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EARTH PHYSICS

SEISMIC FORECAST USING GEOSTATISTICS

VALERIU GRECU, DORU MATECIUC

National Institute for R-D for Earth Physics, Bucharest – Magurele, C.P. MG-2, Romania
E-mail: val@infp.ro, dmateciuc@infp.ro.

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Abstract. The main idea of this research branch consists in the special way of constructing a new type of mathematical function as being a correlation between a computed statistical quantity and another physical quantity. This type of function called *position function* was taken over by the authors of this study in the field of seismology with the hope of solving – at least partially – the difficult problem of seismic forecast [1], [4].

The geostatistic method of analysis focuses on the process of energy accumulation in a given seismic area, completing this analysis by a so-called *loading function.* This function – in fact a temporal function – describes the process of energy accumulation during a seismic cycle from a given seismic area.

It was possible to discover a law of evolution of the seismic cycles that was materialized in a so-called *characteristic function.* This special function will help us to forecast the magnitude and the occurrence moment of the largest earthquake in the analysed area.

Since 2000, the authors have been evolving to a new stage of testing: *real – time analysis*, in order to verify the quality of the method. There were five large earthquakes forecasts.

Key words: aftershocks, geostatistics, earthquake prediction, seismic forecast, seismic cycle, seismicity.

1. INTRODUCTION

Disastrous phenomena have occurred during the whole mankind's history and they will also occur in the future, horrifying large human communities by their catastrophic effects. We are speaking about geophysical (large earthquakes, volcanoes, sudden changes of the climate), social (great wars, the disappearing of some civilizations), medical (big epidemic diseases) phenomena.

1.1. PROCESSES AND PHENOMENA

In nature, any physical, chemical, economical, political system evolves in time, accumulating energy or states of stress, specific to any evolution. This evolution will be further below called *process*. The different rates of the stress accumulation or internal energy make that different kind of processes be very slow, such as astrophysical processes, or very fast (nuclear processes). Between these extremes there are some special kinds of processes, described by an average rate of evolution, with high impact over the population (geophysical, political, social processes). Inside any kind of process there are systems that have different mean rate of accumulation.

In order to limit our debate only to seismology, we may observe that in the same geological unit there can exist different adjoining seismic areas characterized by different rates of energy accumulation. This makes a lack of poise appear in the state of stress between neighbouring areas. When these lacks of poise reach some critical values, an energy discharge will occur. This energy discharging could be more or less dangerous. We will call this *dangerous phenomena*. Analysing the phenomena from seismology point of view it can be observed that, in a given seismic area, a process of energy accumulation takes place along a large interval of time (tens or hundreds of months) in order to be discharged in the final stage by a large earthquake. This interval of time will be called as *seismic cycle*. Seismic cycles, together with the parameters that characterize them will be debated in the following sections.

It can be said that the entire universe could be considered as being made of a multitude of evolving systems, in the shape of processes (from cosmic processes up to microbiological ones), every process being characterized by a beginning and an end. In other words, every physical, chemical, biological, etc. process lasts a finite interval of time and ends through a phenomenon, often disastrous, starting at the same time a new evolution process. It results *a cause – effect relation*, the cause being represented by the evolution process and the effect being the discharging phenomenon that ends the evolving process. It is interesting to observe that the disastrous phenomena that end the evolving processes are more spectacular by the effects they produce, entering most of the cases in the collective memory. That is why the history confined only the phenomena accompanied by the disastrous effects, neglecting in all cases the process which generated these phenomena (large earthquakes, volcanoes, wars, etc.). The terrifying character of these phenomena determined the scientists to try to predict the future occurrence of some similar natural disasters. What is common to all these prediction studies is the fact that at the beginning all scientists looked for special signs, clews that could possibly be correlated with the future disastrous phenomena. Nowadays terminology calls all these signs as *precursory phenomena*. The fact that in most of the cases such an approach in the prediction researches did not lead to the anticipated results it is easy to be explained by the scientists' tendency to focus only on the phenomenon itself, neglecting the process which generated the respective phenomenon [4]. In this way, it becomes easy to understand that, without the study of the process of energy accumulation, it is almost impossible to estimate the magnitude of the disastrous effect.

1.2. EARTHQUAKE PREDICTION OR SEISMIC FORECAST?

In a given seismic area, a process of energy accumulation takes place, process that can last for a very long interval of time (tens, hundreds or even thousands of months). At the moment at which the accumulated energy outruns some limits a phenomenon of energy discharging, called earthquake, will occur. The larger the discharged energy is, the more disastrous the effects will be.

The history mentions large earthquakes that affected huge territories, having a great impact over the human communities that lived in respective areas. So, the scientists' desire to predict the future large earthquakes appears to be entirely justified.

