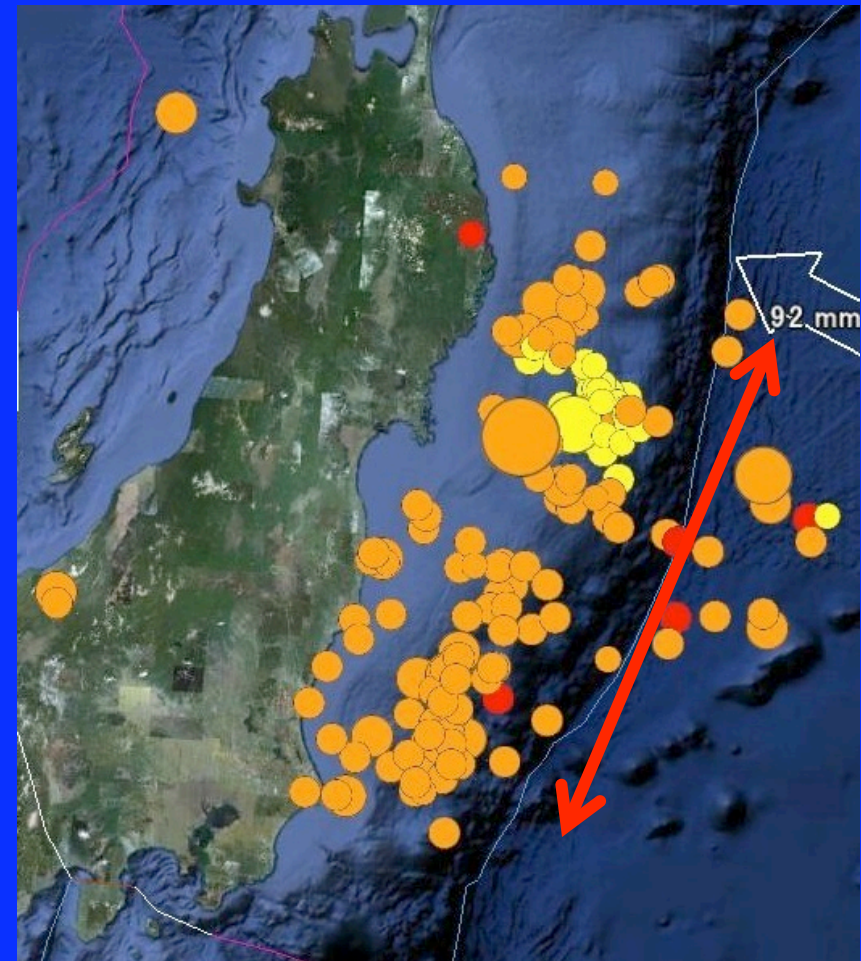
J. Mori

# Giant earthquake broke five segments



Expected Earthquake Sources  
50 to 150 km segments  
M7.5 to 8.2

(Headquarters for Earthquake Research Promotion)

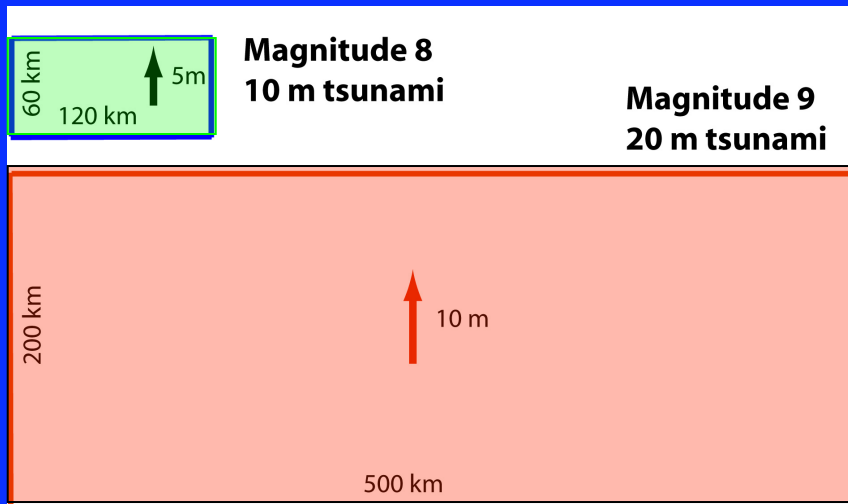


2011 Tohoku Earthquake  
450 km long fault, M 9.1

(Aftershock map from USGS)

J. Mori

# Planning assumed maximum magnitude 8 Seawalls 5-10 m high



Stein & Okal, 2011

*Tsunami runup  
approximately twice fault  
slip (Plafker, Okal &  
Synolakis 2004)*

