Mmax: Ethics of the Maximum Credible Earthquake

Roger Bilham, CIRES and Department of Geological Sciences,
University of Colorado, Boulder CO 80309-0399

Abstract

The prediction of earthquakes or their forecast is associated with uncertainties in timing that are generally not easy for the public to assimilate. Estimates of the maximum credible earthquake (Mmax) in a region, which excludes considerations of time, may also result in public concern. In one view it is indefensible to withhold findings of relevance to public safety, yet in another the release of this information may cause alarm, or set in motion a chain of circumstances that may unsettle other scientists, cause public anxiety or financially depress sectors of the economy. Two examples are discussed in India where the revelation of international scientific discussions of Mmax by news media both alarmed the public sector, and taxed civic authorities tasked with responsibilities for the mitigation of earthquake risk. Since the scientist is fundamentally responsible for the disclosure of sensitive information to news media, to what extent is the scientist also morally responsible for the subsequent chain of events? In the USA the National Earthquake Prediction Evaluation Committee (NEPEC) provides a possible model for the delivery of sensitive information to the public avoiding the potential pitfalls of sensationalism. A recent evaluation of Mmax in the New Madrid Seismic Zone, for example, provided a consensus view of diverse opinions already known to the public. It is not clear, however, that a NEPEC confirmed assessment of Mmax newly derived by a team of scientists would be handled by the world's press with any greater sensitivity than in the past.

Key words: Seismic Hazard, Ethics, Mmax, Nuclear Power Plant, Jaitapur, Kashmir, New Madrid Seismic Zone, NEPEC.

Introduction

How does one educate a society endowed with abundant information that often requires expert opinion if it is to be correctly evaluated? In particular how does society identify the expert opinion that provides the most plausible interpretation of a future that will affect its members? The diversity of opinions and interpretations in news media and the worldwide web bring with them no absolute stamp of credibility. To the casual browser of the worldwide web, the crafted writings of a crackpot can carry the same weight as the considered opinion of a group of scientists. However, even the most uninformed visitor usually accesses some minimal but critical tools for sifting information. Schwartz and Morris (2011) distinguish four types of credibility invoked by those attempting to distinguish reliable from unreliable information on the world-wide web:

1. *Presumed credibility* based on a knowledge of the source (e.g. United Nations statistics) or the supposition of its trustworthiness from domain identifiers like " .gov".
2. *Surface credibility* is derived from the balance of professional content and the absence of slang, superfluous adjectives, and obvious errors in grammar or page construction.
3. *Earned credibility* influenced by a site's historically dependable information (e.g. BBC news vs. a personal blog).

4. *Reputed credibility* based on recommendations from others or public acknowledgement of their integrity in the form of international or other recognized awards.

These qualifiers apply equally to web-based, television or newspaper sources. In the web as well as in news media *surface credibility* can often mislead, concealing hidden agendas or biased points of view. Surface gloss in such cases may subdue other estimates of credibility. It is for this reason that professional presentation of information is identified as a fundamental method for establishing what others may perceive to be credible (Fogg et al., 2003). The importance of, and varied forms for, establishing credibility in its numerous guises were recognized in World War II in the development of the discipline of deception known as disinformation (Jones, 1978).

Scientific findings may be judged by each of the four criteria for credibility listed above. Indeed, scientists themselves use identical criteria, if not to evaluate the work of their peers, to decide whether to invest time in reading an article closely for its potential contribution to scientific advance. This chapter addresses problems inherent in informing the public of scientific findings, and the ethical dilemma that can accompany the transfer or non-transfer of sensitive information.

Right and wrong: gut decisions and approaching danger

At this point it is necessary to digress from issues of credibility briefly to a consideration of issues of right and wrong. A subsequent discussion of earthquakes and ethics requires a working definition of moral behavior if we are to interpret some behaviors as appropriate and others as unacceptable.

There is some evidence to suggest that our species is predisposed at birth to distinguish certain types of behavior that form the basis of human ethics (Hauser, 2006). From experimental observations of children faced with simple moral decisions, Hauser concludes that many decisions are based on evolutionary hard-wired behavioral patterns that underlie our notions of good and bad. For example, game-playing experiments showed that 90% of all participants automatically would save 5 hitchhikers from a runaway tram, by deflecting a tram to a branch line where only one victim would be killed (c.f. Figure 1b). He concludes that humans have inherited these early behaviors because ancestors that did not exhibit them were less adapted to survive.

A loose interpretation of Hauser's bimodal tests is illustrated graphically in Figure. 1. An approaching out-of-control tram approaches a switch (we shall later consider the tram as metaphor for an earthquake). In the figure a participant is asked to decide between inaction or diversion of the trajectory of the oncoming wagon. In 1a. he must decide between saving members of his species at the expense of another. In 1b. his decision is to save many people at the expense of a single person. In 1c. he is disposed to save family relatives (the white flag team) at the expense of strangers (the black flag team). All the decisions have outcomes that are unpleasant, but unless one is a psychopath the decisions are obvious - to switch the dangerous wagon to a path that minimizes the perceived effects of an approaching disaster.

The decisions, once made, are black-and-white choices. Not to decide is to decide. There is no half-way option. It is perhaps no accident that "yes-or-no" information can be easily assimilated and communicated to society, and uncertainty less so.