We can define two different ways in order to estimate the parameters of the disastrous earthquake in a given seismic area.

a) focusing the attention only on the discharging phenomenon (large earthquake) together with a complete neglect of the process of energy accumulation;

b) studying the seismic energy accumulation process.

a) By the unilateral study of the energy discharging phenomenon (i.e., disastrous earthquake), the hope that in the future, more or less far off, the prediction of the magnitude and the moment of occurrence of the next earthquake will be successful, was created. This hope was so strongly induced in the people's mind that even today, after tens of years of failures, it is still believed that in a plausible future a method that specifies the day and the hour of the future disastrous earthquake, will be discovered. All the methods used to achieve these objectives could be framed in *the seismic precursory searching* category. In all these methods one can talk about *the earthquake prediction* because they propose themselves the localization in time of a punctual event (i.e., a large earthquake which will occur in the future). It is easy to understand that all these methods failed more or less in spite of the insistence they were promoted with [2, 3, 5].

Analysing only the final part of a process it will never be obtained useful information about the amplitude of the loading process, rate of energy accumulation and therefore it becomes impossible to obtain any information concerning the magnitude of the final discharging phenomenon. Further below it will be shown that the amplitude of the discharging phenomenon (the magnitude of the next large earthquake) is determined by the parameters of the charging process and the moment of the occurrence of the discharging phenomenon depends on the mean rate of energy accumulation.

It is relevant that all the prediction methods from this category do not offer much information about the amplitude of the discharging phenomenon precisely because these methods neglect the charging process.

b) In the last years a new kind of methods have tried to match the process of energy accumulation: the *b* value, analyse of seismic gaps and geostatistic analysis.

If the obtained results offered by these methods are still far from our expectations this could be explained by the qualities and the deficiencies of the respective methods. Anyway, theoretically speaking, these kinds of analyses create the premises for obtaining useful information about the next large earthquake, in a given seismic area, precisely because these methods analyse the cause of the occurring of these large earthquakes: the charging process.

These methods propose themselves to estimate the future evolution of the charging process, therefore in this case we can speak about *a seismic forecast*.

Beginning with the next section the geostatistical analysing method will be described. Because this method could be new for some of the readers, we will present in section 11 the analyses for five seismic cycles ended by large earthquakes:

Taiwan (Chi – Chi)	1999	$M_S = 7.7$
El Salvador	2001	$M_S = 7.8$
Peru	2001	$M_S = 8.2$
Fiji Islands	2002	$M_S = 7.6$ & $M_S = 7.7$
Kuril Islands	1994	$M_S = 8.1$

Each of these cycles presents different and interesting situations for the study of the seismic cycles.

2. SEISMIC CYCLES

In a given seismic area, the seismicity evolves in the shape of charging – discharging cycles, known as *seismic cycles*. A general example of such seismic cycles is presented in Fig. 1.

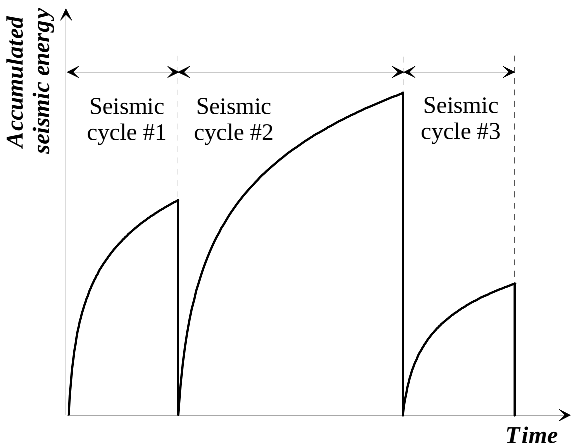


Fig. 1 – Seismic cycles from a given seismic area.

A seismic cycle can be defined by an interval of time in which a quantity of energy is accumulated in order to be discharged in the end of the cycle by a disastrous earthquake. In Fig. 2 we represented a single seismic cycle in order to analyse the parameters which define it. Taking into consideration the fact that the cycle begins its evolution at the moment t_0 and ends it at the moment t_f we can easy define the length of the seismic cycle as:

$$L = t_f - t_0 \,. \tag{1}$$

From a practical point of view we will always consider $t_0 = 0$, so the length of the cycle can be rewritten as:

$$L = t_f \,. \tag{2}$$

At the end of the cycle, the accumulated energy will be discharged by a disastrous earthquake. In many cases this energy is discharged not only by a main shock but by two or even three shocks having comparable sizes.

