ePAD: Earthquake Probability-based Automated Decision-making for Earthquake Early Warning

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Introduction

The benefits and feasibility of *Earthquake Early Warning* (EEW) are becoming more appreciated throughout the world. An EEW system detects an earthquake initiation based on a seismic sensor network and broadcasts a warning of the predicted location and magnitude shortly before an earthquake hits a site. The typical range of this lead time is very short, around tens of seconds to a minute, which is a huge challenge for applications taking advantage of EEW.

Many applications, such as stopping traffic from entering a bridge that has a predicted high probability of damage, releasing an evacuation alarm in dangerous buildings or an emergency shut down of a facility, suffer from substantial economic loss if a false alarm happens. Therefore, the decision of whether to take a mitigation action should involve sophisticated cost-benefit analysis. Since the time between the warning and the arrival of the strong shaking is very short, special attention must be paid to rapidly calculate the probabilistic predictions and to automate the decision making for the mitigation actions. Human intervention would likely use up too much of the short lead time, preventing the mitigation from being activated in a timely manner. This motivates the development of an earthquake probability-based automated decision-making (ePAD) system.

Recent approaches on automated decision system cannot explicitly handle multiple-action decisions and exclude lead time, the most important factor in decision-making for EEW applications. In ePAD, we use expected economic loss as a basis for rational decision-making, and the *Pacific Earthquake Engineering Research Center* (PEER) *Performance-Based Earthquake Engineering* (PBEE) methodology is used for seismic loss estimation during the decision process. The concepts of *Decision Function, Decision Contour* and *Surrogate Model* are utilized to achieve fast computation and to allow comparison between various decision criteria. A value of information (VOI) model motivated from optimal policy searching for control or robotic problems is developed to handle the lead time of EEW and its uncertainty.

1. EEW in California: CISN ShakeAlert System

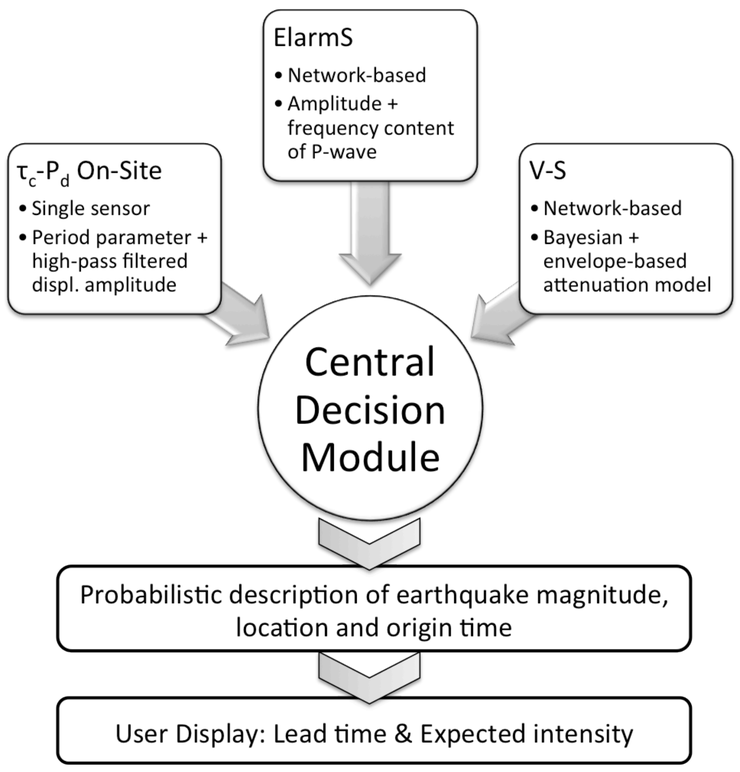

Figure 1: The CISN ShakeAlert System combines the outputs of 3 early warning systems each based on a different theory:

- τ_c-P_d on-site algorithm
- Earthquake Alarms Systems (ElarmS)
- Virtual Seismologist (V-S)

All 3 systems receive data from the same CISN seismic network:

1. Station triggered
2. Each system runs its own algorithm to produce PDFs of:
   (i) earthquake magnitude
   (ii) location estimation
   (iii) origin time
3. All results integrated in the *Central Decision Module*, which produces a single set of PDFs for above 3 components

2. Decision Criterion and PBEE

Let $\Omega_a = \{a_0, a_1, \ldots, a_n\}$ be the set of alternative mitigation actions, where a_i denotes initiating a certain action for $i = 1 \ldots n$, and a_0 denotes not to initiate any action; $U(DV)$ be the utility of decision variable (DV); $E[X|Y,a]$ be the expected value of X given Y for action a, and $D(t)$ be the data from EEW as a function of time t. Then:

Take Action iff $$\hat{a} = \underset{a \in \Omega_a}{\operatorname{argmax}}\, E[U(DV) \mid D(t), a]$$

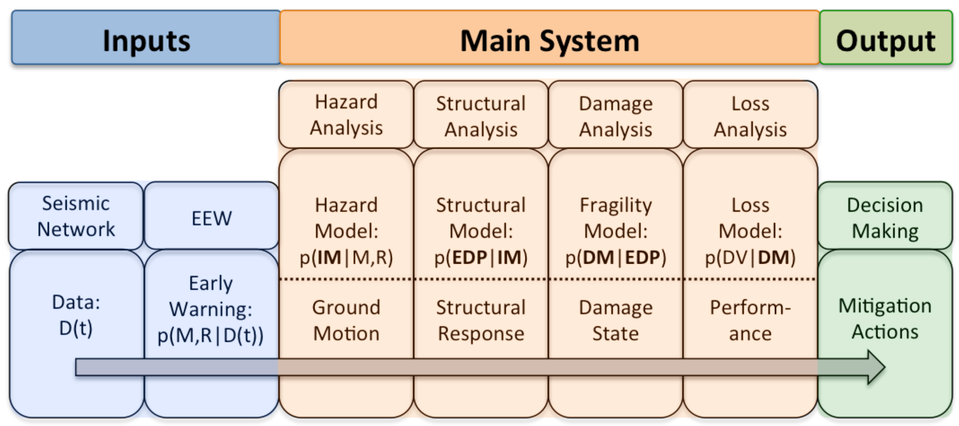

Figure 2: This figure shows the PEER PBEE methodology for calculating the expected utility. M and R are the magnitude and site-to-event distance of the incipient earthquake; **IM** is the ground shaking intensity measure; **EDP** is a vector of engineering demand parameters, and **DM** is a damage state measure for all the vulnerable components in the structure.

3. ePAD Framework and Key Concepts

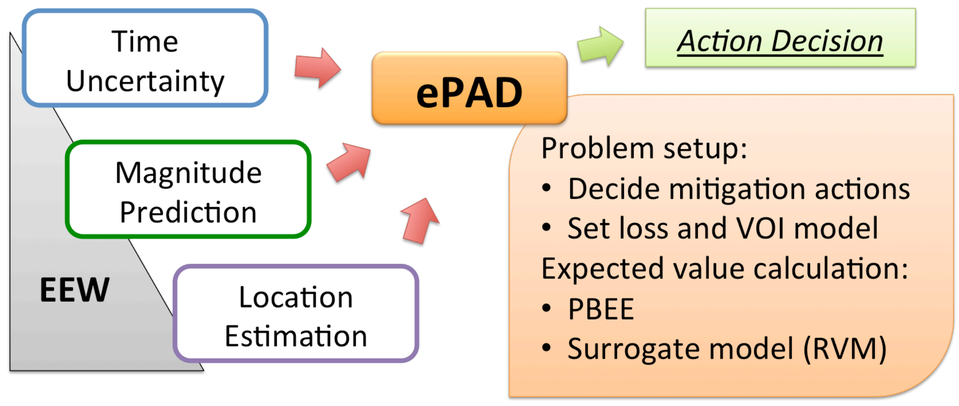

Figure 3: This figure shows the complete framework of ePAD.

1. Choose target mitigation action with corresponding DV
2. Perform cost-benefit analysis based on PBEE methodology [If chosen models are too complex for fast computation → surrogate model (e.g. relevance vector machine (RVM) – Bayesian machine learning technique for sparse model regression)]
3. Once the EEW system provides early warning PDFs (as shown in section 1), ePAD quickly gives out automated decision on what action to take (including the possibility of no action)

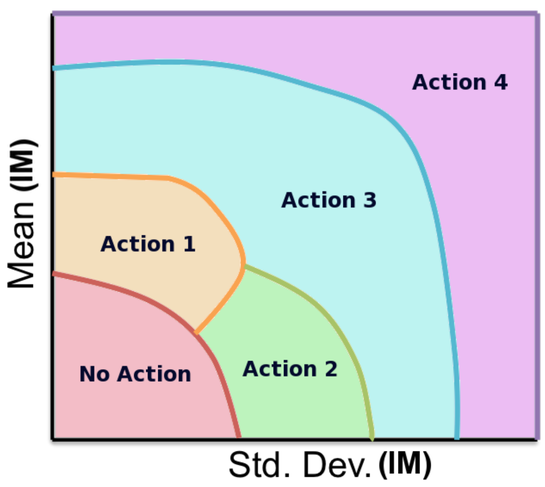

Figure 4: Analysis on decision behavior is based on *decision contours* - curves that separate different actions in a input domain. Various decision criteria can be re-written in an unified form (basic idea for *decision function*) and if a Gaussian model is assumed for EEW input, above shows an example of decision contours for a given scenario.