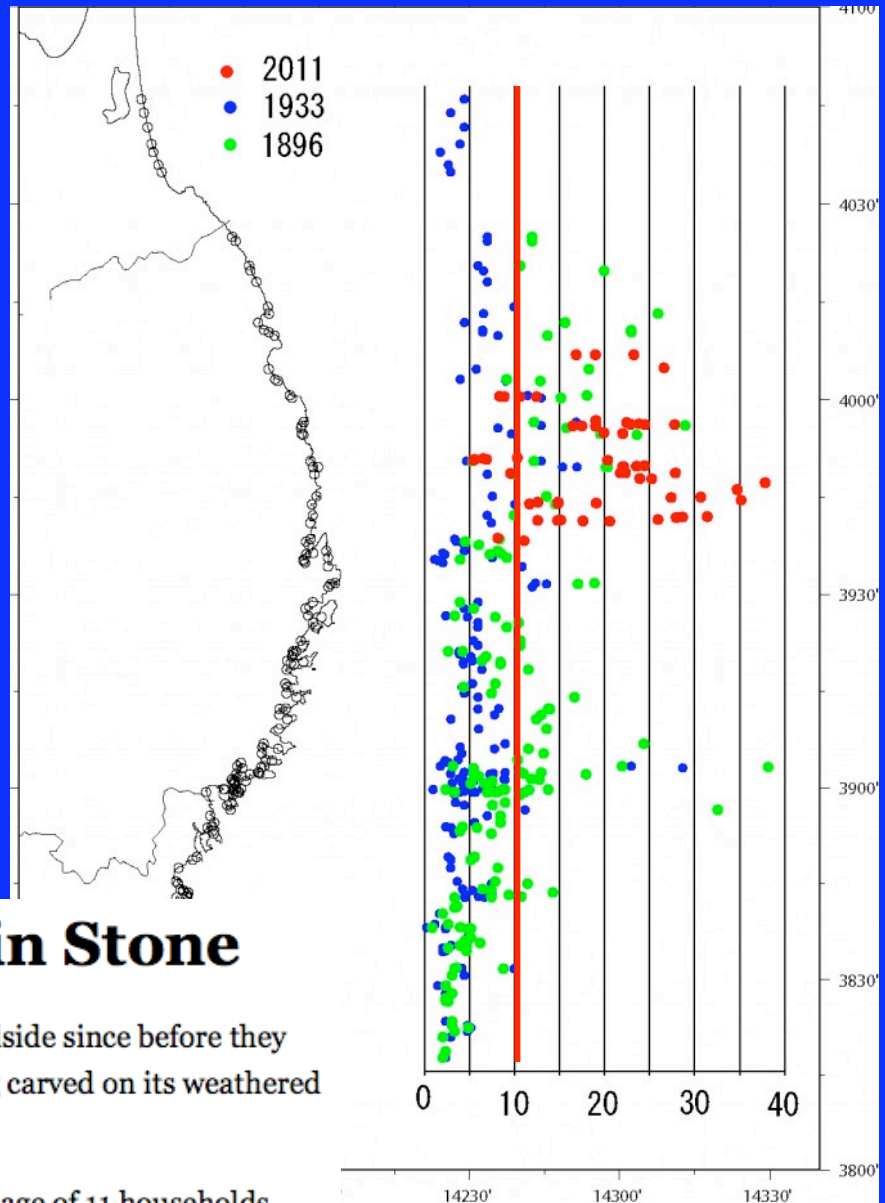
*M9 generated much  
larger tsunami*



NYT

CNN

# Didn't consider historical record of large tsunamis



## Tsunami Warnings, Written in Stone

By MARTIN FACKLER

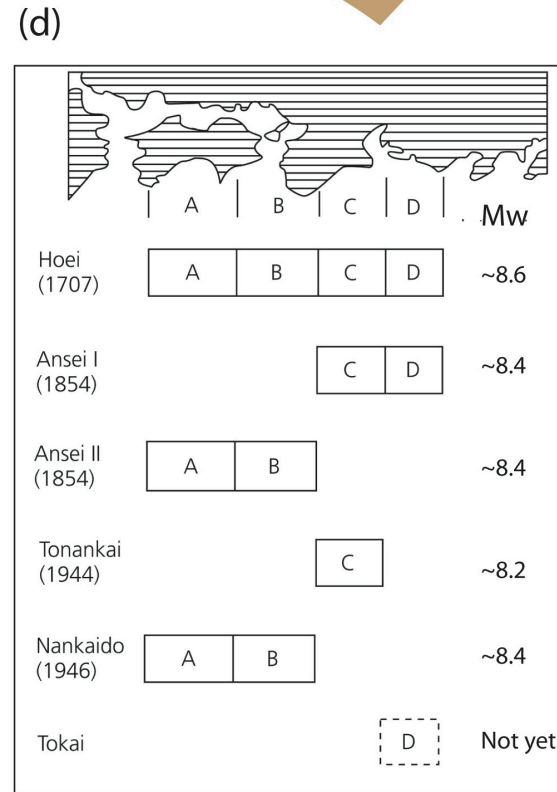
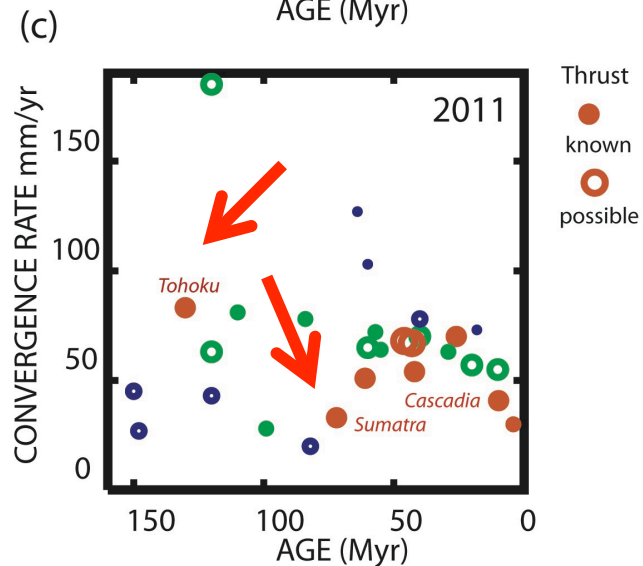
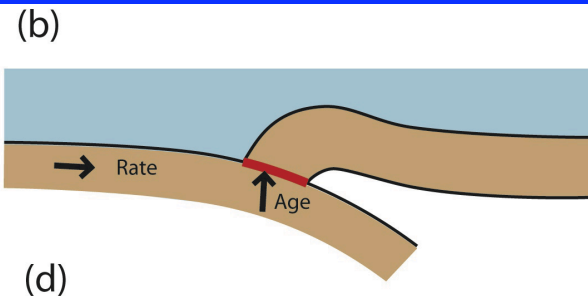
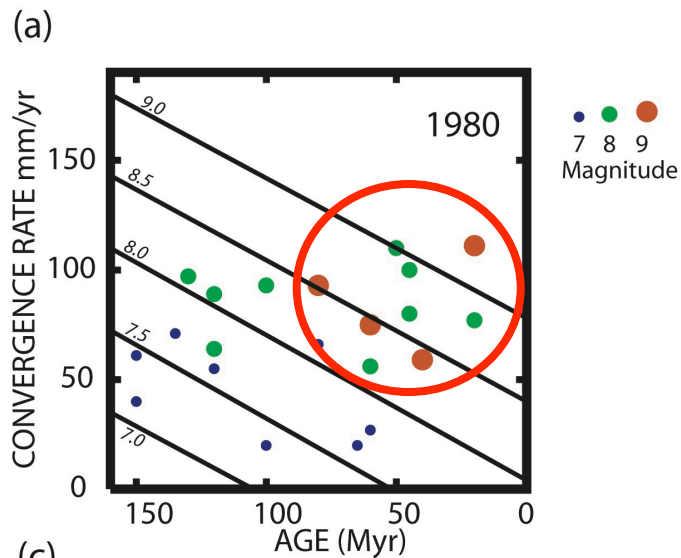
ANEYOSHI, Japan — The stone tablet has stood on this forested hillside since before they were born, but the villagers have faithfully obeyed the stark warning carved on its weathered face: “Do not build your homes below this point!”