The quantity of the discharged energy translated in terms of magnitude of an earthquake will be designated by M_f (magnitude of the final earthquake). When a seismic cycle is ended by a single shock (called *final earthquake*) the magnitude M_f will represent the magnitude M_S of the final earthquake. In the cases in which the seismic cycle is ended by two or three shocks, the magnitude M_f will represent the magnitude of an earthquake which discharges the same energy equal to the sum of energies discharged by the final shocks. In section 11 we will meet seismic cycles ended by single shocks (*Peru*, *Taiwan and El Salvador* seismic cycles) and also a cycle ended by two shocks (*Fiji* seismic cycle).

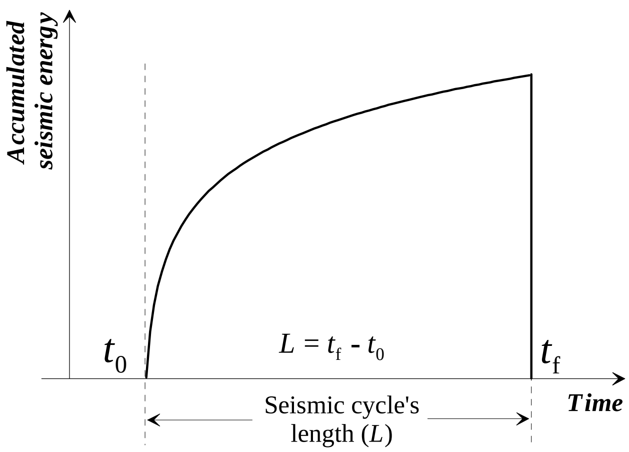


Fig. 2 – A single seismic cycle. t_0 - the beginning of the seismic cycle, t_f - the end of the seismic cycle, L - the length of the cycle in months.

The term *final earthquake* was chosen to define the earthquake which ends the cycle unlike the earthquakes (hundreds or even thousands) which occur during the cycle, called as *ordinary earthquakes*. The final earthquake has some interesting properties:

- *it is always the largest earthquake which occurs in a given seismic cycle;*
- *this earthquake ends the evolving seismic cycle, starting in the same time a new seismic cycle.*

It is obvious that the main goal of any method for the seismic forecast is represented by the estimation in real – time of the parameters L (the length of the seismic cycle) and M_f (the magnitude of the earthquake which will end the cycle). The geostatistical method is built as to be able to estimate both the length L and the magnitude M_f at every moment t_i of the evolving cycle.

It will be seen in the next sections that these two parameters can be estimated and these estimations become better and better in the last part of the cycle's evolution. To advance in our analysis we need two working hypothesis:

1. *every final earthquake discharges the entire accumulated energy during the seismic cycle from the analysed area;*
2. *the frequency and the magnitudes of the ordinary earthquakes that occur during the evolving cycles are managed by the rate of energy accumulation.*

3. VIRTUAL SEISMIC CYCLES

Let us now consider a given seismic area in which a seismic cycle evolves. This cycle started at the moment t_0 and will be ended at the moment t_f by a final earthquake having the magnitude M_f. This cycle is characterized by its length L and by the magnitude of its final earthquake M_f. It will be seen that these two parameters are determined by the magnitudes and by the position in time of the ordinary earthquakes which occur during the evolution of the cycle. We will call this cycle as *real seismic cycle*.

We will introduce a new kind of cycle, necessary in the future development of the geostatistical analysis, the so-called *"virtual seismic cycle"*.

Let us now consider a moment t_i inside the interval $[t_0, t_f]$:

$$t_i \in [t_0, t_f]\,. \tag{3}$$

We will construct a new interval of time, as follows:

$$[t_0, t_i]\,. \tag{4}$$

If we attach to this interval of time the real string of ordinary earthquakes which occurred during that particular interval of time, we will obtain a *virtual seismic cycle* ($\boldsymbol{V}_i$).

The parameters which characterize this virtual seismic cycle will be:

$$\begin{aligned} &l_i = t_i - t_0 && \text{the length of the (i) } \textit{virtual seismic cycle}; \\ &M_{max}(t_i) && \text{the magnitude of the "final earthquake" which could end the i}^{th}\ \textit{virtual seismic cycle}. \end{aligned} \tag{5}$$

This magnitude, $M_{max}(t_i)$, represents the magnitude of a virtual earthquake whose occurrence would discharge the whole energy accumulated in the interval $[t_0, t_i]$. Geostatistics is able to compute the parameter $M_{max}(t_i)$ considering as input data the magnitudes of ordinary earthquakes occurred in the interval of time $[t_0, t_i]$.