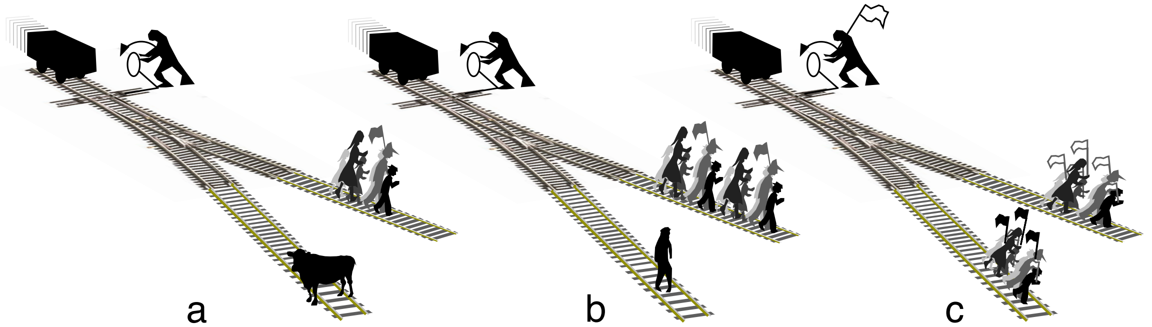

Figure 1 Instinctive moral reactions inherited by humans. Under game-like conditions a person must decide which way to deflect approaching danger a. Survival of the species (the cow represents an alternative species). b. Survival of the majority (90% of Hauser's participants chose to save the group and to sacrifice the individual), and c. Survival of the kinship group (family members carry white flags).

Another example of a hard-wired response inherited by humans is one ingeniously explored by Darwin (1871) – our human propensity to blush with shame. Blushing signals to a group that an individual admits personal discomfort with a recent or pending antisocial transgression. On finding that blushing was a common trait in many cultures Darwin concluded that shame offered an evolutionary advantage for our ancestors (Boehm, 2012). Darwin also considered that a tribe whose members included many that were patriotic and courageous would be victorious over other tribes, thus ensuring the survival of certain complex behaviors that we now categorize as virtuous. We commonly encounter advanced forms of shame nowadays in the form of political cover-ups. Less common is the embarrassment of scientists who are reluctant to abandon pathological scientific findings, such as, for example, the proposition of cold fusion (Close, 1992).

This chapter is not the place to explore the thousands of books and articles that have been written on the subject of the paradox of moral behavior (c.f. Gaur, 2014). It is sufficient to note that human evolution has provided us with certain basic tools that assure the survival of the species, the advantage of the tribe, and the survival of the group at the expense of the individual (Figure 1). In this chapter I shall naïvely assume that the complex ethical behavior of individuals or groups of individuals in society are founded upon a small number of inherited survival instincts that give rise to actions we consider morally correct.

Earthquake prediction and forecast, and a vulnerable public

Most scientific findings published between the covers of academic journals are of interest only to other scientists. However, occasionally something surfaces that is an important result, a secure and insightful foundation on which to advance future science, or a discovery that may impact society.

The study of earthquakes provides numerous opportunities for the identification of information of importance to the public. For example, the research of historical evidence for the power and reach of former destructive earthquakes in a region has implications for the required resistance of new construction to future shaking. Less interesting to the public, but of great utility to the earthquake engineer responsible for public housing might be the identification of locations where earthquake shaking can be amplified. The discovery that buildings may have just escaped failure in a previous earthquake with short shaking duration, and that they may not be so lucky in a future one of longer duration, would also be noteworthy. But by far the most important of public earthquake issues concerns the forecast or prediction of the time, magnitude and location of future earthquakes.

The specific time, magnitude and location of future earthquakes cannot at present be predicted, although there have been times when scientists have been optimistic that prediction might be possible (Hough, 2010). For some seismologists this optimism remains (Jordan et al., 2011), but attempts to predict earthquakes from the observation of physically observable changes that have preceded some earthquakes have been shown not to be reproducible ubiquitously, and have now mostly been discarded.

Given that at present damaging earthquakes cannot be predicted, an educated public should be predisposed to discredit any announcements of the time and place and magnitude of future earthquakes. However, the public is in general unaware of the current inability of scientists to predict an earthquake for tomorrow, or for next week or for next year. Moreover, even among seismologists the announcement of a pending earthquake would not be discredited without learning first the reasoning adopted for its prognostication, because there is always the possibility that the announcement of a new prediction has been based on a potentially successful new discovery. Thus it is recognized that earthquake predictions are likely to surface from time to time, and that assessments of their credibility will require evaluation.

For these evaluations the public seeks guidance from that small segment of the seismological community who have taken a special interest in the study of the physical, historical and statistical processes that precede earthquakes, gleaned from previous patterns of earthquake sequences. In 1980, at a time when the sensitivity and potential pitfalls of earthquake prediction were recognized, the US formed the National Earthquake Prediction Evaluation Council (NEPEC), a group of a dozen experts designated to advise the director of the USGS on timely warnings of potential future disasters. Similar bodies exist in many countries of the world. Their task in the US is not to undertake earthquake prediction research but to evaluate the credibility of the warnings and findings of others.

Earthquake prediction is a special (and currently unsuccessful) case, of a successful discipline known as earthquake forecasting. It is quite common for seismologists to evaluate the approximate location and probable magnitude of an earthquake with a qualified statement of when it will occur. Uncertainties in the forecast are quantified through statistical probability – a numerical estimate of the chances of specified earthquake occurring within a specific time interval. As such, the forecast typically has a time aperture of many decades. In practice, such forecasts have great benefit for society because they provide engineers and city-planners with sufficient time to outline and implement building codes for a region prior to the occurrence of an earthquake. A successful short term earthquake prediction (were it possible) in a city of unreinforced buildings would not prevent the destruction of infrastructure and dwellings, although lives could be saved through emergency mobilization of the public.