Residents say this injunction from their ancestors kept their tiny village of 11 households safely out of reach of the deadly tsunami last month that wiped out hundreds of miles of Japanese coast and rose to record heights near here. The waves stopped just 300 feet below the stone.

NYT 4/20/11



Lack of M9s in record seemed consistent with model that M9s only occur where lithosphere younger than 80 Myr subducts faster than 50 mm/yr (Ruff and Kanamori, 1980)



Stein & Okal, 2011

*Disproved by Sumatra 2004 M9.3 and dataset reanalysis (Stein & Okal, 2007)*

*Short record at most SZs didn't include rarer, larger multisegment ruptures*

## In Japan, Seawall Offered a False Sense of Security



Ko Sasaki for The New York Times

A ship that was swept ashore in the tsunami of March 11, damaging part of a breakwater, seen Wednesday in Kamaishi, Japan, 50 miles south of Taro. [More Photos »](#)

By NORIMITSU ONISHI  
Published: March 31, 2011

TARO, Japan — So unshakable was this town's faith in its sea wall and its ability to save residents from any tsunami that some rushed toward it after a 9.0-magnitude earthquake struck off the coast of northeast Japan on the afternoon of March 11.

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[✉](#) E-MAIL

*NY Times 3/31/2011*

*Expensive seawalls - longer than Great Wall of China - proved ineffective*

*180/300 km swept away or destroyed*

*In some cases discouraged evacuation*

*Similar problems occur worldwide*

## **Seismic Crystal Ball Proving Mostly Cloudy Around the World**

Failing at quake prediction, seismologists tried making fuzzier forecasts, but Japan's megaquake is only the latest reminder of the method's shortcomings

20 MAY 2011 VOL 332 SCIENCE [www.sciencemag.org](http://www.sciencemag.org)

*Many destructive earthquakes - including 2010 Haiti and 2008 Wenchuan (China) events - occurred in areas predicted to be relatively safe.*

*Shaking in large earthquakes is often significantly higher than predicted (Kossobokov and Nekrasova, 2012) and so causes many more fatalities than expected (Wyss et al., 2012).*

# “What can we, and should we do, in face of uncertainty?”

*Some say we should rather spend our resources on the present imminent problems instead of wasting them on things whose results are uncertain.*

*Others say that we should prepare for future unknown disasters precisely because they are uncertain”.*

Hajime Hori, Emeritus professor of economics,  
Tohoku University

## Japan Revives a Sea Barrier That Failed to Hold




Ko Sasaki for The New York Times

**Japan's Failed Breakwaters:** Nori Onishi reports on the failure of breakwater systems in protecting against large waves along Japan's coastline.

By NORIMITSU ONISHI

Published: November 2, 2011

KAMAISHI, Japan — After three decades and nearly \$1.6 billion, work on Kamaishi's great tsunami breakwater was completed three years ago. A mile long, 207 feet deep and jutting nearly 20 feet above the water, the quake-resistant structure made it into the Guinness World Records last year and rekindled fading hopes of revival in this

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 COMMENTS (27)

 EMAIL

*Too expensive  
to rebuild for  
2011 sized  
tsunami*

*Political  
decision to  
rebuild  
seawalls ~ as  
they were*

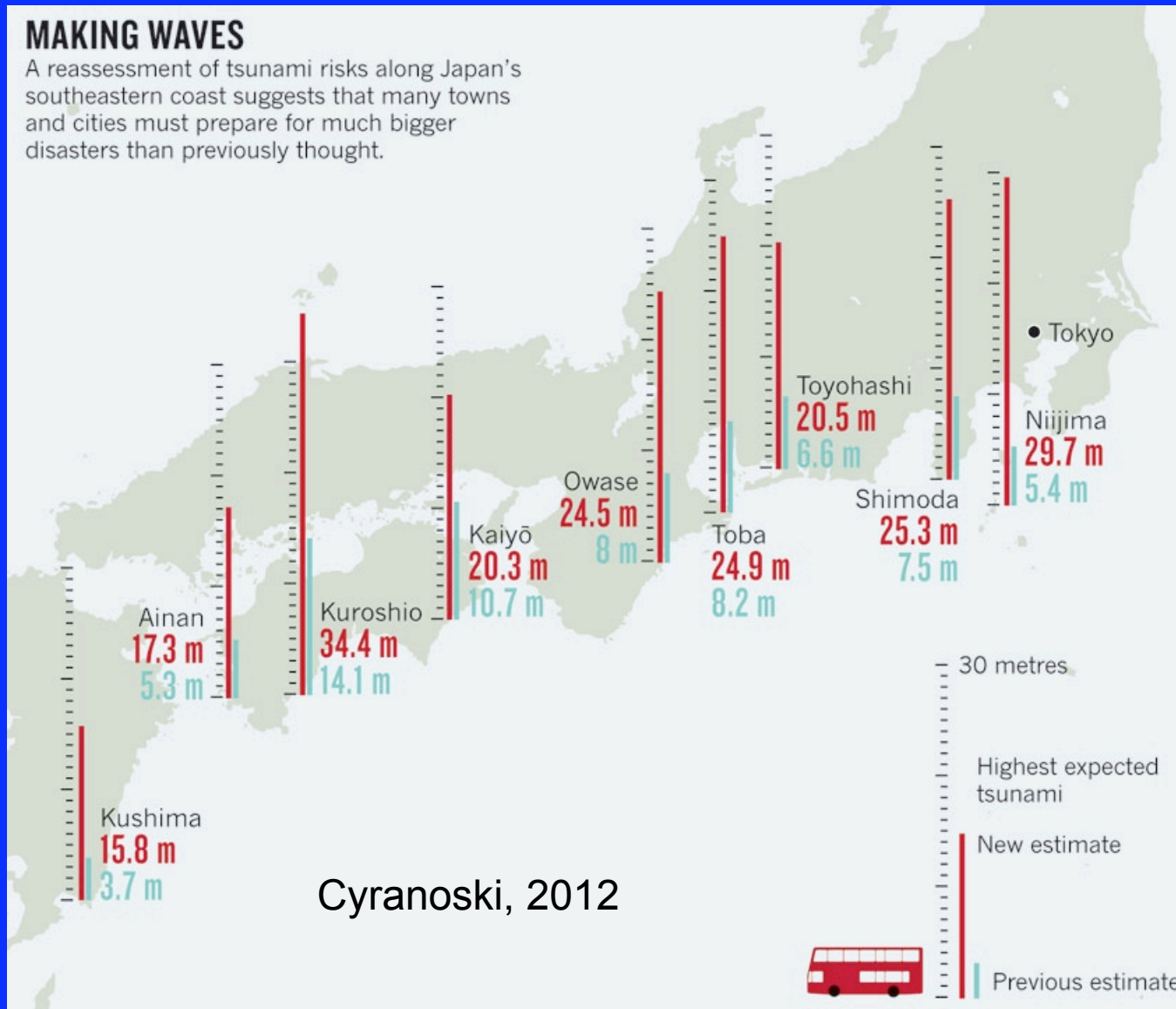
*“In 30 years  
there might be  
nothing left  
there but fancy  
breakwaters  
and empty  
houses.”*