Let us now consider an increasing string of values t_i which tends to t_f. According to this, we may build an increasing string of virtual seismic cycles ($\boldsymbol{V}_i$) of the type $[t_0, t_i]$. It is easy to observe that:

$$\begin{aligned} L &= \lim_{i \to n} \left(l_i \right) \\ M_f &= \lim_{i \to n} \left(M_{max}\left(t_i \right) \right) \end{aligned} \tag{6}$$

where L is the length of the real seismic cycle, M_f is the magnitude of the final earthquake that will end the real seismic cycle, l_i are the lengths of the virtual seismic cycles ($\boldsymbol{V}_i$) and $M_{max}(t_i)$ are the magnitudes of the final earthquakes which, theoretically, could end these virtual seismic cycles.

Thus, we can interpret a real seismic cycle as a superior limit of an increasing string of *virtual seismic cycles*.

4. SEISMIC POTENTIAL FROM A GIVEN SEISMIC AREA

In a given seismic area, a quantity of energy is accumulated in time. Thus, this area becomes more and more dangerous from the seismic activity point of view. This danger index is given by the quantity of accumulated energy and can be described by a function of time. The larger quantity of accumulated energy means a bigger risk of a large earthquake occurrence.

It is interesting to estimate this danger in every moment of the seismic cycle in order to prepare the institutions of the state for a common action.

The computed parameter $M_{max}(t_i)$ (*the final earthquake* for the virtual seismic cycle $\boldsymbol{V}_i$) estimates the accumulated energy since the beginning of the cycle until the moment t_i. This parameter gives us the magnitude of the largest earthquake which may occur in the interval of time $[t_0, t_i]$.

For example, for a particular seismic cycle evolving in a given seismic area we have already computed after 100 months of the cycle's evolution the value $M_{max}(100) = 7.0$. This value told us that the largest ordinary earthquake which may occur in the first 100 months would be anyway smaller than $M_S = 7.0$. In other words it can be said, at least from a theoretical point of view, that an earthquake larger or equal with the one having a magnitude as large as $M_S = 7.0$ is out of question.

From a practical point of view the largest earthquake which can occur in that interval of 100 moths is much more smaller. It is obvious that on the moment t_i = 100 months this index of danger is not very high for a seismic area from, let's say, *the Ring of Fire* (where earthquakes as large as M_S = 8.7 may sometimes occur), but could be very high for European countries and the USA.

Going on with our analysis we may find, for example, $M_{max}(200) = 8.0$. This value indicates us that the area under analysis has already become a very dangerous one, because ordinary earthquakes as large as M_S = 7.5 can occur. We may note here that such large earthquakes are always very disastrous in any area.

It can be said that the area under analysis has a bigger seismic potential at the moment t = 200 months comparing with the seismic potential at the moment t = 100 months.

As a conclusion, we may say that the computed "final earthquake for virtual seismic cycles", $M_{max}(t_i)$ represents in fact an estimation of the danger index at every moment t_i, for the analysed area.

Tables 3, 5, 7, 9, 11 from section 11 shows us (column #4) the computed values $M_{max}(t_i)$ for different peculiar moments of some seismic cycles' evolution.

5. LOADING FUNCTION

In this paper we will often use the terms *future* and *past*. In order to avoid confusions we will establish a convention.

Let us consider a moment t_i as follows:

$$t_i \in [t_0, t_f] \tag{7}$$

All the parameters computed for any moments $t < t_i$ will be denominated as *past in relation with* t_i.

All the estimations made for every $t > t_i$ will be denominated as *future in relation with* t_i.

From section 4 we understood that, computing the parameters $M_{max}(t_i)$ for every t_i's we estimate in fact the danger index of the analysed seismic area. We also stated that this parameter, $M_{max}(t_i)$, gives us the superior limit of the magnitudes of the ordinary earthquakes occurred in the interval of time $[t_0, t_i]$. Actually this information has no practical signification as much as, in the moment t_i when we computed the parameter $M_{max}(t_i)$, we have already known the magnitudes of the ordinary earthquakes that have occurred in the interval $[t_0, t_i]$. Much more, these magnitudes represent the input data for computing the value $M_{max}(t_i)$.

Thus, it would be interesting for us to be able to estimate in the future the seismic potential $M_{max}(t_j)$ in relation with t_i (for any $t_j > t_i$) in order to know the superior value of the ordinary earthquake's magnitude in the following months from t_i. In order to do it, we need to build the so-called *loading function* of the cycle.