The ethics of three well-known cases of earthquake prediction are discussed by Sol and Turan (2004). The first two of these predictions were initiated by US individuals and the third by the US scientific community. All three predictions were failures, and Sol and Turan (2004) consider the consequences to the general public of all three undesirable. The cases are well known (Hough, 2010): the 1981 Brady/Spence prediction for Peru, the 1990 Iben

Browning prediction for the New Madrid region of the USA, and finally the 2004 Parkfield earthquake that occurred later than expected on the San Andreas fault. The authors discuss the ethical dilemma associated with the issuance of predictions justified by the need to alert people to impending danger, and contrast them with the consequences of predictions that result in distress of local populations. They conclude that "the publication of unwarranted hypotheses that are of immediate concern cannot be justified by appealing to a principle of absolute freedom of speech", since they lead to public anxiety. They furthermore reject the notion that the resulting heightened awareness of earthquake risk attending these predictions is beneficial, since this violates an ethical principle that individuals should not be used as merely a means to an end. Figure 1b illustrates the instinctive opposite, the probability that in an evolutionary sense the common good may be preferable to the distress of the individual. Dolce and di Bucci (2014) examine practical solutions to this dilemma.

The complexities invoked in considering the ethics of earthquake prediction borrow from the basic moral instincts evolved in humans mentioned in the previous section. The earthquake is the tram and the scientist, or group of scientists potentially control, if not a switch, a megaphone to alert those in the path of the tram of its approach. Let us dismiss for a moment our current inability to predict earthquakes (which amounts to not knowing the timetable of the trams in figure 1). The scientist convinced of a prediction must decide whether to alert the people to get out of the way of the expected tram, or to remain silent. Clearly if he is convinced that an earthquake is approaching, most people would agree he has a moral duty to alert the people involved. However, if his hypothesis is wrong the outcome is that he may unnecessarily alarm the people in the path of the tram. Again most people would agree that he has done the right thing in announcing that in his view, the people are better off out of the way.

It is only when we introduce some real life complexities into a well-meant prediction can we compromise the moral predicament of the predictor. Let us imagine that in the path of the tram are senior citizens with heart ailments sensitive to fright, or that the rail crosses a bridge over a raging torrent requiring those threatened by the approaching tram to leap to possible death. In this case the outcome of a failed prediction may be worse than not making the prediction, and most people would consider it morally questionable. Moral aspects of such decisions are considered by Kelman, (2014).

Earthquake predictions are rare, and currently not credible, and will not be considered further in this chapter. More important, but less perilous, are the moral consequences of forecasting and discussing scenarios for future damaging earthquakes.

A hypothetical case of nuclear power involving ethical decisions

Let us imagine that a nation has decided to construct a large nuclear power plant somewhere in its country. Physicists, engineers and economists would be involved in the selection of the type of power plant from a short shopping list of national and/or international nuclear plant vendors. The selected design and vendor combination would be no doubt one chosen with a good safety record based on levels of credibility selected by government officials responsible for power production.

The cost of the power plant is a decisive factor, and a simple cost/benefit analysis usually governs the final decision. Thus the total construction/operating cost must be capable of delivering power at rates lower than the anticipated cost per kilowatt of electricity from other means (kWH/$), for the anticipated duration of the plant. Various hidden costs might be subdued or excluded in this decision. Should the societal consequences of nuclear power vs. coal fired plants be considered? That is, should one consider the undesirable loss of livelihood to coal miners, or should the undesirable global consequences of carbon emissions be balanced against the costs and dangers of storing nuclear waste indefinitely? Should worst-case meltdown conditions, or the clean-up costs of a major accident be included in the cost-benefit analysis? Should construction costs include de-commissioning costs at the end of the design life of the plant? Often such considerations are apportioned to sub-committees designated to decide and provide information to a higher level decision maker, thereby absorbing moral decisions at a level remote from the decision to proceed.

At some fundamental level even the kWH/$ cost of the power plant is not a fatal issue that opponents and proponents may raise in discussions. On the one hand opponents can argue that nuclear power must be avoided at all costs since a severe accident may result in undesirable mutations to the human race and other species, and on the other hand proponents can argue with equal conviction that the replacement of coal-fired plants with nuclear power will ensure fewer climatic changes and assure the survival of species. A third path invoking renewable energy is omitted in the discussions considered here, which with certain caveats would avoid both these undesirable outcomes.

Let us return to the decisions faced by a government body attempting to solve the need for future power. Having decided on the type of reactor the next step in the process would be to choose a location for the plant. Some economic and physical considerations are common to all types of steam-generating plants: the need to be located sufficiently close to the user community that transmission costs are reasonably low, and the need to be close to abundant water for cooling purposes essential in the conversion of heat into electrical power. Special safety considerations are naturally considered for nuclear power plants. Unlike coal, plutonium is toxic to life, and hence the most important problem to address is to minimize the accidental exposure of people to toxic and radioactive release. Favored solutions are to place the power plant far from large population centers, and downwind and downstream from any agricultural regions upon which local populations depend. The avoidance of natural processes that might compromise plant stability are equally important: coastal tsunami, flooding, landslides, future earthquakes or volcanic eruptions.

The need for a go/no-go decision is easy where branch decisions are black-and-white, but often this will not be the case. For example, the placement of a nuclear power plant where population density is low does not mean that populations in the selected site will be zero. The decision is analogous to the decision to divert the tram to the path with fewer casualties (Figure 1b). This is an effortless decision, predicated by, that in the unlikely event of a radioactive leak, placement of the plant in a remote area spares the majority at the expense of the minority who live closer. A moral decision becomes only more difficult when secondary issues of concern to the minority close to the power plant are considered. Examples might be that in the course of normal operation (the accident-free operating status envisaged by proponents) the increase in temperature of local cooling water may damage the local ecology, threaten an endangered species, or reduce fish populations. Again the disadvantages to the local population when weighed against the advantages to the majority will result in a possibly uncomfortable (but inevitable) decision in favor of the majority.

The consideration of future natural disasters whose occurrence near a planned nuclear power plant may introduce an unforeseen accident, requires evaluation by a broad spectrum of scientific experts (meteorologists, oceanographers, hydrologists, volcanologists and seismologists) whose written statements typically confirm self-evident, non-contentious physical conditions near a plant. The issue of future seismicity and associated coastal tsunami generation is often less transparent. Earthquakes are transient, largely invisible phenomena that occur irregularly. Not all earthquakes occur at plate boundaries and it is almost impossible to say that an earthquake has never occurred, or will never occur at a location of interest. Recourse in such circumstances must be made to the calculated probability of an earthquake based on several considerations, many of which may be uncertain.

