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MAGNITUDE-PATTERN ADAPTIVE EARTHQUAKE OCCURRENCE MODEL FOR A FAULT

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ABSTRACT

The proposed model combines a physical approach to the earthquake process on a single fault with statistical adjustment of the model macro parameters. Earthquake activity on a known fault is evaluated from the available information on the past fault behavior. The parameters of the model are obtained in adaptive manner and the confidence bounds on the parameters are estimated using the bootstrapping technique. The model is extended to simulate site ground motion hazard using empirical attenuation functions. A preliminary example of the model application to the Northern portion of the San Andreas fault is provided.

KEYWORDS

Earthquake occurrences, fault simulation model, site hazard analysis, bootstrap sampling.

INTRODUCTION

The latest developments in the earthquake occurrence theory put under scrutiny the traditional assumptions of log-linear relationship between the event magnitude and its frequency expressed through a Guttenberg-Richter relationship, and the constant hazard rate feature inherited from the Poisson model. It has become apparent that a number of well studied faults exhibit significant regularity with characteristic events recurring on the same segment and that the likelihood of a large event usually decreases after another large event occurrence on the same seismic source. In order to represent characteristic fault behavior as well as to incorporate the seismic gap hypothesis, several non-Poissonian models of earthquake occurrences were developed.

The stochastic time-predictable (Anagnos and Kiremidjian, 1984), slip-predictable (Kiremidjian and Anagnos, 1984) and random slip rate (Suzuki and Kiremidjian, 1991) models consider time dependence between large events, however they assume that these events are space-independent. The generalized semi-Markov model (Lutz and Kiremidjian, 1993) takes into account time- and space- dependence of large earthquakes. These models consider only the largest events because of their dominating energy contribution. Meanwhile, the incorporation of the smaller size events would help to improve the statistical significance of the results generated by a model of fault behavior.

The hybrid recurrence model (Wu, Cornell and Winterstein, 1995) estimates seismic hazard by taking into account both the small and the large events. It assumes that small events form a Poisson process and follow the Guttenberg-Richter magnitude-frequency relationship, whereas characteristic events constitute a renewal process. Lamarre, Townsend and Shah (1993) use a renewal process of earthquake occurrences and a bimodal cumulative magnitude distribution to be able to consider all size events. These models do not represent all size events as the outcomes of the same slip accumulation and release process.

Most of the discussed models do not provide confidence intervals on the estimated parameters. Hence the reliability of the forecast is unknown. In the cases where the confidence intervals are calculated the theoretical applicability of the employed procedure is not shown.

The model described in this paper considers accumulation and release of slip along different fault segments as the earthquake underlying process. In addition, it uses classical dislocation theory to generate slip redistribution after an event along the fault. It also considers segment boundaries as energy dissipating barriers which allow to simulate the characteristic segment behavior as well as 'cascade' events which rupture more than one segment. The fault is represented as a set of interacting cells. A normalized rather than actual slip is introduced to be able to simulate different size events on cells with fixed dimensions. The assumptions and mechanism of the model enable the simulation of small, moderate and large events resulting from the same slip accumulation and release process. The model uses bootstrapping to obtain confidence intervals on the parameters of interest.

As an illustration, the model is applied to a section of the San Andreas fault. Based on this application a site hazard curve is constructed to estimate the hazard at a particular site for a 50 year time interval.

MODEL DESCRIPTION

The objective of the proposed model is to generate a sequence of earthquakes of magnitude 3 and greater in some future time period on a particular fault. In order to make such a forecast the model parameters are adjusted to a certain magnitude pattern represented in the earthquake catalog. The fault is divided into segments identified by differences in seismic behavior. The properties of the medium within a segment are uniform. The segments, in turn, are composed of cells of fixed length and depth. A cell is the most elementary unit of the model: all the slip is both accumulated and released on the whole cell. In case of events for which the rupture length and depth are smaller than the cell length and depth, normalized slip is introduced. It is the accumulated slip that has to be released on the entire cell in order to generate the magnitude corresponding to such an event. For the events rupturing more than one cell the released slip distribution is calculated according to the dislocation theory. The interaction of the segments is regulated by the boundary energy barriers that control slip transmission between the cells of adjacent segments.