Computing the seismic potential of the analysed area $M_{max}(t_i)$ for every moment t_i we will obtain a string of pairs of values:

$$t_i \Rightarrow M_{max}(t_i). \tag{8}$$

Plotting these values, in Ox-axis representing t_i and in Oy-axis the computed values $M_{max}(t_i)$, we will obtain a curve that gives us an image of the cycle's evolution. Fitting these points we will obtain *the loading function*, which always has a logarithmic shape:

$$M_{max}(t) = a \times \log_{10}(b \times t), \tag{9}$$

where a, b are two constant values computed from the best-fit function. These two constant values are characteristic for the evolution of each seismic cycle. For every *virtual seismic cycle* $\boldsymbol{V}_i$ we will find a similar function:

$$M_{max}(t) = a_i \times \log_{10}(b_i \times t), \tag{10}$$

where a_i, b_i are also two constant values which characterize every virtual seismic cycle $\boldsymbol{V}_i$. Having *the loading function* of a virtual seismic cycle $\boldsymbol{V}_i$ (with the length $l_i = t_i - t_0$) we will be able to extrapolate this function in the future in relation with t_i and to obtain the next values $M_{max}(t_j)$, $t_j > t_i$ and then, to forecast the seismic potential in the next months from t_i.

Thus, we will be able to find the superior magnitudes for the ordinary earthquakes that will occur in the future.

Comment. The extrapolation process requires a special attention because it asks as an essential condition of obtaining realistic results the necessity that in the future the process will need to evolve in the same parameters as in the past. Even if this condition is fulfilled in many cycles, there will still be some other situations in which an unexpected earthquake will drastically change the evolution of the cycle. In section 11 we will find such special cases and the encountered anomalies will be further discussed.

6. MEAN RATE OF ACCUMULATION PROCESS

A seismic cycle represents an evolving process in which a big quantity of energy is accumulated being discharged by the final earthquake. Analysing a large number of seismic cycles we will observe that this accumulation process is not uniform in its entire evolution. Every seismic cycle is more violent in its first part of the evolution and slower in the second part. Much more, the acceleration and the deceleration in the accumulation process can be noted in many cycles.

It results that a mean rate of evolution of the accumulation process must be defined, in order to evaluate the seismic cycle from a dynamical point of view.

Because the loading function has a logarithmic shape, showing us that the process of accumulation is not uniform, we will divide the length of the cycle L in small, equal intervals for which a uniformity of the process can be expected.

In Fig. 3 we graphically describe this process of quantifying. Considering that, on these small intervals (? t = 1 month) the process of accumulation can be considered as uniform, we will define *the rate of evolution* on this small interval as:

$$S_{\mathrm{i}} = \frac{M_{\max}\left(t_{\mathrm{i}+1}\right) - M_{\max}\left(t_{\mathrm{i}}\right)}{t_{\mathrm{i}+1} - t_{\mathrm{i}}}. \tag{11}$$

Having n equal intervals in a whole seismic cycle we may compute the mean rate of accumulation process as:

$$S_{\mathrm{a}} = \frac{\sum_{\mathrm{i}=1}^{n}\left(S_{\mathrm{i}}\right)}{n}. \tag{12}$$

This parameter characterizes the evolution of the accumulation process at the level of the entire seismic cycle. According to the values of this parameter we shall encounter violent cycles, (S_{a} very big) or, on the contrary, slow cycles (S_{a} very small.

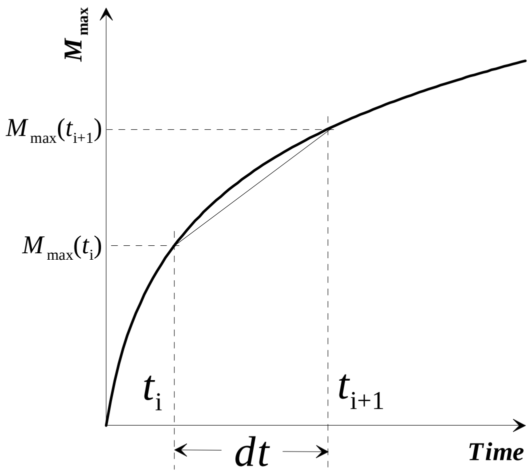


Fig. 3 – The quantifying of the loading function.

Together with the parameters L and M_{f} which characterize the seismic cycle from a statical point of view, S_{a} parameter characterizes the seismic cycle from a dynamic point of view. So, until now, we found three parameters which characterize a given seismic cycle: L, M_{f}, S_{a}.

It is obvious that the virtual seismic cycles $\boldsymbol{V}_{\mathrm{i}}$ can also be characterized by a mean rate of accumulation, computed on the length of the virtual cycle ($l_{\mathrm{i}} = t_{\mathrm{i}} - t_0$).

We will note this mean rate for every virtual seismic cycle as $S_{v,i}$, so, this kind of cycles will be characterized by the following parameters: l_i, $M_{max}(t_i)$, $S_{v,i}$.