The possible occurrence of one or more future earthquakes is not an issue that will normally prevent the construction of a nuclear power station, although in some nations the proximity and amplitude of potential intense shaking can condemn a site as unsuitable should certain prescribed limits be approached or exceeded. No existing nuclear power plant has ever been destroyed directly by shaking near, or even above, its design shaking limits. The Fukushima reactor shut down safely ≈100 km from a magnitude 9 earthquake only to be flooded 50 minutes later by a tsunami. For most nuclear power plants the possibility of future violent shaking merely requires the introduction of various additional safety elements in the construction of the plant. These elements will, of course, add to the cost of the plant and its kWH/$ economics, and hence it would be naïve to imagine that the prospect of future seismicity has little relevance to the viability of a chosen plant location. Doubling the construction cost would not necessarily double the cost of electricity, but it would most certainly make it less competitive. To render a nuclear power plant safe during shaking, an engineer requires an estimate of the probability of future shaking, and quantitative estimates of the amplitude and duration and frequency of probable extreme ground motions during the design life of the power plant. For this he/she consults a seismologist.

Quantifying future earthquakes where few have occurred historically

Seismologists have established a number of methods to investigate future seismicity (See Wyss, 2014). Where earthquakes are sufficiently frequent and the historical record sufficiently long it is possible to recognize patterns indicating the probably recurrence intervals between damaging earthquakes. In some locations, however, the history of a region is short compared to the time between damaging earthquakes. For example, the historical record could be 200 years long, with intervals of a thousand years between earthquakes. The absence of a damaging earthquake in such cases does not necessarily imply that an earthquake cannot occur. It may mean than an earthquake has been brewing for 999 years and could occur one year after plant completion.

In such circumstances it is necessary to extend the historical record backwards, from hundreds of years to hundreds of thousands of years using geological evidence for the slip on earthquake faults in the area. Through excavation geologists can quantify the amount of offset of earth's surface along faults and determine the timing of these offsets (see Meghraoui, 2014). Various mechanical constraints apply to earthquake faults: the longer the fault - the larger the possible earthquake; the closer the fault - the higher the possible accelerations; the less eroded the fault scarp - the more recent the historical earthquake. One question that is particularly important concerns whether a fault that has not slipped in an earthquake for a very long while, is more, or less, likely to slip again. If it could slip again it is defined as a *capable* fault. In 1996 the definition of a *capable* fault adopted in the USA for the purposes of nuclear site investigations was that the fault has to have slipped once in the past 35,000 years, or recurrently in the past half million years. In other countries different definitions apply, and there has been a recent tendency to realize that a simple numerical definition for all earthquake regions may be inappropriate. The International Atomic Energy Agency (IAEA, 2012) has suggested that periods as long as the Pliocene (2.6-5.3 MyBP) should be considered where earthquakes are infrequent. A recent proposal in Italy is to consider a fault capable if it has slipped in the past 0.8 Myr in Italy's extensional terrain, and capable if it has slipped in the past 2.6 My years in Italy's compressive tectonic region (Galadini et al., 2012).

Guidelines for the proximity of capable faults are also prescribed in some detail. No capable fault of length x km can be located closer than distance y km to a nuclear power plant, where x and y are varied in accordance to anticipated shaking from the largest credible earthquake that can occur on a fault with those specified dimensions. Extreme examples are x=1 km where y=1 km, and x=40 km where y=200 km. The largest credible earthquake in a region is known as M_{max} and is discussed in a following section.

Hence it is reasonably simple for a nuclear agency to request a report from a competent group of seismologists and geologists to check-off all the requirements for safety required by nuclear construction engineers. Having determined the probability for slip of each mapped fault during the design life of the plant, earth scientists are no longer involved in the planning process. Based on the reports of the probability for shaking intensity, frequency and duration, the engineer designs the plant and provides the cost estimate to the planning team.

Societal pressures and moral principles

In the above site evaluation process it will be noted that neither the seismologist nor the geologist is confronted with moral decisions. His or hers is a strictly professional commitment to do the best possible job with the tools available. The acquisition of geological data may be subject to different interpretations, but if these are discussed transparently it is often possible to place numerical uncertainties upon them that can provide engineers with probabilities for design purposes.

In practice, however, other pressures may be at work within the planning committee. For example, if the cost of the project will be prohibitive if it is designed for accelerations exceeding 0.5g compared to modest accelerations of 0.2g, evidence supporting these high accelerations will be examined with microscopic detail, in the hope of detecting any flaw in the data or reasoning that has led to this economically undesirable conclusion. From the point of view of the planning team two interpretations may be from equally credible sources- team-A and team-B, but the opinion of team-A may permit a halving in construction cost compared to the finding of team-B. Team-B has identified a fault that may have slipped in a Magnitude-7 earthquake within 10 km of the power plant in the past few millennia, and team-A has interpreted this same fault to have not moved in 5 million years. At this point the planning team has a clear dilemma - to include B's higher risk estimate and accept the higher cost, or to examine the credibility of B's calculations in the hope that they can be refuted.

Since expert opinions are involved, and the planning team may not have the expertize to undertake the refutation of team-B and it must go to another credible alternative – expert team-C for advice, in order to dismiss, or to reconcile, opposing conclusions. The four credibility criteria discussed earlier in this chapter might be invoked to avoid introducing the opinions of team-C, but clearly it would be unwise for the planning committee to go to team-A to refute the conclusions of team-B, because team-A believe their conclusions to be correct.