*NY Times 11/2/2011*

# Could a similar megatsunami - much bigger than planned for at present - strike further south?

## MAKING WAVES

A reassessment of tsunami risks along Japan's southeastern coast suggests that many towns and cities must prepare for much bigger disasters than previously thought.



*No evidence of such events in past here*

*No tectonic reason why not*

*How likely?*

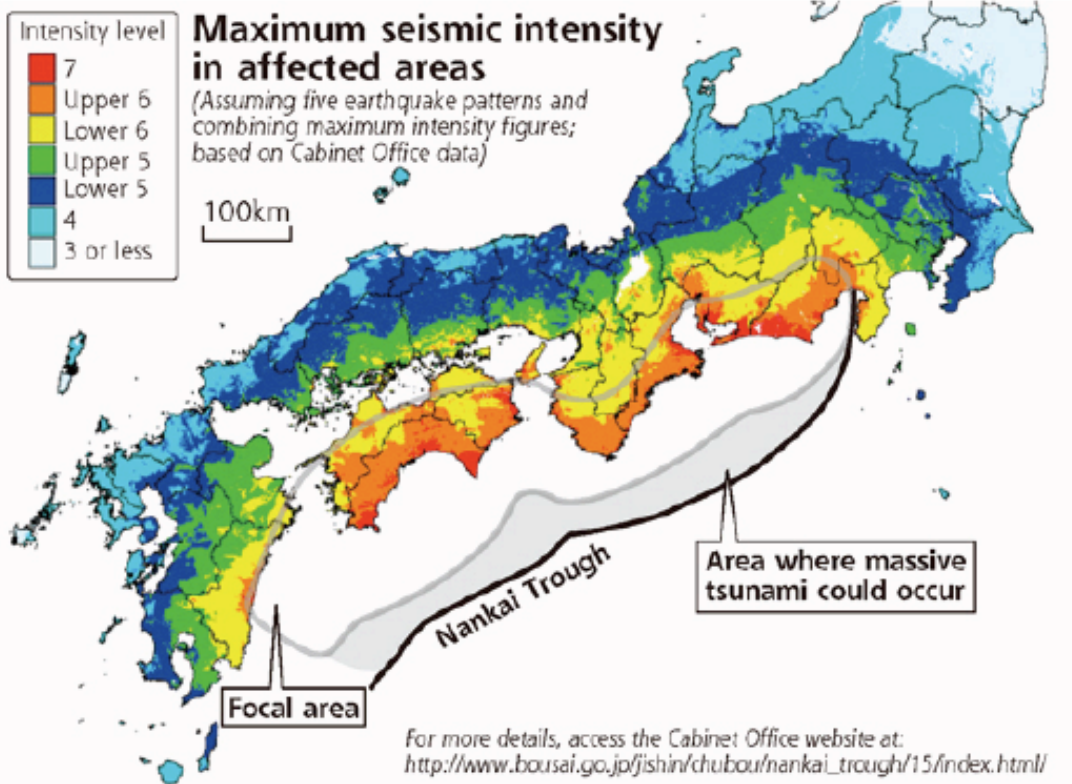
*What to do?*

# BTW, Get Ready for a 34 Meter Tsunami



3 comments, 1 called-out

+ Comment now



*"the question is whether the bureaucratic instinct to avoid any risk of future criticism by presenting the worst case scenario is really helpful..."*

*What can (or should be) done? Thirty meter seawalls do not seem to be the answer."*

*Forbes 4/2/2012*

## How to formulate rational policy?

Because defending against natural hazards is similar to defending against human enemies, we consider an approach like that introduced by R. McNamara, Secretary of Defense, in 1960's to formulate budget to address possible threats.

Multidisciplinary systems analysis approach "is a reasoned approach to highly complicated problems of choice in a context characterized by much uncertainty; it provides a way to deal with different values and judgments ...It is not physics, engineering, mathematics, economics, political science, statistics...yet it involves elements of all these disciplines. It is much more a frame of mind" (Enthoven and Smith, 1971).



# Systems Analysis

**What's the problem?**

**What do we know & not know?**

**What are we trying to accomplish?**

**What strategies are available?**

**What are the costs & benefits of each?**

**What is an optimum strategy given  
uncertainty?**

In hazard mitigation, as in defense,  
our goal is to decide *how much is enough*.

*Example: how large must U.S. nuclear force be to deter U.S.S.R. nuclear attack?*

*Criterion: inflict unacceptable damage even after attack*

<b>1-megaton equivalent, deliverable warheads</b>	<b>% Industrial capacity destroyed</b>
100	59
200	72
400	76
800	77
1200	77
1600	77

*Enthoven and Smith, 1971*

*Costs of exceeding 400 Mt offer little benefit*

*Two simple models illustrate this approach*

1) Use stochastic model to select an optimum mitigation strategy against future tsunamis

2) Use deterministic model that does not require estimating essentially unknown probabilities, to consider whether new nuclear power plants should be built.