We will later see that the virtual cycles will accept another new parameter useful in the process of real cycle's length forecast.

7. CHARACTERISTIC FUNCTION

During the analysis of a seismic cycle from a given seismic area an obsessive question appears. Always, it seems that the answer of that question can help the scientists to advance into the seismic forecasting field. Let us suppose a seismic cycle from a given seismic area. This cycle will have, for example, a length L = 200 months and will be ended by a final earthquake of magnitude M_f = 7.5. The question is:

Why does this cycle end after 200 months by a final earthquake characterized by $M_f = M_{max}(200) = 7.5$ *and the cycle does not continue to end after 300 months (as an example) by a final earthquake of magnitude* $M_f = M_{max}(300) = 7.5$? *Why, on the contrary, the cycle did not end after, let's say, 100 months by a final earthquake having the magnitude* $M_f = M_{max}(100) = 7.5$?

It is possible that the cycle was ended after L = 200 months by a final earthquake of magnitude $M_{max}(200)$ = 7.5 by chance. As a conclusion, the occurrence of that final earthquake of magnitude $M_{max}(200)$ which will end the cycle after L = 200 months represents a random phenomenon. On this hypothesis, the seismic forecast (and much more, the earthquake prediction) becomes extremely difficult.

Another hypothesis can be imagined in which a strange external phenomenon will trigger the final earthquake that ends the cycle's evolution. On this hypothesis, any forecast method will ask for searching that external phenomenon in order to have any chance of success. However, it is necessary to wonder what kind of such an external phenomenon can explain these values (L and $M_{max}(L)$) as much as after tens of years of researches in the field of seismology, no scientist had observed it yet.

Last, but not least, another exciting hypothesis can explain the end of a seismic cycle. It is possible that an internal physical law (specifically for seismology) manages the evolution of the seismic cycle. It is obvious that this hypothesis gives us some hopes that seismic forecast could be performed.

In order to verify this third hypothesis, the authors analysed 22 exhausted cycles from some countries located in different areas of *The Ring of Fire*: Japan, Philippines, Indonesia, New Zeeland, Chile, Peru and Bolivia. For every seismic cycle there was built the loading function, then it was computed the mean rate of accumulation S_a. In Table 1 it can be found a number of 22 pairs of values, every pair of values representing an exhausted analysed seismic cycle.

Table 1

Examples of exhausted seismic cycles

No.	L (months)	S_a (units of magnitude /month)	No.	L (months)	S_a (units of magnitude /month)	No.	L (months)	S_a (units of magnitude /month)
1	100.9	0.029926	9	197.2	0.017417	17	287.4	0.012046
2	108.8	0.029735	10	197.3	0.017417	18	296.0	0.010887
3	113.0	0.029452	11	198.6	0.017983	19	316.3	0.009606
4	143.0	0.023957	12	201.4	0.017111	20	318.7	0.009175
5	154.4	0.021730	13	209.0	0.017907	21	343.6	0.007768
6	176.8	0.020128	14	212.3	0.016047	22	463.0	0.002543
7	186.2	0.018923	15	225.0	0.016201			
8	189.6	0.019747	16	232.6	0.015500			

It is easy to observe that an inverse ratio relation between the length of the seismic cycle and the mean rate of accumulation values can be established.

To visualize this correlation there were plotted in Fig. 4 all these points, *Ox*-axis referring to the mean rates of accumulation and *Oy*-axis to the lengths of the seismic cycles. Every point from this plot represents an exhausted seismic cycle. Fitting these points it can be found the so-called *characteristic function*:

$$L = c \times \exp\left(d \times S_{\mathrm{a}}\right), \tag{13}$$

where c and d represents two parameters computed during the fitting process.

In our case the parameters c and d have the following values: c = 526.938928 months, d = –54.078422. It results that, for seismic areas located on *The Ring of Fire* the characteristic function has the form:

$$L = 526.938928 \times \exp\left(-54.078422 \times S_{\mathrm{a}}\right). \tag{14}$$

From a geological point of view the common characteristic of these seismic areas consists in the fact that the process of energy accumulation is managed by the subduction phenomenon. A few comments about the characteristic function can be made.

7.1. The correlation between the length of the seismic cycles and their mean rates of accumulation demonstrates that the process of energy accumulation is managed by clear internal laws which make a seismic cycle to be ended when its mean rate of accumulation and the length verify (14).