However, there may exist a moral justification for the planning team to both accept the findings of team-A, and team-A's adverse judgment of the findings of team-B. Let us suppose that both the planning group and team-A share information freely between each other as part of the same funding organization. We could call them the white-flag group. Team-B, in contrast, may be part of a not-for-profit research group that carries black-flags or no flags. In such a situation the white-flag planning team may feel compelled to accept the white-flag team-A's judgment.

Although, this hypothetical case might be considered a form of corruption, the white-flag participants may have concluded that black-flag carrying team-B has a hidden agenda. For example, the planning committee may suspect that team-B may has been influenced by members of the local population at risk from a possible nuclear accident and thereby may have weighted their uncertainties in interpretation towards higher safety margins. Team-B may be suspected of being funded by an alternative energy supplier keen to replace nuclear power with renewable technologies. Team-B may be a member of a organization known to be against nuclear power. Implicit in these considerations are the planning team's suspicions that the black-flag team may themselves be morally corrupt. A similar suspicion attended Richard Perle's characterization of the motives of seismologists during discussions of the Nuclear Test Ban treaty in 1986 (Richards, 2014).

Alternatively, team-A may feel their own credibility is threatened if team-B is right and they may be shown to have missed important clues (Darwin's inherited shame factor). They also may feel justified in not releasing the extent of their tests, or in delaying the publication of their site investigation tests to either the white-flag or the black-flag community, in order to undertake further tests to discredit team-B's findings.

Various tools are available to the planning committee once it has determined that team-B's conclusions are both undesirable and possibly untrustworthy. They are as simple as they are effective – to demolish the credibility of team-B's arguments, to highlight minor but inconsequential errors in their scientific assertions, and to use rhetoric to assure the public that "the needful has been done" by their trusted white-flag team, or even to banish members of team-B suspected of owning a black flag.

Fortunately scientists are distanced from such political issues since they have established impersonal methods for scientific discussion. Scientific tests can be undertaken of team-A's and team-B's hypotheses that once complete, will potentially support decisive conclusions acceptable to both teams, and by the engineering and scientific community at large. If the site is considered unsuitable, a new one must be chosen. If the findings of seismic safety are considered unnecessarily pessimistic, the chosen site will be adopted.

The planned Jaitapur Nuclear power plant in India

The preceding is a conjectural discussion examining aspects of decisions related to the planned Jaitapur nuclear power plant south of Mumbai on the west coast of India, and readers should be aware that it is possible that these suppositions may be biased by the closeness of the author to some of the issues discussed. The Jaitapur nuclear plant is planned to be the largest in the world (Jaitapur, 2013). The detailed geological site investigation has, at the time of writing, yet to be made public, and the plans concerning the power plant have yet to be finalized. In late 2012 my coauthor, Professor Vinod K. Gaur, and I published an article suggesting that earthquakes similar to those that occurred ≈110 km north of the site in 1967 (Mw≈6.3 Koyna) and ≈400 km to the NE in 1993 (Mw≈6.2 Latur) could not be excluded from occurring closer to Jaitapur, were a capable fault identified near the proposed site (Bilham and Gaur 2011). This was followed by an article by Rastogi (2012), a seismologist advising the Nuclear Power Corporation of India (NPCIL), assuring readers that there were numerous errors in our article and "that all apprehensions raised have been considered by the geologists and seismologists involved in site investigations". Specifically this article describes a 50-km-long inferred fault 10 km distant from the planned power plant considered inactive, i.e not *capable* of slip in a future earthquake. A published rejoinder (Gaur and Bilham, 2012) suggested that were this a *capable* fault its offshore projection would pass within 5 km of the site, and its dimensions would permit a local maximum credible earthquake Mw>6.5, and hence thorough testing of its absence of activity in the past several thousands of years would appear to be vital. At the time of writing it is uncertain that any of these tests have been undertaken.

Shortly after the first of these discussions on the seismicity of Jaitapur was published, I was asked whether I would be willing to answer questions from members of the Indian Press on the 2011 article (Raina, 2012). I did so in January 2012 on my way to give an invited plenary talk in Ahmedabad at a conference on earthquakes in central India (. The press who attended this talk highlighted the difficulty of characterizing seismicity near Jaitapur given its short history of earthquakes, and the occurrence of a M>6 earthquake 110km to the north in the preceding decades. But the headlines used by the media were designed to arrest the attention of readers. These ranged from the factual to the sensational, and required the Nuclear Power Corporation of India (NPCIL) to defend their reports concerning seismic safety provided to them by their consultants. The official response (NPCIL, 2013, The Hindu 12 Aug 2012) reasserts the care with which investigations have been undertaken and the concurrence of seismic safety among the three seismologists who have contributed their expertize. (also see postscript).

Is M_{max} appropriate for public consumption?

The maximum credible earthquake (e.g. Cornell, 1968; Griffin, 1996; Wyss , 2014) that can occur in a region (termed M_{max}) is an estimated upper earthquake magnitude limit for considerations of future seismicity. For hypothetical future earthquakes M_{max} can be calculated from the product of earthquake rupture area times the amount of slip that can be sustained by a rupture of this size, given certain information about the strength of the fault that ruptures. The maximum credible earthquake on a fault 35 km long is of the order of Mw=6.5, but if the fault is 80 km long the earthquake could be as large as Mw=7.0 (one of the uncertainties in the Jaitapur discussion above). In relatively few places has M_{max} been confirmed by observation, since earthquakes often rupture just a part of a fault or plate boundary. Two recent earthquakes, however, exemplified M_{max} for the plate boundary segments on which they occurred: the 2004 Indonesia/Andaman Mw=9.2 earthquake and the 2011 Tohoku Mw=9.1 earthquake.