*These models can be generalized to mitigation policy situations involving other natural hazards.*

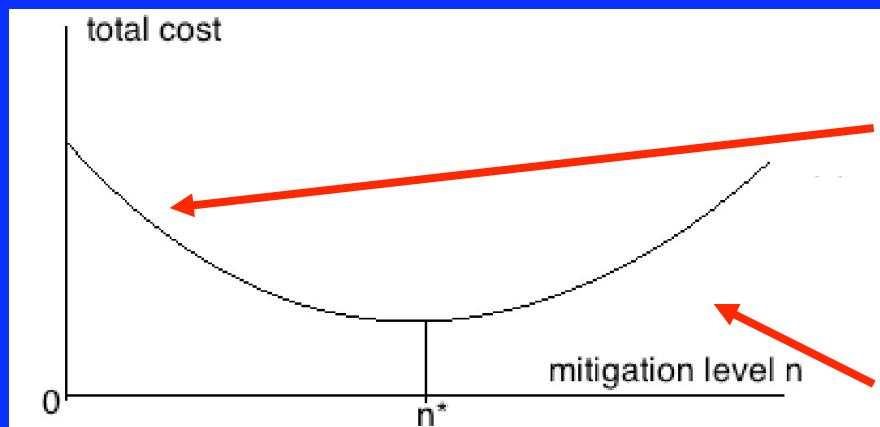
# Stochastic model

*Optimal level of mitigation minimizes*

*total cost = sum of mitigation cost + expected loss*

*Expected loss =  $\sum$  (loss in  $i_{th}$  expected event  
x assumed probability of that event)*

For tsunami, mitigation level is seawall height or other index  
Loss depends on tsunami height & mitigation level

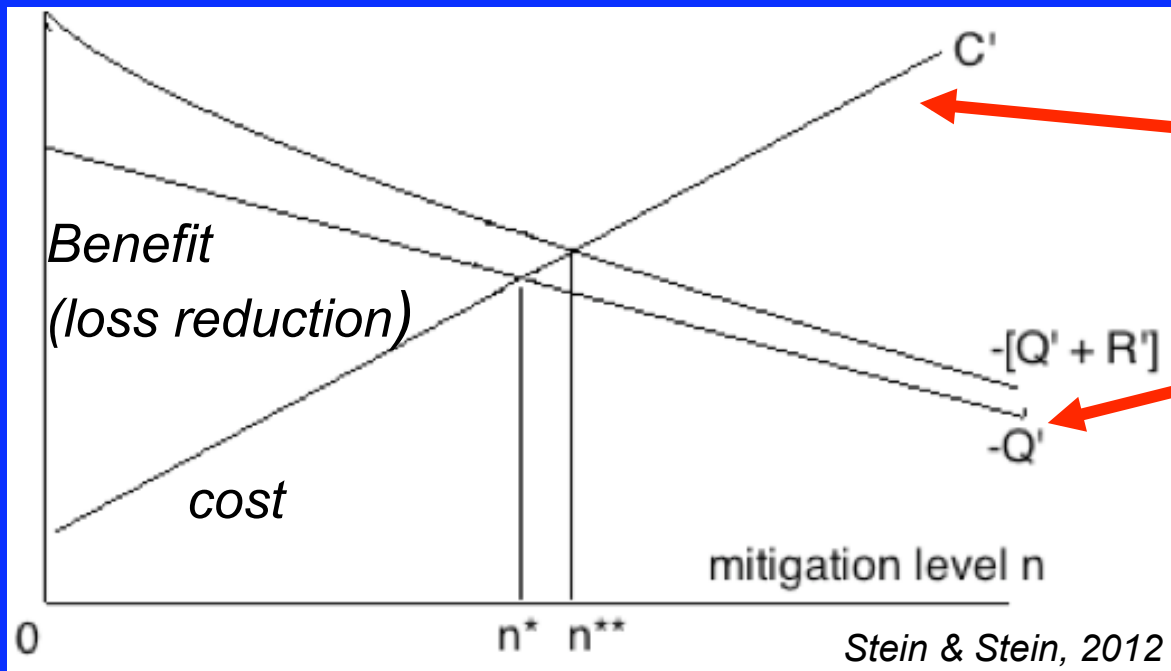


Less mitigation decreases construction costs but increases expected loss and thus total cost

More mitigation gives less expected loss but higher total cost

# Including risk aversion & uncertainty

Consider marginal costs  $C'(n)$  & benefits  $Q'(n)$  (derivatives)