Assumptions

The moment magnitude is used as a measure of earthquake size. It is calculated by the empirical formula of Hanks and Kanamori (1979). For an event that ruptures more than one cell the seismic moment is the sum of individual cell moments. In this case the cell which initiates the earthquake is called the triggering cell. The slip released on the triggering cell is determined by the mechanism described below. The slip released on a non-triggering cell is determined from the following equation:

$$D_{ji} = \min\left[0, \left(D_{ii} \cdot \frac{k_{ji}}{k_{jj}} - B\right)\right], \tag{1}$$

where D_{ji} is slip released on cell j due to event on cell i; and k_{ji} is stress on cell j due to unit slip on cell i (triggering cell). B is the amount of slip which is dissipated on the energy barrier in case when the cells i and j belong to different segments and B = 0 otherwise. Values k_{ji} for each cell are calculated from dislocation theory assuming homogeneous medium (Dieterich, 1991):

$$k_{ji} = \frac{G}{2\pi(1-\nu)} \cdot \left[\frac{1}{X_{ji}} - \frac{1}{X_{ji-1}}\right], \tag{2}$$

where G is the shear modulus, ν is the Poisson's ratio, X_{ji}, X_{ji-1} are the distances from the center of the cell i to the bounds of the cell j.

The amount of slip released on the triggering cell depends on the accumulated slip on the cell by the time of the event and the slip release coefficient. Slip accumulates along the fault linearly with a rate specific to each segment. The time of an event is determined for each cell from a lognormal distribution which has different parameters for each segment and depends on the segment activity rate. The slip release coefficient is a random parameter. It determines the portion of the accumulated slip that is released in an event. Since small magnitude events occur much more frequently than the large ones and the logarithm of the slip release coefficient is roughly proportional to the event magnitude, it is natural to assume that the logarithm of the slip release coefficient is exponentially distributed.

Let y be the slip release coefficient. It must be bounded between the values which correspond to the smallest possible event (y_{min})and 1 (in which case the whole amount of the accumulated slip is released in an event). This coefficient can be expressed as follows:

$$y = 10^{(1-x)\cdot \log(y_{min})}, \tag{3}$$

where x is a random variable bounded between 0 and 1 and distributed according to the equation:

$$F_X(x) = \frac{1-e^{a\cdot x}}{1-e^{a}}, \tag{4}$$

where a is the parameter which will be adjusted during the simulation. The slip release coefficient, y, varies from segment to segment and depends on the magnitude pattern associated with the segment.

Mechanism

The model runs in two modes or regimes: adjustment and forecast. In the adjustment mode the parameters of the model are determined and in the forecast mode the hazard for a particular site is evaluated for a time period of interest. The mechanism of the adjustment mode is shown on the flow-chart (Fig. 1). The following notation is used in the flow-chart. H(I) is the event catalog, I is the number of events in the catalog; H(i) = < magnitude, time, coordinates >. C(J) is the array of cells, J is the number of cells; C(j) = < coordinates, depth, length, initial slip >. The initial slip for all the cells is set equal to the level of slip sufficient to generate the largest possible event on a cell in case of its rupture. S(K) is the array of segments, K is the number of segments; S(k) = < slip rate, initial mean time to the next event (TM), initial parameter a of the release coefficient (RC) as defined in eq. (4) >. N is number of simulations, T is the time of one simulation, n is the current simulation number and t is the current time.