For these two regions seismologists had failed to quantify M_{max} on the plate boundary. Prior to the occurrence of the 2004 rupture the previous largest historically known earthquake in the region (Mw=7.9) occurred in 1881 in the Nicobar islands. In the Tohoku region an Mw=8.4 was considered probable although a previous earthquake in AD869 may have been larger. In 2004 the death-toll was approximately 230,000 and in 2011 the death-toll was approximately 20,000. In both cases the accompanying tsunami was unexpectedly damaging. Would knowledge of M_{max} have resulted in authorities undertaking a substantially different risk-mitigation strategy, or does it take the actual occurrence of M_{max}, to confirm that mitigation measures are warranted? Alternatively, is it possible that these two examples have been sufficient to alert authorities in analogous regions that risk mitigation strategies for worst-case earthquake scenarios have utility? To what degree is a seismologist morally responsible for assessing M_{max}?

These are interesting questions. Answers to the first must surely be speculative, and although a tsunami warning system has now been initiated in the Indian ocean as a result of the 2004 disaster, it is by no means certain that it will be functioning before the next mega-earthquake possibly 1000 years hence. Answers to the second might respond favorably to the notion that society has been provided with two warnings in a decade and should be vigilant to a future unexpectedly large earthquake. In neither case was the timing of these two great earthquakes an issue that could be contemplated in a predictive sense, but M_{max} is a measure of energy release that, had it been widely available, could have influenced the height of tsunami defenses in Japan, or the location of emergency generators whose post-tsunami failure led to a meltdown in some of Fukushima's reactors, or could have mandated the availability of a siren-based tsunami warning system on the coasts of India and Sri Lanka.

In that seismologists are responsible for the study of earthquakes, and that most seismologists are funded by the public, a case can be made that they have a moral obligation to inform the public of the largest anticipated earthquake in a region (Kelman, 2014). Wyss et al., (2012) and Wyss (2014) go further and assert that the moral responsibility of the seismologist extends to providing a quantitative evaluation of the societal consequences of the occurrence of this M_{max}. The question arises whether M_{max} has been underestimated in other seismic zones, or whether the seismic community has unwittingly withheld this information from the public at risk elsewhere in the world. A related question is whether the public should be informed of M_{max}. For example, a civil engineer might argue that knowledge of M_{max} in a region has no practical value whatsoever to an individual, its numerical utility being just one of the many inputs used by building authorities responsible for seismic building codes, or for engineers involved in the specific design of critical facilities in a region.

Mmax in the New Madrid Seismic Zone

For the past 40 years Mmax in the central USA has been available to the public as a result of sequence of powerful earthquakes in 1811 and 1812 near the New Madrid seismic zone (NMSZ) region of Louisiana and Missouri. In the largest of these earthquakes the Mississippi River briefly flowed upstream, sand was vented from the ground, masonry buildings near the epicenter collapsed, and people felt the earthquake at great distances. Although deformation rates measured by GPS are low, small earthquakes are common in the region (Stein, 2011). Since these earthquakes occurred before the development of seismometers, estimates of the magnitudes of the earthquakes must be based on eyewitness accounts, all of which are subject to interpretative errors. Early estimates of the magnitude of the earthquakes suggested magnitudes of $M_b \leq 7.4$ (Nuttli, 1973), but a 1996 study assigned maximum magnitudes of $M_w=8.0$ (Johnson, 1996). This resulted in a general perception that for the purposes of earthquake resistant construction code Mmax should be considered to be 8.0, a value that demanded considerable investment in civic infrastructure (Stein, 2010).

There is now unanimous agreement that the 1996 magnitudes had been unjustifiably inflated. The most obvious reason for this is that there is no known fault large enough to sustain a $M_w=8$ earthquake near New Madrid, given a reasonable physical frictional strength and inferred slip of the fault system that is believed to have caused the earthquakes. In 2009 (Fact Sheet 2009-3017) the USGS describe the earthquakes as "*several of magnitude from 7-8 in the past 4500 years*". In the most recent study currently available, and with the stamp of approval from the USGS review process, the original nineteenth century accounts were re-evaluated and the magnitude of the first and last strongest earthquakes in the sequence were determined to be $6.7<M_w<6.9$ and $7.1<M_w<7.3$ respectively (Hough and Page, 2011). In 2011, due to the wide range of proposed magnitudes, and to the startling (for some) realization that the New Madrid earthquakes may have barely exceeded $M_w=7$, NEPEC formed a special subcommittee to evaluate the credibility of all published evaluations (NEPEC_NMSZ, 2011).

The subcommittee found itself unable to recommend a single correct answer and instead argued "*that measures of uncertainty such as standard deviations are large, about 0.5 magnitude units*". Yet despite some of the standard deviations being significantly less than 0.5 magnitude units the committee undertook a consensus approach effectively averaging disparate conclusions, in lieu of identifying flaws in reasoning in contending studies, an approach that might have led to a more decisive conclusion. In defending this approach the committee accepted a range of magnitudes (averaging $M_w=7.5$) with the caveat that an improved magnitude estimate would attend the availability of new instrumental data from a large earthquake in a similar region.

Unlike the case of M_{max} for the planned Jaitapur power plant, the New Madrid M_{max} dispute concerns earthquakes that many members of the public knew had already occurred. The deliberations of the select committee were indecisive about $M_{max,}$ but the resulting uncertainties (based on a logic tree assessment that included numerous other factors) resulted in estimates of anticipated ground motions that differed by a factor of two (for 0.2% probability of exceedance of peak ground acceleration in the next 50 years).

The select subcommittee specifically defined their moral boundaries in the report as follows: *"Our panel has concentrated on the scientific issue of hazard assessment; we did not evaluate engineering or policy issues in our review. Those questions are best left for professionals and politicians who are qualified and/or positioned to make informed societal-risk decisions".* In their first sentence, the select committee, clarifies their absence of bias, and in their second it passes the burden of their uncertain but expert judgment, onward to those responsible for the safety of people. The report of the select subcommittee was evaluated by the NEPEC committee and forwarded verbatim to the director of the USGS with the comment that it presented "*a balanced summary of what is and what is not known about the seismic hazard in the NMSZ*" (Tullis, 2011).