More mitigation costs more

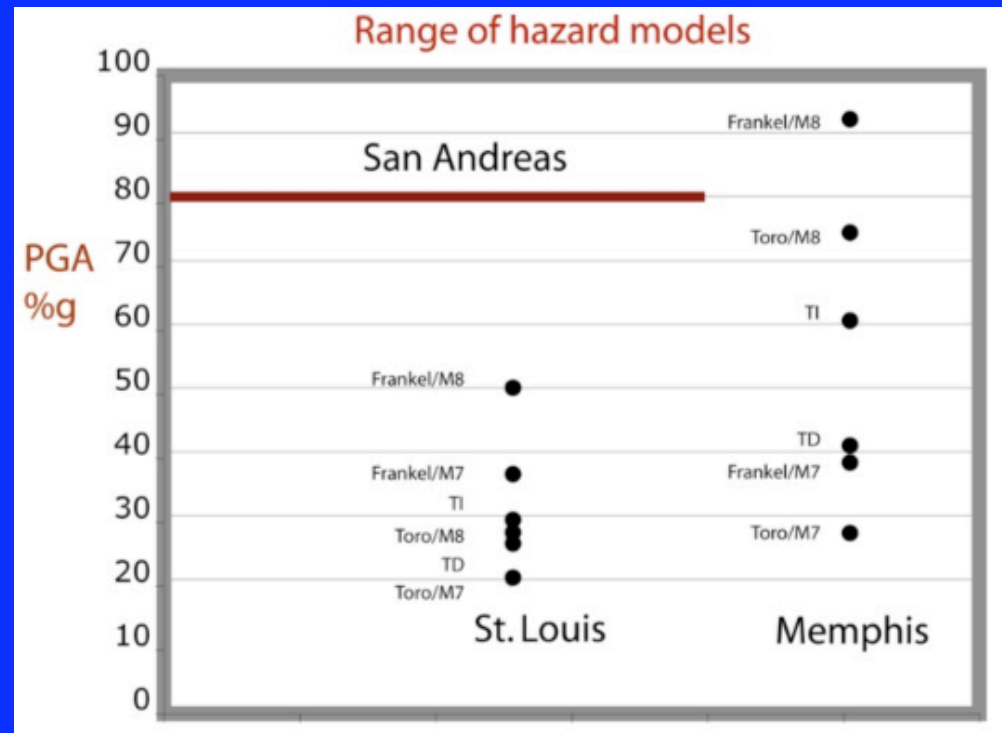
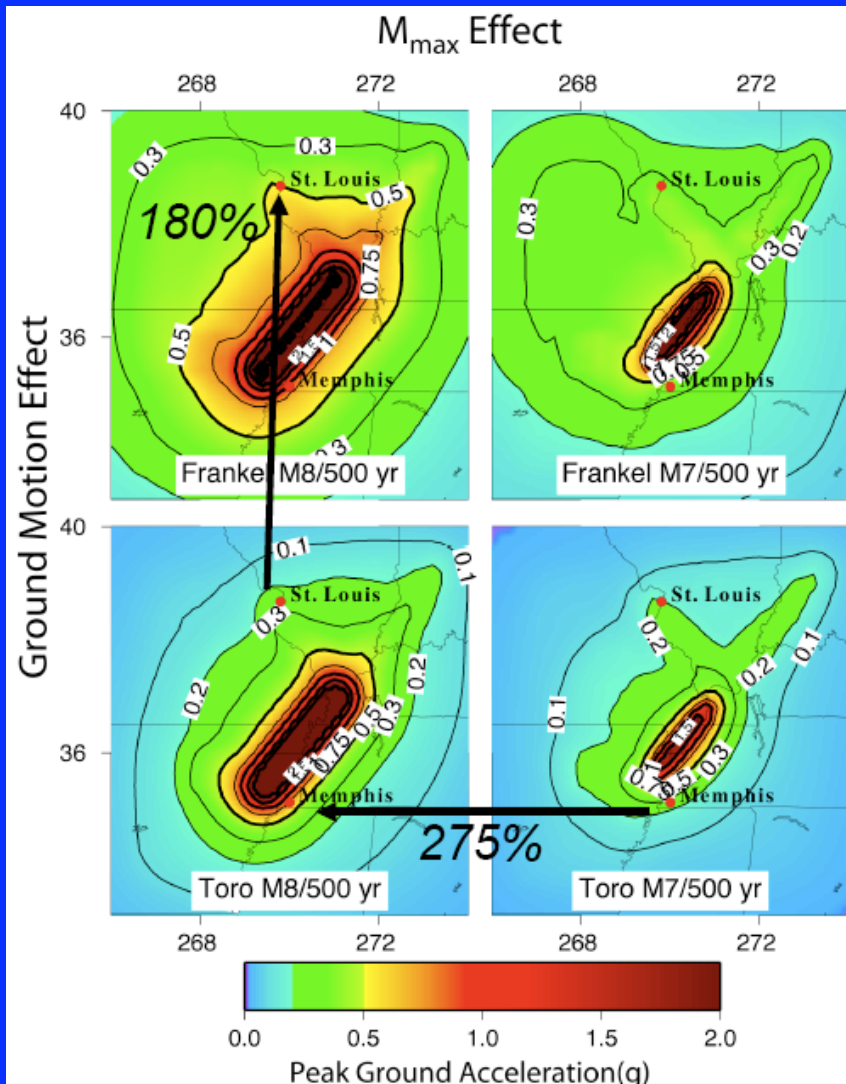
But reduces loss

Optimum is where marginal curves are equal,  $n^*$

Uncertainty in hazard model & mitigation efficiency causes uncertainty in expected loss. We are risk averse, so add risk term  $R(n)$  proportional to uncertainty in loss, yielding higher mitigation level  $n^{**}$

**Crucial to understand hazard model uncertainty**

# Similar approach for earthquake – predict shaking in future earthquakes for different assumed magnitudes & ground motion models



Stein et al, 2012

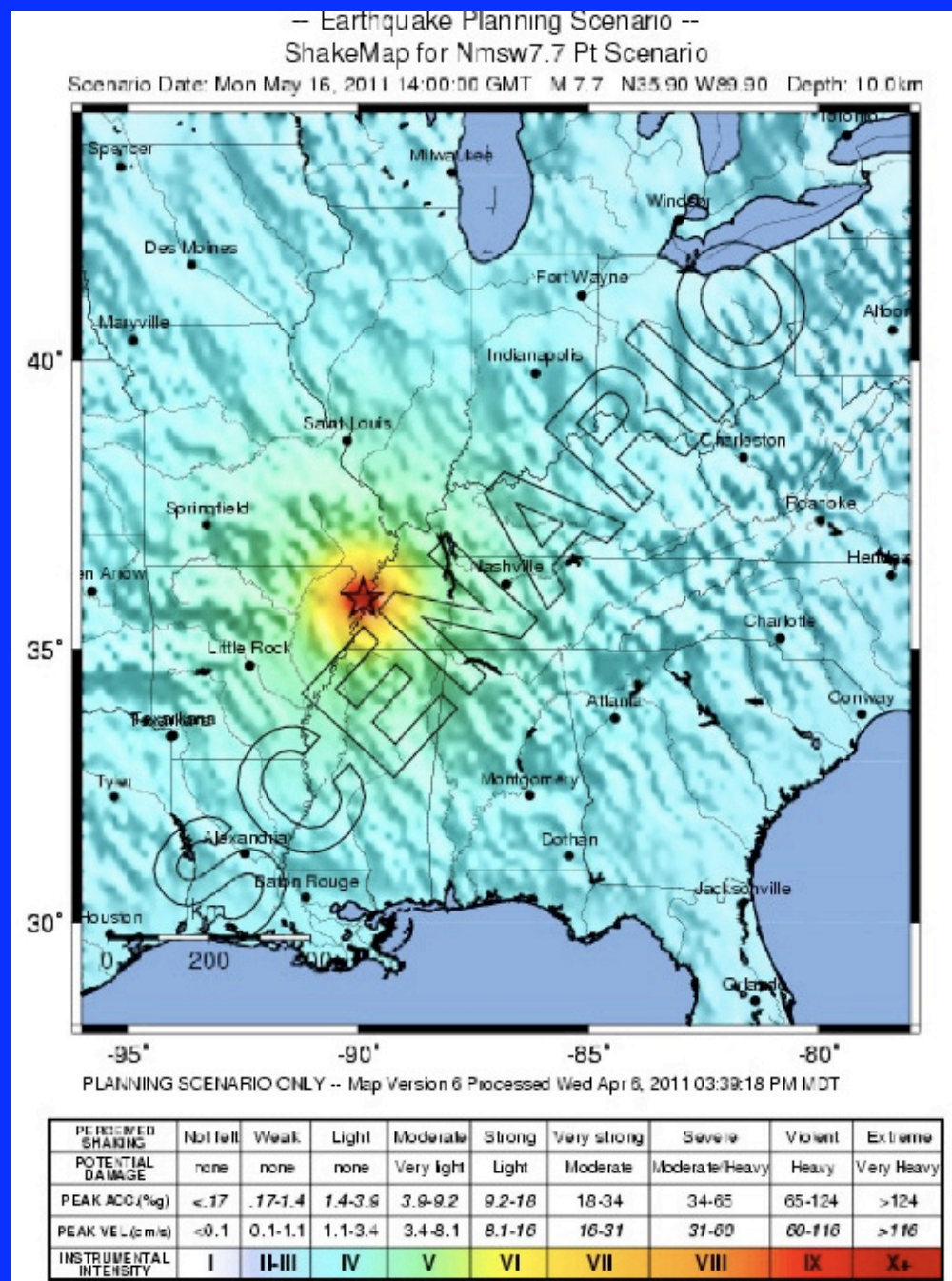
Newman et al, 2001

For assumed magnitude, ground shaking model, and mitigation level can estimate loss