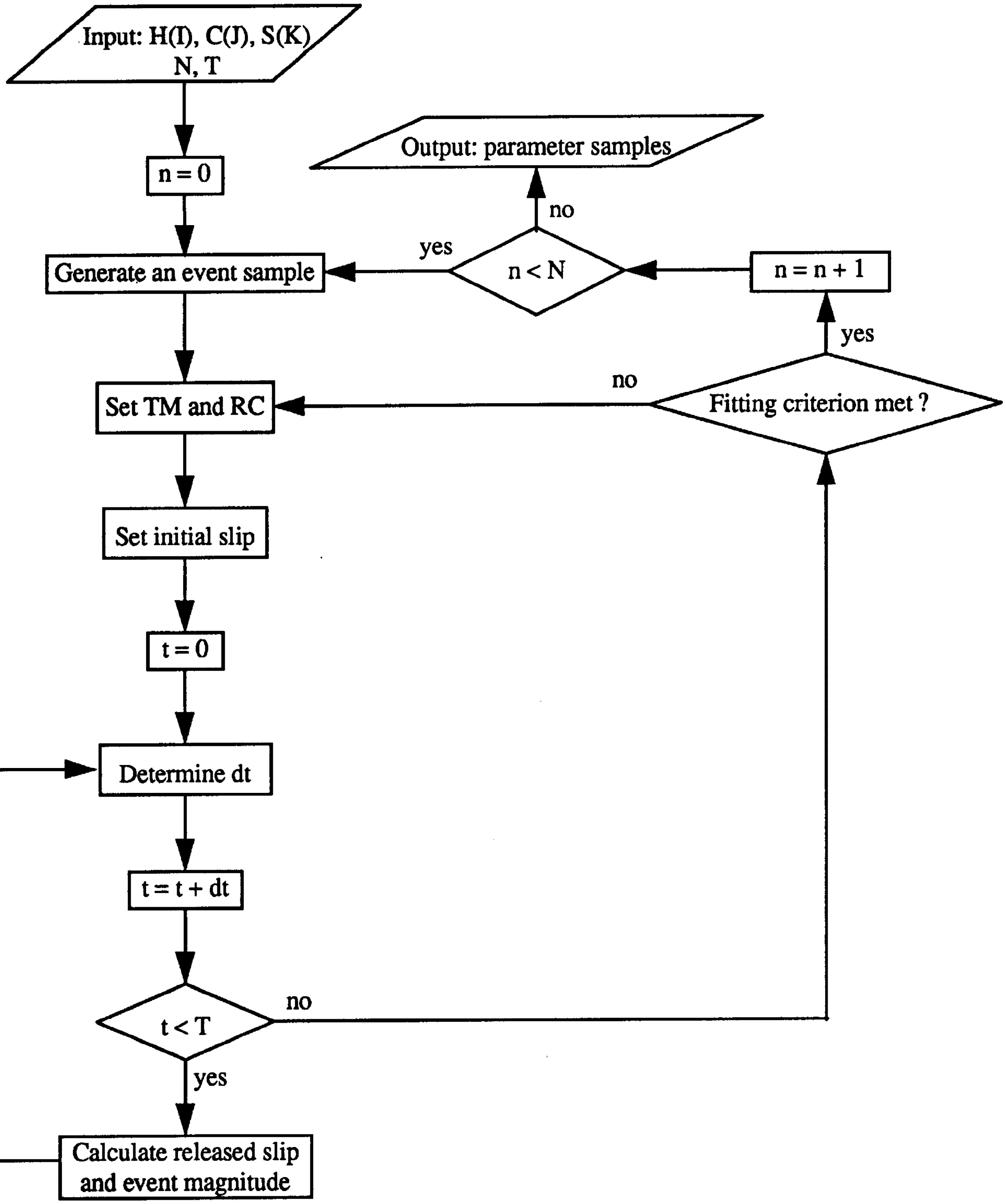

Fig. 1. Adjustment Mode Mechanism.

The adjustment mode consists of N simulations which result in N values for the parameters of interest (mean time to the next event, parameter a of the slip release coefficient). The value of N is empirically set to the level that guarantees no further significant improvement in confidence intervals on parameters. Each of the simulations is run as an iterative procedure until the fitting criterion is met. Each iteration has a fixed time length T, where T is set to exceed the return period of the largest event at least 10 times. This requirement provides the necessary level of statistical significance of the obtained results.

A separate bootstrap sample for the events is generated for each simulation according to the procedure described below in the section "Data Processing". The application of the bootstrap procedure generates a set of parameter estimates that allows to construct empirical confidence intervals.

Mean time to the next event for each segment and the parameter a of the slip release coefficient are the adjustable parameters. At the first simulation they are set equal to the initial values. In the subsequent iterations they are adjusted to reduce the discrepancy in the fitting criterion.

Time to the next event on the fault, dt, is determined as the minimum of the times to the next event of individual cells. The cell that corresponds to the minimum time is selected as the triggering cell. The time to the next event for a cell is a random variable that is updated according to its distribution after the cell ruptures.

The amount of slip released in an event is determined according to the following procedure. First the slip release coefficient is generated for the triggering cell. The released slip is calculated on the triggering cell by multiplying the slip accumulated on the cell and the slip release coefficient. Then it is checked whether the slip should propagate to any other cells. If it does propagate to the other cells then the slip released on those cells is calculated according to the eq. (1). Any events with potential magnitude less than 3 are ignored (the cell does not rupture). The seismic moment and the moment magnitude of the simulated event are calculated depending on the slip released on all the affected cells.

The fitting criterion consists of two components: the difference between the number of the simulated and sample events and the difference between the total slip released in simulation and in the sample. The first component is used to adjust the mean time to the next event, while the second determines the parameter a of the slip release coefficient. The fitting criterion is met when its norm falls below some predefined level. Since the model is designed to meet a certain pattern of magnitudes and the number of the large events is significantly less than that of the small ones, the application of the released slip as the fitting criterion provides a natural way to assign weights to the various magnitude ranges.