This evaluation of Mmax and its consequences for the NMSZ NEPEC succeeded in clarifying diverse and contradictory information already available to the public and to engineers in the region. That the concluding values for Mmax for future earthquakes differed little from the median value considered by the subcommittee for the 1811/12 earthquakes was possibly a coincidence. One can imagine, however, a different scenario in which a single evaluation of Mmax is available, with no alternative scenarios for the NEPEC committee to consider. In these circumstances we may speculate that the NEPEC committee would undertake an approach similar to that which they adopted in the Brady-Spence prediction. They would presumably attempt to understand the physics and tectonics associated with the estimation of Mmax from published materials and, in the absence of clarity, they would then quiz the seismologist or team of seismologists concerned directly, by requesting interviews or invited presentations. The first approach distances itself from details of the method, but the second approach dissects the data, the physics and the interpretation at a much more fundamental level. The members of the committee would no doubt weigh the consequences of their judgment with the moral burden of knowing that their collective verdict would subsequently form the basis of government policy.

Mmax for the Himalaya

The Himalaya are a seismic belt where knowledge of M_{max} is important for the design of a building code. Earthquakes here affect the populations of six nations: Pakistan, India, Nepal, Bhutan, Bangladesh and southern Tibet. The total population within reach of damaging shaking in Himalayan earthquakes exceeds 50 million (Bilham et al., 2001). The largest earthquake observed recently in the Himalaya was the Mw=8.6 Assam earthquake of 1950, although it is probable that the 1505 central Himalayan earthquake (Ambraseys and Jackson, 2003) may have released 4 times more energy with $M_w \approx 9.0$, given that slip locally exceeded 20 m (Kumar et al. 2010). If the entire Himalaya slipped >20 m, the amount observed in trench excavations of the 1505 earthquake (Lavé et al., 2005; Kumar et al., 2010) in a single Kashmir-to-Assam earthquake its magnitude would be Mw≈9.3 and rupture would have a duration of tens of minutes. This unprecedented magnitude represents M_{max} for northern India. However, our current limited understanding of the behavior of the Himalaya based on the past millennium of earthquakes is that the Himalaya slips in shorter segments with correspondingly smaller magnitudes. Few seismologists in the region have considered a Mw=9.3 possible, and even the notion of a Mw=9 earthquake in the Himalaya is considered by some improbable (Srivastava, 2013).

A numerical estimate of M_{max} for the Kashmir region, the westernmost segment of the Himalaya was discussed at a scientific meeting in December 2011 (Bilham et al., 2011) and subsequently published (Schiffman et al., 2013). This eight year study by an Indo/Pak/US team considered thirty-three scenario earthquakes with magnitudes varying from a low of Mw=7.4 (partial rupture) to a maximum of Mw=9.0 (rupture of the entire Kashmir/Kishtwar region). The highest magnitude estimate (M_{max}) assumed 23 m of slip of the region between the 2005 Kashmir Mw=7.6 and the 1905 Kangra Mw=7.8 earthquakes, which the study concluded had a low probability, but could conceivably occur at >1800 year intervals.

The presentation of this information would normally have gone unnoticed, especially since it was the penultimate 15-minute talk of a five-day meeting of multiple concurrent sessions where the results of more than 20,000 different contributions had been presented. Barely 20 scientists were present, much lower than in many of the previous talks, and conference organizers were already clearing up the room. However, it was singled out by the press office of the American Geophysical Union (AGU) as worthy of a press release, and within days numerous newspapers had headlined the news warning of a Mw=9 earthquake in Kashmir. Accounts in Indian newspapers, and those in Kashmir, included none of the discussion of uncertainties or the methods used, but gave much space to consequent damage, with memories of Japan 2011 and the Andaman islands in 2004 prominent in the reporting. The November 2013 published report (Schiffman et al., 2013) that provided the numerical details of the 2011 discussion in San Francisco passed unnoticed by the press.

In December 2011 the immediate response of Kashmir authorities had been to reassure the public that there was no cause for alarm, no earthquake having been predicted, or even forecast. Subsequently, in the weeks following the news, civic authorities in Kashmir organized various school earthquake safety programs and responded to questions from concerned citizens. In the spring of 2012 a scientific meeting in India, led by concerned seismologists based in Hyderabad, independently evaluated the science underlying the AGU presentation, discredited the observations and concluded that the finding could be dismissed as baseless sensationalism (see postscript). In Oct 2012 the National Disaster Management Agency (NDMA) and the Ministry of Earth Sciences, government of India organized a workshop to discuss earthquake disaster preparedness in the Kashmir valley. Since then funding for new seismic and geodetic studies have been approved in Kashmir to supplement, and to presumably test, the sparse data on which the initial findings had been based.

At a fundamental level M_{max} information is inappropriate for assimilation by local disaster agencies. The information constitutes neither prediction nor forecast since it comes with no estimate of time (with the exception of an unstated and inferred estimate of minimum recurrence interval based on geodetic convergence rates). In the case of the Kashmir M_{max} leak, the fate of the information and its capacity to mislead and distress was sealed once the news media had captured the story. The people and the civic authorities in Kashmir learned of this information via sensational newspaper reporting, a delivery method that is clearly inappropriate for a measured response, since the authorities were effectively having to absorb the information, and to formulate an appropriate response to the information simultaneously.