This case  
10-100 fatalities  
~ \$100B damage

Examine range of parameters & use to find optimum

<http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2011/20110516.php>



Problem - as Kanamori (2011) notes in discussing why "the 2011 Tohoku earthquake caught most seismologists by surprise"

"even if we understand how such a big earthquake can happen, because of the nature of the process involved we cannot make definitive statements about when it will happen, or how large it could be."

What strategy to adopt if we can't usefully estimate probability or bounds are too large?



# *The destruction of the Fukushima nuclear power plant prompted intense debate in Japan about whether to continue using nuclear power*

## Japan Backs Off Goal to Phase Out Nuclear Power by 2040

NYT 9/19/2012

By HIROKO TABUCHI

Published: September 19, 2012 | 8 Comments

TOKYO — In an abrupt turnabout, the Japanese government on Wednesday stopped short of formally adopting a goal it announced just last week to phase out nuclear power by 2040.

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Yuriko Nakao/Reuters

Protesters unhappy with Japan's nuclear energy policy chanted slogans outside Prime Minister Yoshihiko Noda's official residence in Tokyo on Friday.

*- Clear economic benefits to using nuclear power rather than more expensive alternatives.*

*- Obvious danger in operating nuclear plants in nation with widespread earthquake and tsunami risks.*

*How to balance optimally the costs and benefits of building nuclear plants?*

*The challenge in comparing the costs and benefits is the uncertainty in estimating the probability of great earthquakes and megatsunamis.*

*This is difficult for the Tohoku coast. We know even less to the south along the Nankai coast, where we have no modern, historical, or geologic observations of megatsunamis, but the Tohoku tsunami suggests that they might occur.*

*Because the stochastic model requires probability estimates, we consider an alternative deterministic model based on ones used in mathematical finance.*

## Benefits and costs

*Investing capital  $k$  in nuclear plant causes real income (GDP)  $X(t)$ , to grow at rate*

$$(1/X(t)) dX(t)/dt = (b - r - vs)k$$

*$(b - r)$  is the return on capital  $b$  less interest rate  $r$*

*Growth is reduced by “shocks” – losses due to large earthquakes or tsunamis – parameterized by  $s$ , times vulnerability factor  $v$ . Over time,*

$$\log X(t) = \log X(0) + [(b - r - vs)k] t$$

Even if we can't estimate probability of "shocks", we know the larger shocks are rarer.

*We thus estimate the "expected" or "risk adjusted" growth using a "likelihood" term reflecting the relative risk of shocks*

$$q(s) = \exp [(1/2)s^2]$$

*The expected real GDP is the product*

$$z = qX.$$

$$Z = \log z = [(b - r - vs)k] + (1/2)s^2$$

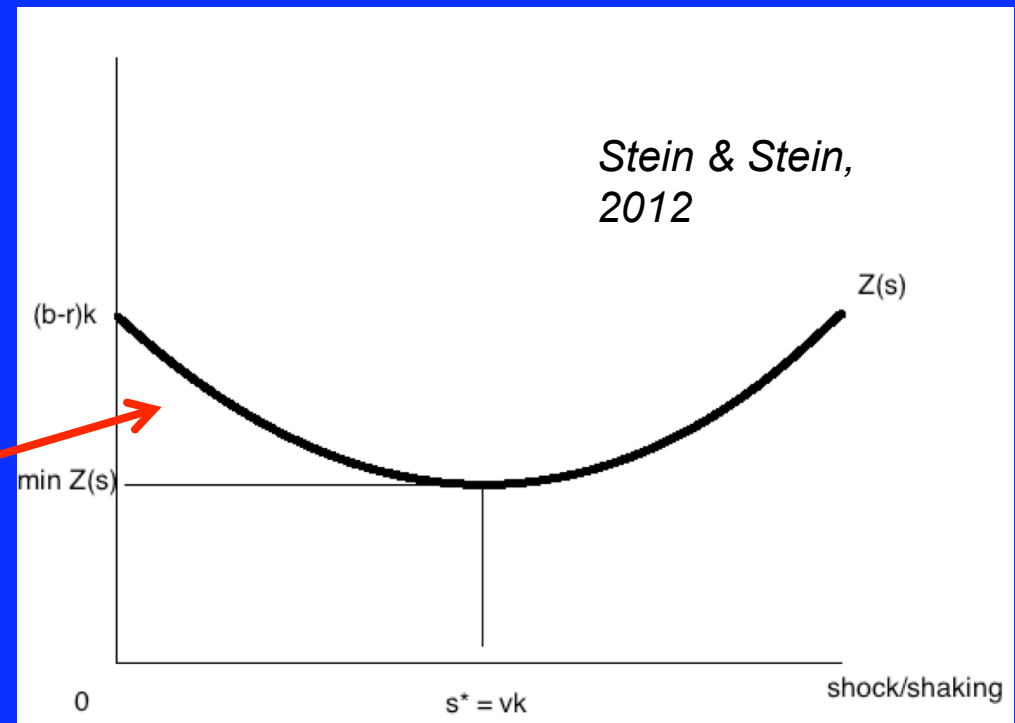
## ***Our min/max strategy to determine the optimum investment in nuclear plants has two stages.***

- 1) Min: Find the worst “expectation” or “likelihood” of the loss due to shocks. This is not the actual worst outcome (which is very unlikely), but the likely or expected worst outcome.***

