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Nuclear WasteTechnical Review Board

Meeting of March 8-9, 1994

Probabilistic Natural Hazard Estimation for Use in Design of Engineered Facilities

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A Bias: I am an ardent supporter of probabilistic methods for this purpose. At each step below ask yourself: does a deterministic method do this as well, as completely, or at all?

1. **Products to Engineers/Decision Makers**
   - **Estimate of the Probability** (mean frequency) **that in the next n years a specified "effect" variable** (or variables) **will exceed a specified level** (or levels). Formats: hazard curves, scenarios, etc.
   - **Provide representative quantitative statements about the epistemic (knowledge-related) uncertainty** associated with these estimates. Formats: sensitivity studies, confidence bands, etc.

2. **Objectives of the Process**
   - **Communicate, coordinate, describe,** integrate, etc. **all the scientific information** (data, evidence, theories, interpretations, etc.) about the relevant elements, identify factors (critical to the conclusion) for further investigation.
   - **Combine this scientific information into** a representative **scrutable, defendable hazard estimate and uncertainty statement.**
   - **Communicate the hazard estimate and the confidence levels** among the various specialists and to the users (technical and other) in the most effective way.
   - **Avoid** implicitly or explicitly **making value judgements in isolation.** Priority setting, risk-cost-benefit analysis, implications of "beyond-design-basis" loads, "how safe is safe enough", etc., are the purview of others in the chain. "Enough is enough" is in this category.

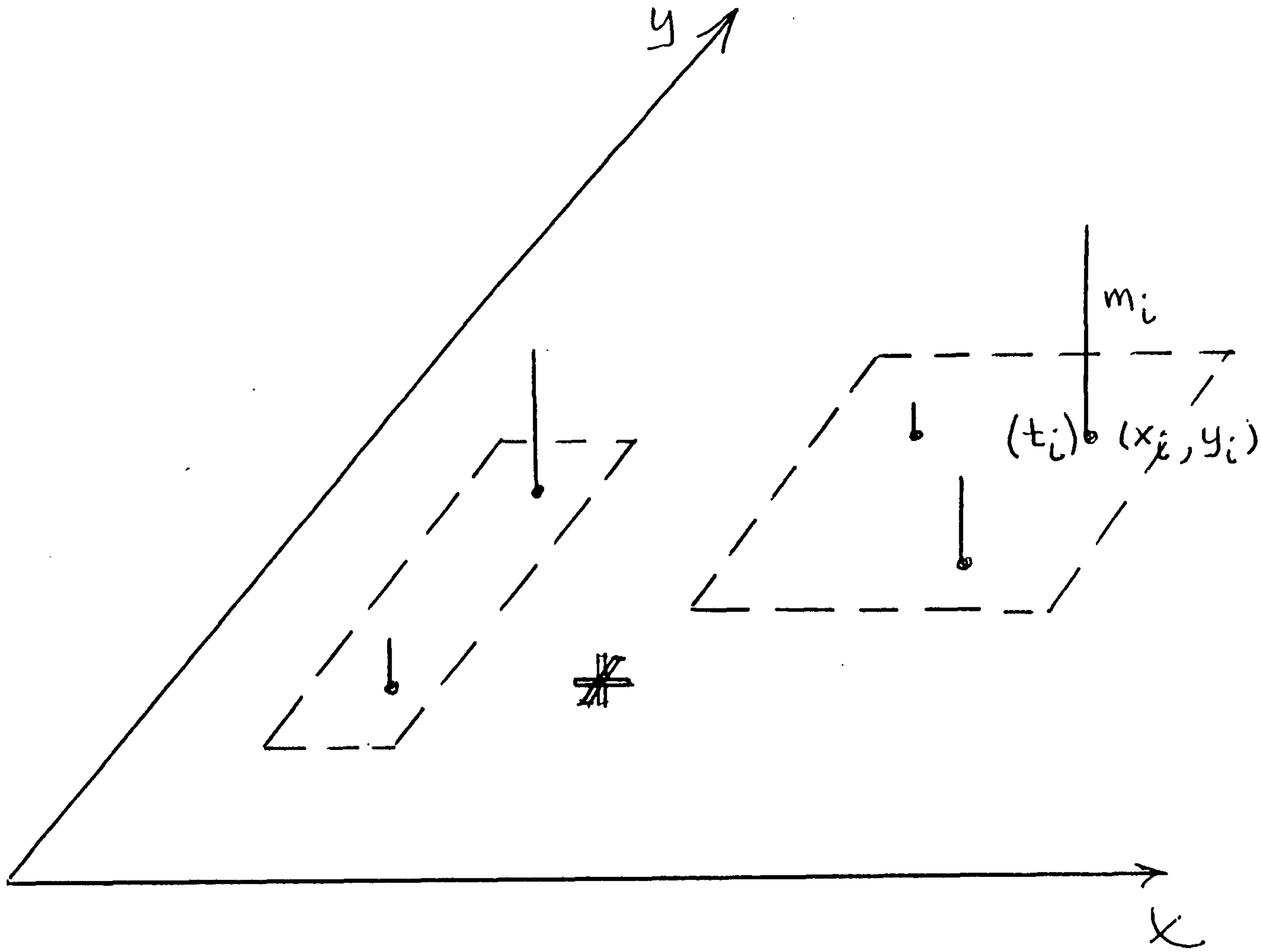
3. **Background**
   - **Probabilistic characterization of "design loads", etc., grew out of engineering need** to provide reasonable and uniform (across sites, across load types, etc.) design bases. Direct-empirical basis: floods and wind loads, since early this century. More structured models for seismic, hurricane winds, and waves, etc., in last 30 years or more.