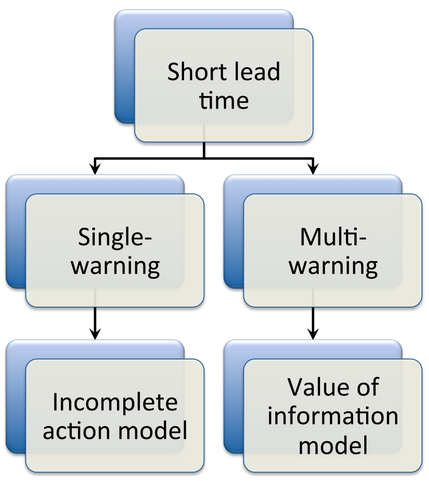

Figure 5: Given a short lead time, there are two concerns: (i) insufficient time to complete actions (ii) excessive time for potential updates of EEW information. Separate models are constructed in each case to allow flexibility on various decision behavior desired by the users.

4. Sample Case Study Results

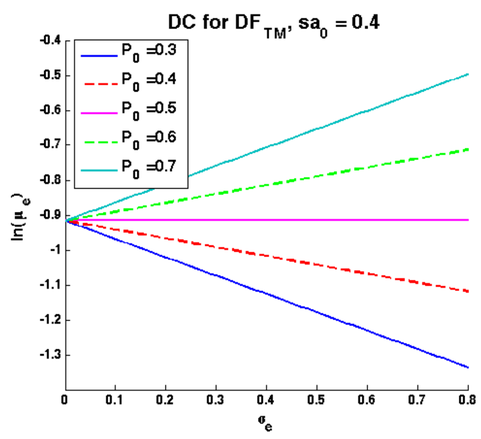

Figure 6: This figure shows an example of how decision contours reflect different decision behavior.

- Assumption: EEW provides Gaussian PDF of intensity measure (μ_e : mean ; σ_e : standard deviation)
- Result: (i) decision is independent to uncertainty → curve with zero slope = risk-neutral behavior (ii) user willing to respond at higher mean shaking level as uncertainty increases → curve with positive slope = risk-taking behavior (iii) vice versa → curve with negative slope = risk-averse behavior.

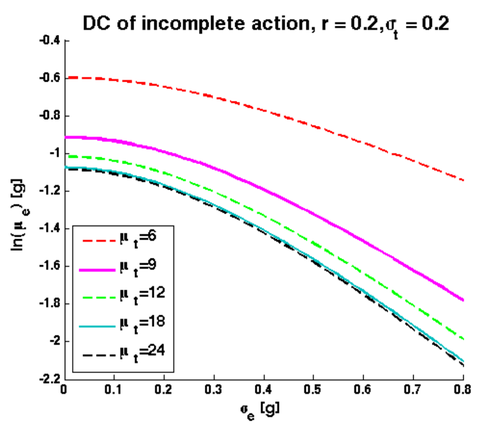

Figure 7: This figure validates the incomplete action model by showing a reasonable shift in decision contours as a function of the mean warning time μ_t.

- *Idea*: μ_t decreases → probability of action completion decreases → benefit of the action decreases → system is less likely to trigger the action
- *Validate*: μ_t approaches or exceeds the time limit for completing the action (20 seconds in this case) → decision contour converges to the same decision contour as if the time factor is not included

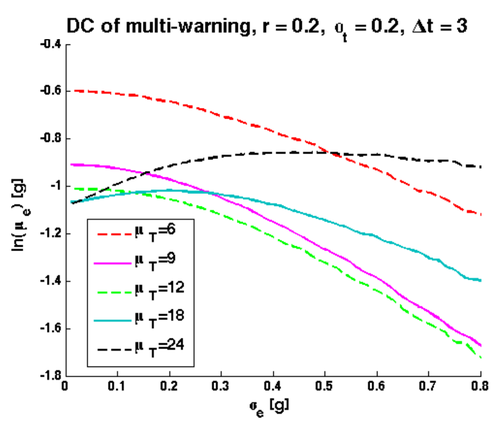

Figure 8: This figure validates the VOI model, as we compare the result with figure 7.

- *Idea*: Multi-warning → future information update → potential of uncertainty reduction → implicit benefit for delaying our decision
- *Validate*: (i) μ_t approaches or exceeds 20 seconds → decision behavior changes from risk-averse to risk-taking (ii) decision at zero uncertainty is not changed
- *Explanation*: Potential benefit of making better decision based on less uncertain EEW information

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