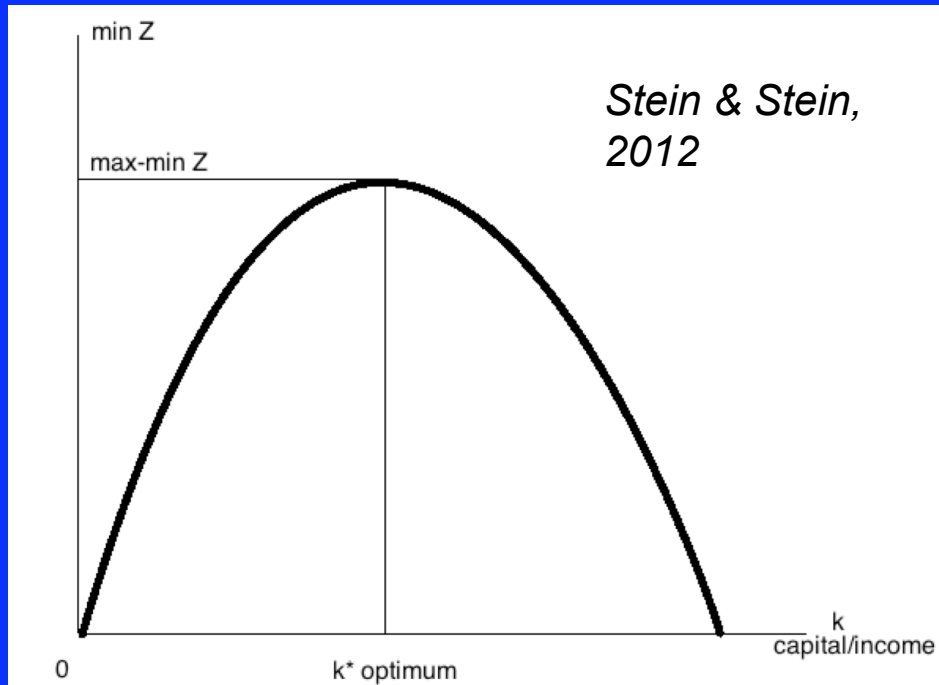
$$s^* = vk$$

$$Z(s^*) = (b-r)k - (vk)^2$$

*Loss from shocks depends on  $k$ , the capital invested, and vulnerability  $v$*



**2) Max: Determine a scale of nuclear plant investment that maximizes the minimum expected real income.**



$$k^* = (b - r)/v^2$$

*Optimum inversely proportional to vulnerability squared*

*Spend less in more vulnerable areas*

***This two-stage approach gives the optimum conditional on the expected worst outcome. In other words, given the harm that nature is most likely to do, this is the optimal investment.***

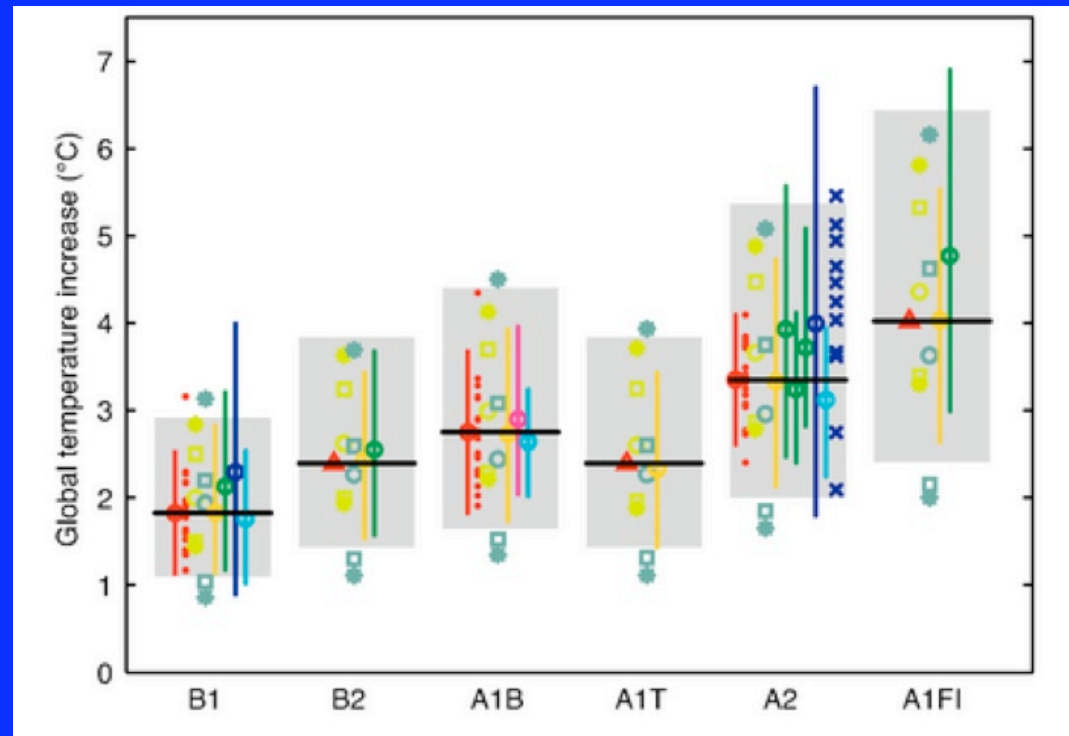
## ***Model thoughts***

*The approaches shown illustrate some ways to formulate strategies to defend society against hazards, given the uncertainty involved in estimating the probability and effects of the rarest and most damaging events.*

*Both stochastic & deterministic models are schematic in illustrating approaches, rather than implementations.*

*One simplification is that they focus on property losses and do not explicitly address life safety. For tsunamis, life safety is better addressed by warning systems that allow evacuations. The nuclear plant example implicitly includes life safety in the indirect costs of a disaster.*

*Similar analyses could be used for other hazards including river flooding and hurricanes (e.g. whether New Orleans defenses should be rebuilt to withstand only a Katrina-sized storm or larger ones) and to explore policies to mitigate the effects of global warming by considering the range of possible effects including the increased threat to coastal communities from hurricanes and rising sea level.*



*Rise in global temperature by 2099 predicted by various climate models. For various scenarios of carbon emissions, (e.g., B1) the vertical band shows the predicted warming (IPCC, 2007).*



## *Implications for math/geo initiative*

*Natural hazards have enormous societal relevance*

*Lots of interest among research community & students*

*Recent events illustrate the difficulty in assessing and mitigating natural hazards due to rare extreme events whose probabilities are poorly known and hard to estimate*

*They pose a wide range of major interdisciplinary intellectual challenges in geoscience and mathematical/statistical sciences, but progress can be made*

*Natural hazards are one of the logical areas to request research & educational (IGERT?) funds, and would be one of the ideal foci for an institute/summer school, etc*