Returning to our example it can be said that the respective cycle was finished after 200 months because on that moment its mean rate of accumulation, $S_a(200)$ and the length of the cycle (L = 200 months) verify (14). During the cycle's evolution the mean rate of accumulation is decreasing meanwhile the interval of time since the cycle's beginning is increasing. So, we can observe that there is only one pair of values t_f, $S_a(t_f)$ when (14) is verified. On that time, a final earthquake will end the cycle's evolution discharging the entire energy that has accumulated since the beginning of the process of seismic energy accumulation.

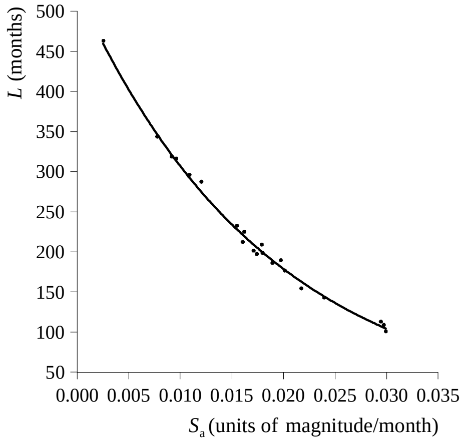


Fig. 4 – The characteristic function.

7.2. If the moment of the final earthquake occurrence t_f is clearly determined by the evolution of the accumulation process (expressed by its mean rate of accumulation) what can we say about the moments of occurrence for the ordinary earthquakes and their own magnitudes? During a cycle's evolution a few hundreds of ordinary earthquakes may occur. Every ordinary earthquake can be considered as a seismic event characterized by two parameters:

$$E_g = E_g\left(t_i,\, M_i\right), \tag{15}$$

where E_g denotes an ordinary earthquake, t_i represents its moment of occurrence and M_i its magnitude.

It results that a seismic cycle represents a real string of events which occur at the moments t_i having the magnitudes M_i. Every interchange inside this string will transform our real string of events into an artificially one. Computing its loading function (for this artificial string of events) other parameters will be found (9).

Thus, it will result a different value for the mean rate of accumulation. According to (14) this artificially cycle will have other length compared with the real value L. In this way we may notice that from all possible combinations of t_i and M_i there is only one combination able to give us the length L: the real combination. So, the real string of values is always unique. We also may observe that the moment of occurrence t_i and the magnitude M_i for every ordinary earthquake which occurs during a seismic cycle is strongly determined by the accumulation process**.** The process of occurrence of the ordinary earthquakes is not a random one and any attempt to analyse this process by a stochastic analysis has no reason.

7.3. The loading function, (9), section 5, characterizes a seismic cycle. Computing the parameters *a* and *b* we will be able to distinguish between two seismic cycles even if these cycles occurred in the same seismic area or in different seismic areas. Computing the mean rate of accumulation (using parameters *a* and *b* of the loading function but also the length of the cycle) we can introduce an *order relation* in the multitude of seismic cycles. So, we must speak about slow seismic cycles (very small values for S_a), moderate seismic cycles or violent seismic cycles (very big values for S_a). It is very interesting to observe that all kinds of seismic cycles can be encountered in the same seismic area.

Unlike the loading function, which describes a single seismic cycle, the characteristic function refers to a lot of seismic cycles that occur on large geological units (i.e., *The Ring of Fire*). A more interesting comment on this subject will be found in section 14.

8. STATUS PARAMETER

In this section, a new useful parameter will be defined: *the status parameter*.

Let us consider a real seismic cycle that evolves in a given seismic area. The evolving cycle is characterized by the following parameters:

• L – the length of the seismic cycle;
• M_f – the magnitude of the final earthquake;
• S_a – mean rate of energy accumulation.

We have already defined in section 3 the so-called *virtual seismic cycles* as follows: for every $t_i \in [t_0, t_f]$, a *virtual seismic cycle* represents the interval of time of length $l_i = t_i - t_0$ together with the ordinary earthquake that occurred inside this interval of time. These virtual cycles are described by their own parameters:

• l_i – the length of the virtual seismic cycle
• $M_{max}(t_i)$ – the virtual seismic cycle's "final" earthquake;
• $S_a(l_i)$ – the virtual seismic cycle's mean rate of energy accumulation.