The logic of the model does not change significantly when it is run in the forecast mode (Fig. 2.). The model is simulated N times: one for each set of the parameters obtained at the adjustment stage. Each simulation consists of W runs. A run is a Monte-Carlo simulation of time length T. In the forecast mode the time T is significantly shorter than that in the adjustment mode (usually less than the return period of the largest event). Consequently, the obtained sequence of events is too short to be representative and the results obtained from a single run would have a significant small sample bias. To overcome this difficulty W Monte-Carlo runs are used.

In the forecast mode the initial slip configuration must correspond to a specific time at the beginning of the forecast period. This is done by subtracting the amount of slip released in the known large events before that time from the initial slip (corresponding to the fault strength) and then adding the slip accumulated after these events on appropriate cells. Peak ground acceleration (PGA) is calculated using an empirical attenuation function.

Data Processing

An earthquake catalog usually is available only for a comparatively short period and it has unequal degrees of completeness in various time periods and magnitude ranges. Even the well-instrumented regions can be considered completely documented only for the last 30 - 40 years. In order to obtain more than one event in each magnitude range the catalog data has to be extended to correspond to a time period several times longer than the return period of the characteristic event. This time is called simulation time. Also, the non-uniform quality of data corresponding to different time periods has to be accounted for.

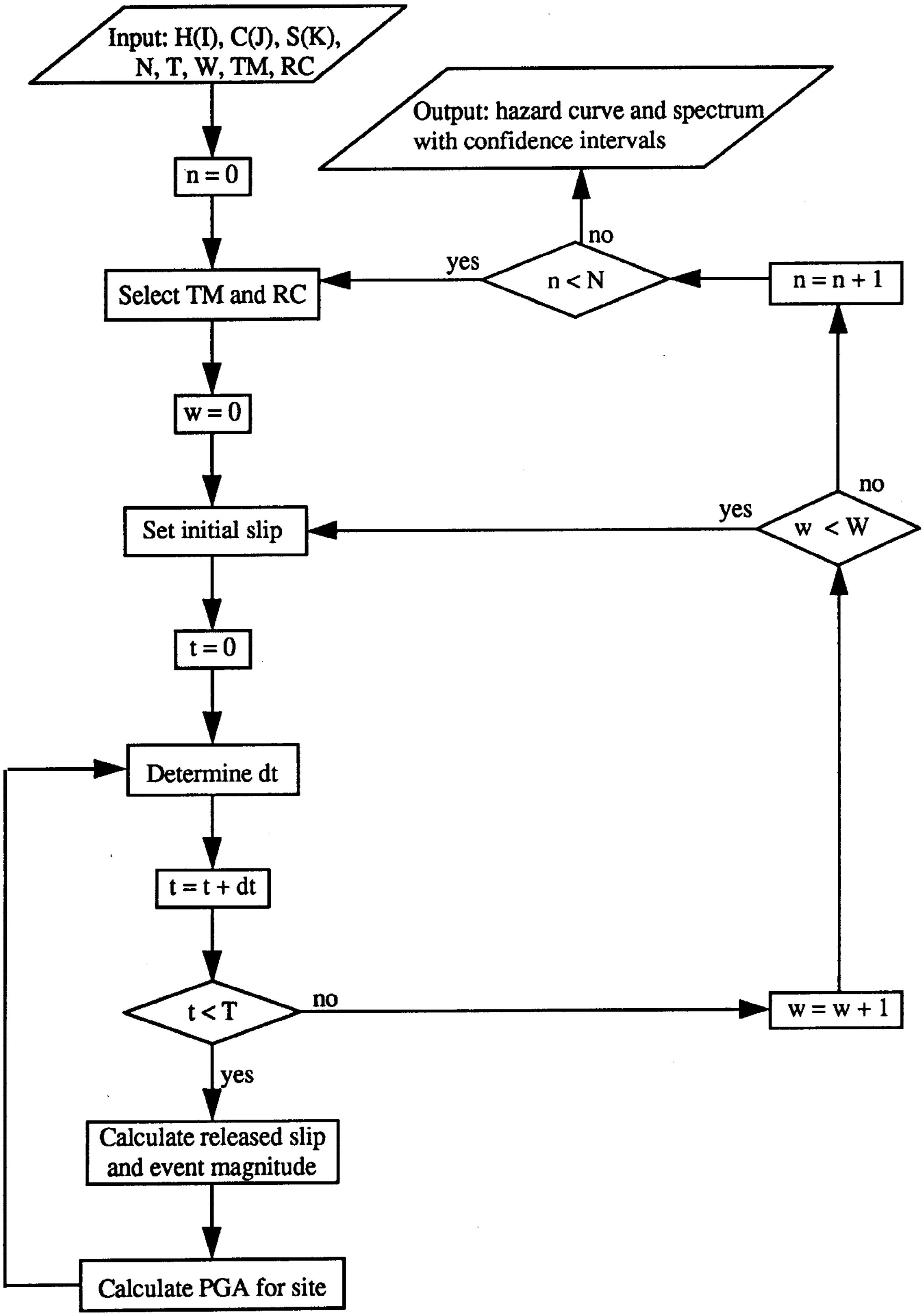

Fig. 2. Forecast Mode Mechanism.