- **Today design** in all countries in all fields **of virtually every engineered facility** for resistance to extreme natural hazards **is based on a probabilistic load definition**: offshore structures, buildings, etc.; wave loads, tornado loads, as well as seismic loads. Remaining exceptions include some critical facilities; e.g. large dams for floods and earthquakes. "Higher tech" fields are more likely today to use a probability basis in more fundamental ways, e.g., if objective is 10^{-3} or 10^{-4} performance goal, assess at 10^{-3} or 10^{-4} load level (as opposed to a 10^{-2} level times an "ad hoc" factor).
- **There is much greater variability, "randomness", and uncertainty in natural hazards than in the engineered system itself.**

  Hence, it is critical that their characterization be probabilistic.
- **What is recent (1980's) and more narrowly applied is: The explicit quantitative treatment of epistemic uncertainty** (parameter value uncertainty, model uncertainty, formal staistical analysis, expert elicitation, aggregation of diverse judgements, etc.). The seismic, nuclear field has been a leader in applying these tools.

4. Basic Structure of Usual Models and Assessment

- **The probabilistic/stochastic model:** a temporal, spatial recurrence model (usually a marked point process) coupled with a random effects model. Examples: Tornado occurs in effect at a point in time and space with random "source" characteristics: maximum wind speed, travel speed, path width, length, and orientation; and with a random field effect; e.g., the mean wind-speed field falls of roughly geometrically on either side of the path center line, but there is variability about the mean. Earthquakes and their effects (ground motion and faulting), and volcanoes and their effects are analogous.
- **Each element of the model requires probabilistic characterization;** e.g., the mean annual occurrence rate of events is non-uniform in space; it may or may not be homogeneous in time; the recurrence process may or may not be Poissonian (e.g., a more general, renewal model permits either clustering or more "cyclic" behavior). The stochastic model should be as complicated as the scientific information requires. Alternative models are commonly retained.