A conclusion to this line of reasoning is that since M_{max} can be of no direct utility to disaster management authorities in a region, and is likely to result in local panic in the hands of journalists, this information should be restricted to discussions among scientists and engineers tasked to develop safety measures in the construction industry. However, had these procedures been adhered to by proactively denying journalistic-access to the information, research into earthquake hazards in the Kashmir Valley may have languished, and may not have received the infusion of research funding and the enthusiasm for disaster management it now enjoys. The role of the journalist in this chain of events is perceived to have been to elevate a passive scientific conclusion to a confrontational pedestal. To subdue its adverse effects on public morale, those responsible for public safety were compelled to characterize the journalistic announcement and its scientific precursor, as scaremongering. Following the logic of Sol and Toran (2004) one would could conclude that the release of M_{max} to the public would fall into the same morally unacceptable class of behavior as earthquake prediction, whereas Wyss (this book) and Wyss et al., 2012), argue that withholding Mmax and its consequences from the public cannot morally be defended.

Discussion

Two examples are provided where the evaluation of earthquake information by seismologists have utility to local populations, but where the intervention of journalists attempting to deliver this information directly to the public has resulted in adverse reactions by civil authorities mandated to gather the same information, and to serve the same local populations. Journalistic commentaries in each case have led to a division of scientific opinions, in the absence of which contentious conclusions would have been resolved through the traditional dialogue of discussion, testing, refutation and eventual concordance. A difference in scientific opinion is confusing to a public provided with no guidance as to the credibility of each opinion. Subsequently journalism played a role in advancing biased conclusions, increasingly divergent from the scientific uncertainties that initiated the discussion.

For the planned Jaitapur Nuclear power plant to proceed its planners require unanimity in the assessment of future seismicity. Specifically its engineers require numerical estimates of shaking intensity before they can design the plant, and their chosen design determines the cost. In the absence of expert opinion among themselves, the planners must apply measures of credibility to its expert opinions, either based on personal feelings, or from estimates of the credibility of its consultants and their opponents elicited from independent authorities. As the web of questioning expands the moral allegiances of those involved become more complex. The issues are as yet unresolved.

In the case of the journalistic reporting of M_{max} to the public in Kashmir, responsible authorities took the correct policy of denying its links to earthquake imminence or forecast, but some scientists went further. The credibility of the research and the correctness of its conclusions were questioned by other scientists without supporting data, and advisors to the government of India deemed it necessary to withhold from one of the researchers the privilege of undertaking further collaborative field research on Indian earthquakes (see postscript).

In both cases international teams considered the data and communicated their findings through normal scientific channels. Subsequently, in both cases, local and foreign researchers have been intimidated from further investigations, and future collaborative investigations have been discouraged. In retrospect it is evident that the intercession of journalists de-railed the scientific process, but it is also evident that the withholding of scientific findings would have required a level of secrecy not normally associated with science. In the case of Jaitapur, no article on its seismicity need have been written. In the case of Kashmir, the discovery of the unusual width of its potential rupture zone could have been buried in the conclusions of reports to funding agencies. Most scientists would consider both actions orthogonal to their mandate for reporting research of interest to the public.

At present there is no simple intermediate mechanism for the delivery of sensitive information to the public. In the USA sensitive seismic findings are refereed by committees such as NEPEC, who are tasked to deliberate on the validity of earthquake predictions and earthquake forecasts, and to provide recommendations to the Director of the USGS, who is responsible for timely warnings of geological disasters. Faced with divergent published conclusions for M_{max} in the New Madrid Seismic Zone (NMSZ), NEPEC formed a subcommittee to consider this and other related but contentious issues. The subcommittee, armed with invited opinions from dozens of non-committee members, chose not to identify a single unique correct solution but to weigh the credibility of all solutions and to examine the potential consequences of these extremes. This was a legitimate stance since the mandate of the committee issued from NEPEC was not to decide, but to comment - "*NEPEC is exercising its responsibility to advise the USGS Director on issues bearing on earthquake forecasting by convening a panel of independent experts to comment on the level of hazard posed by future large earthquakes in the NMSZ".* The written report was reviewed by NEPEC and passed on to the director of the USGS without further judgment.

In summary, the Director of the USGS was (and is) mandated to provide timely warnings of potential geological disasters to the public, the members of the NEPEC committee were mandated to advise and recommend findings to the Director, their select subcommittee was mandated to comment on the diversity of findings to the committee, and the subcommittee solicited further opinions to broaden the data base upon which their commentary was based. At no point in this process are there recognizable moral forks in the path from opinion to product. The team approach in effect used largely external estimates of credibility in accepting the findings of authors with diverging opinions. The net result was a creditable analysis of community-agreed statistical uncertainty, but it is not clear that an engineer about to build a hospital in the New Madrid Seismic Zone would not have preferred a more aggressive investigation of the fundamental reasons why some opinions could not be rejected.

Conclusions

The seismologist interested in future earthquakes contributes a small but crucial link in a safety chain, which if undertaken while adhering to the tenets of scientific investigation and reporting, requires no moral judgments or ethical considerations. The preceding discussion, however, illustrates that some scientific results require the scientist to withhold information likely to cause public anxiety. Bad news about Mmax, either whispered by seismologists to each other, or proclaimed through the megaphone of journalists, follow paths whose outcomes must both be considered undesirable, and hence require moral judgments. Alternative procedures currently available in the USA are cumbersome and ineffective alternatives for the release of sensitive seismic information, although they make no moral demands on participants. The weakness of the NEPEC model is that in the only case where a decisive evaluation of M_{max} would have been of great benefit to local seismic hazard studies, the process fell short of probing below the surface of some of the published claims of authors. It is not clear how the public in a populated region previously considered seismically quiet would receive a NEPEC confirmation, and a recommendation for public release, of a new discovery for an unexpectedly large value for M_{max}, even were it accompanied by a vanishingly small probability for its imminence.

Postscript

On 19 May 2012 the Indian government barred the author's entry to India (Bagla, 2012). No explanation was given and he was deported to the US on the same plane on which he had arrived. A few weeks after the publication of Bagla's article the Indian Home office classified the author's scientific publications as journalism and attributed deportation to the inappropriate use of the tourist visa that Ahmedabad conference authorities had approved for his January 2012 plenary talk.

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