A modified bootstrap method is used in this model to obtain a representative data sample over long time periods. First, magnitude ranges and corresponding time periods, which represent the best available data quality, are selected. For example, all large events and only recent small events from a catalog should be considered. Then, each of the selected sub-samples is bootstrapped (sampling with replacement) as many times as necessary to correspond to the simulation time. All the generated sub-samples are of the same quality and correspond to the same period (simulation time). They represent the final target sample with which the results of the simulation will be compared. Individual samples are developed for each segment since each segment parameters are different and have to be adjusted separately.

As it was already mentioned in the previous section, the simulation has to be carried out several times in order to get low variance on the estimated parameters. A new bootstrap sample is generated for each simulation cycle and confidence bounds on the parameters are calculated at the end of the simulation.

Application

The model is applied to the Northern portion of the San Andreas fault. This fault has been studied extensively and its behavior is well documented. The segmentation suggested by USGS Working Group, 1990 is used here. The fault is divided into three segments: North Coast (340 km), Mid-Peninsula (60 km) and Southern Santa Cruz Mountains (40 km). The cell length and depth are equal to 10 km which roughly corresponds to a magnitude 6 event (Wells and Coppersmith, 1994) in case the whole cell ruptures. Earthquake catalog provided by the National Geophysical Data Center of NOAA at Boulder, Colorado is used as the input to the model.

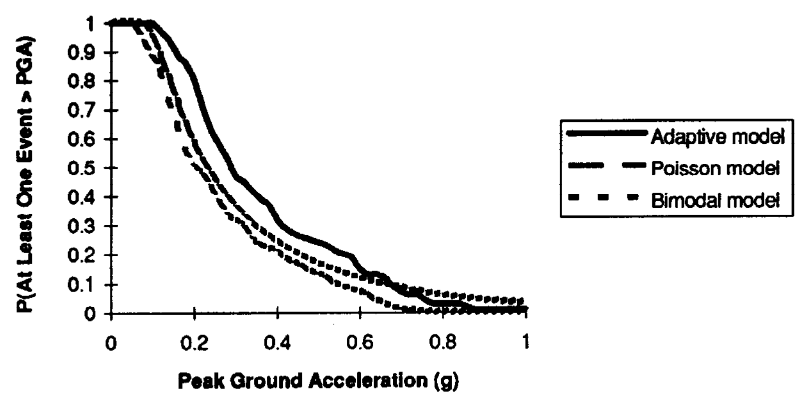

Fig. 3. Site hazard curves for the site (-122.4, 37.8) for 50 years.

The PGA-s are calculated according to the Boore, Joyner and Fumal (1993) attenuation law to estimate the site hazard. A preliminary site hazard curve generated by the presented model is shown on Fig. 3. along with the analogous curves obtained from the Kiremidjian and Shah (1975) Poisson model and the Lamarre, Townsend and Shah (1992) bimodal occurrence model.

CONCLUSIONS

An earthquake simulation and site hazard estimation model is developed that has the following features. Small to moderate events happen independently in time and space, since there is always some necessary amount of accumulated slip and the times to the next event are identically distributed for all the cells. The small amount of slip released in a small event is accumulated fast enough to allow another small event to occur at the same location. They appear to form a Poisson process which is known to adequately represent such events. In contrast, large events can only happen if there is necessary amount of slip (cannot be in small time after a large event) on the cell and if the release coefficient is close to one. This makes such events to be dependent in both time and space. Note, that different behavior of events of different sizes results from the same assumed physical processes and not from considering a particular stochastic process for each event type. Because of the modular structure of the model each class of the assumptions can be modified according to a better theory results, which makes the model very flexible.

This model is different from those currently available in that its parameters are adaptive. It allows for the estimation of the confidence intervals on the parameters using bootstrapping. Energy barriers provide characteristic segment behavior and also make it possible for several segments to rupture in a single event. These cascade events are simulated very rarely which corresponds to observations along many sources.

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