- **A vector of parameter values is identified and values estimated;** the mean annual rate now and in the future. Some parameters may also vary spatially. Critical parameters <u>may</u> be limits; e.g., upper bound magnitudes, maximum displacements. Here deterministic and probabilistic approaches to setting a design basis <u>may</u> share a common focus.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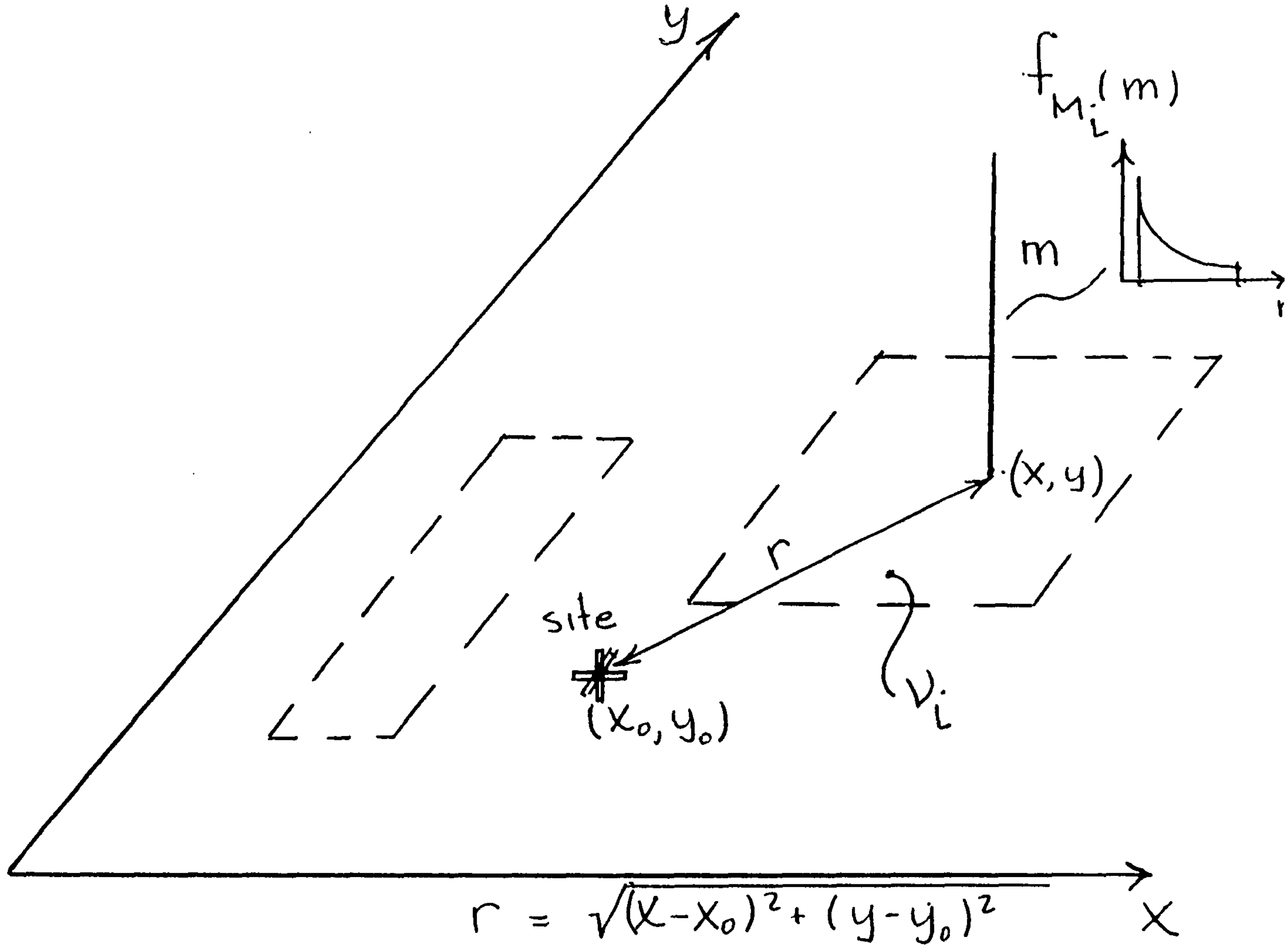

$$r = \sqrt{(x-x_o)^2 + (y-y_o)^2}$$

$$p = f(m, r)$$

$$= 1 - \Phi\left(\frac{\ln a - \ln(q(m,r))}{\sigma_{\ln a}}\right)$$

- **Numerical analysis**: For these models, complex as they may be, this step should not be a barrier. Nor need this step be one that causes a lack of transparency. That comes next.

- **Uncertainty Assessment, Elicitation, Aggregation**

  The "simple" objective is a point estimate of each parameter value and a probability distribution describing the (epistemic) uncertainty about that value. The reality is that:

  (1) The model is complex (in order to capture what is known) involving many parameters which may vary over time and space; **uncertainty analysis adds another dimension on top**; therefore, the description, characterization, communication, formal estimation, elicitation of uncertainty in individual's interpretation, etc., are difficult to do, to comprehend, to make transparent, etc.

  (2) The concept of "parameter" estimate and uncertainty has to be extended in extreme cases to include alternate models (theories) and "relative weights".

  (3) Important cases should reflect diversity of experts' interpretations.

  (4) The process of eliciting uncertainty in expert technical interpretations has not been without its difficulties. Scientists are not necessarily trained or gifted in uncertainty analysis, expression, communication, etc. Experts in these topics cannot be expected to have deep knowledge in the relevant fields of science. Yet they must interact effectively.

  No major project should underestimate the difficulty of this part of the process. Insufficient care can distort the "answers". Yet it is necessary to the communication to forward in the design /decision process.

5. Examples

- As mentioned, virtually all structures today are designed based on loads with specified mean return period. Traditionally, the design basis was linear elastic behavior under "not unexpected load levels", e.g., 100-year mean return periods. But more recently, more advanced practice has had a second-level design check at the level of near-failure (implying non-linear structural behavior) for loads with annual frequencies approximately equal to the target failure probability ("performance goal"). Examples include the Norwegian Petroleum Directorate wind-wave-current criteria for offshore structure design, and American Petroleum Institute guidelines for seismic design and re-evaluation. This practice culls out brittle, non-redundant systems, and it better characterizes site-to-site differences in hazard at the levels that really matter to safety, but it requires natural hazard estimates in the 10^{-3} to 10^{-4} range.
  (This practice would likely have avoided the catastrophic life loss potential that the failure of several long-span parking garage failures in the 1994 Northrdige represented.)

- The evaluation of probabilistic seismic hazard estimation for U. S. nuclear power over the last 20 years is on the whole a success story in my opinion, but one not without its difficulties. It has made it possible to make realistic probabilistic risk assessments that permit comparison with other initiators, and to develop new probability-based design bases. The robustness of the estimates has been a continuing issue. The current level of agreement between EPRI and LLNL Eastern U. S. hazard estimates (medians and, now, means) is hopefully a stable one.

6. Issues and Problems

- **Of necessity we are dealing with very <u>rare</u> events,** implying

  (a) the need to exploit all relevant information, be it measured data or expert interpretation;

  (b) it is necessary to combine sources of information: model building, space-for-time exchanges, analogues, etc., and this demand expert interpretation;

  (c) the preferred approach is one of building a physically-based model and deducing very small probabilities and combinations of not-so-small probabilities;

  (d) the final results are difficult to test by formal statistics and the judgements are difficult to calibrate.
- **Multiple disciplines are involved**; communication and cross-training are essential and time-consuming. Probability is common but not universally practiced language.
- **The results are often used in a highly visible arena**, with a perhaps contentious environment, with implications with respect to defensibility, concensus, etc.
- **Probabilistic analysis is non-trivial and not familiar to all involved.** The physical processes are spatial and temporal and vector-valued. The corresponding (less familiar) probabilistic models are, therefore, not trivial. The added dimension of uncertainty characterization is still more difficult and much less familiar, and, indeed, not fully mature as a (social) science. To be complete, therefore, it is difficult to maintain transparency to all concerned. Both developers (scientists) and users (engineers, managers, decision-makers) must make an effort. Perhaps, more effort is needed at the interface to improve the communication to insure trust.

I was aked to comment on:

- **Krinitzsky's Kriticisms:** I am familiar only with his "Hazard of Hazard Analysis" article in Civil Engineering magazine: yes, the use of probability is dangerous but so is the use of axes, power saws and brain surgeon's scalpels. Are the alternatives less so?

7. Yucca Mountain Specific Issues

- **The long-time frame** has implications with respect to:

  (a) sensitivity of certain assumptions, e.g., the **Poisson versus Non-Poisson** decision is less critical for those events whose mean recurrence time is less than the facility life;

  (b) the need for clear thinking about the **statement of the criteria**: how, if at all, is a 10^{-2} risk in 10^{-4} years different from a 10^{-6} risk per year if all processes are stationary? (Most engineering life safety criteria are expressed in annual terms and for good reasons.) If they are not different, is the question only whether or not the physical process is stationary (in a 10^{-4} year time frame)? And then only non-stationary to a degree (e.g., a factor of 10 or more in 10^{-4} years) greater than current uncertainty bounds in the current annual rate? Given the discounting in consequences (including lives lost) permitted in modern risk-cost analyses, future events are less important than current ones, implying less sensitivity of decisions to uncertainties about the distant future. (And, yes, discounting of future lives lost is consistent with inter-generational equity concerns; current capital resources buried 'unnecessarily' at Yucca Mountain will deprive future generations of some of the benefits of compounded technological growth that must be delayed for lack of capital.)

- The fact that **the facility involves radioactive waste** implies that this is very serious business and that the scientists must, therefore, do a state-of-the-art job analyzing and communicating the natural hazards and their uncertainties; this implies using the most complete tools available (i.e., probability and uncertainty analysis) even if the users, reviewers, decision makers, etc., have to make an increased effort to improve their understanding and comfort.

- Within the limits of my understanding (which are severe in the first case), **volcanism and earthquakes are equivalent problems** from the perspective of this general overview of probabilistic natural hazard assessment.

*Does either of **two deterministic methods of determining a design basis earthquake (the EUS or the California version) apply in the Yucca Mountain short-history, very low displacement rate context?**