For every virtual seismic cycle it can be built a loading function. Let us suppose that this real cycle evolves in a region for which the characteristic function is known:

$$L = c \times \exp\left(d \times S_a\right). \tag{16}$$

Using the characteristic function we are now able to estimate the length of the virtual seismic cycle:

$$L_x\left(l_i\right) = c \times \exp\left[d \times S_a\left(l_i\right)\right]. \tag{17}$$

It is obvious that this estimation differs from the real value (l_i) of the virtual cycle. As a general rule, this estimation $L_x(l_i)$ is bigger than the value of the virtual cycle. It results that the estimation made under these circumstances is bad (even very bad in some special cases). In order to quantify “how bad” this estimation is, we have to compute the so called *status parameter* of the virtual seismic cycle:

$$x\left(l_{\mathrm{i}}\right)=\frac{L_{\mathrm{x}}\left(l_{\mathrm{i}}\right)}{l_{\mathrm{i}}}. \tag{18}$$

For an increasing string of values $t_{\mathrm{i}} \in [t_0, t_{\mathrm{f}}]$

$$t_{\mathrm{i}} < t_{\mathrm{i+1}}, \tag{19}$$

we can build a string of increasing virtual cycles having the lengths:

$$\begin{aligned} &l_{\mathrm{i}} < L, \\ &l_{\mathrm{i}} < l_{\mathrm{i+1}}. \end{aligned} \tag{20}$$

So, every virtual seismic cycle can be characterized by the following parameters:

- l_{i} – the length of the virtual seismic cycle;
- $M_{\max}(t_{\mathrm{i}})$ – the virtual seismic cycle’s “final” earthquake;
- $S_{\mathrm{a}}(l_{\mathrm{i}})$ – the virtual seismic cycle’s mean rate of energy accumulation; (21)
- ?(l_{i}) – the virtual seismic cycle’ *status parameter*.

This string of *status parameters* ?(l_{i}), each one characterizing a virtual seismic cycle, has a number of interesting properties. For a given real seismic cycle, the string of *status parameters* can have the specific features enclosed in one of the following two groups of special characteristics:

Group #1

$$\begin{aligned} &x\left(l_{\mathrm{i}}\right)>1, \text{ for every } l_{\mathrm{i}}<L \\ &\frac{\mathrm{d}x\left(l\right)}{\mathrm{d}l}<0 \\ &\lim_{l_{\mathrm{i}}\to L}\left[x\left(l_{\mathrm{i}}\right)\right]=1.0; \end{aligned} \tag{22}$$

Group #2

$$\begin{aligned} &x\left(l_{\mathrm{i}}\right)<1, \text{ for every } l_{\mathrm{i}}<L \\ &\frac{\mathrm{d}x\left(l\right)}{\mathrm{d}l}>0 \\ &\lim_{l_{\mathrm{i}}\to L}\left[x\left(l_{\mathrm{i}}\right)\right]=1.0. \end{aligned} \tag{23}$$

Because of its specific features, the status parameter gives us useful information in the forecasting process. Let us consider an evolving real seismic cycle and the moment t_i, when the last analysis was already made. So, the virtual seismic cycle, $\boldsymbol{V}_i$, having the length $l_i = t_i - t_0$, must be the longest virtual cycle ever built for this real seismic cycle. However, we do not know yet the values t_f and L at the moment t_i of the analysis. Computing the status parameter ?(l_i) for the moment t_i we will be able to estimate how long the interval ? $l_i = t_f - t_i$ should be. This estimation is possible due to (22, 23) specific features of the status parameter which specify: *the closer the computed status parameter ?(*l_i*) to the limit value* ?(L) = 1.0 *is, the smaller interval of time remains until the final earthquake will occur*. The reciprocal statement is also valid.

9. FORECAST FUNCTION

Analysing a real seismic cycle from a given seismic area for which a characteristic function is already built, we will construct a string of increasing virtual seismic cycles:

$$l_1 < l_2 < l_3 < \ldots < l_i < \ldots . \tag{24}$$

Every virtual seismic cycle is characterized by its status parameter ? (l_i). So, we will obtain new strings of values, as follows:

$$x\left(l_1\right) > x\left(l_2\right) > x\left(l_3\right) > \ldots > x\left(l_i\right) > \ldots \tag{25}$$

for the *Group #1* of the specific features or:

$$x\left(l_1\right) < x\left(l_2\right) < x\left(l_3\right) < \ldots < x\left(l_i\right) < \ldots \tag{26}$$

for the *Group #2* of the specific features. In both cases we may write:

$$\lim_{l_i \to L}\left[x\left(l_i\right)\right] = 1.0 . \tag{27}$$

Attaching the values ? (l_i) to the values l_i, $\left(\xi\left(l_i\right) \leftrightarrow l_i\right)$, we may construct the so-called *"forecast function"*. If this function can be described by elementary functions the extrapolation operation can be performed and we will now be able to estimate the length of the virtual cycle for which ? = 1.0. We have already shown that the virtual cycle characterized by ? (l_j) = 1.0 represents just the real seismic cycle and l_j is called an estimation of the real seismic cycle's length ($L_{est} = l_j$).

Every virtual cycle, especially in the last part of the cycle's evolution, will enrich the forecast function with a new point and the extrapolation will be more realistic. For every virtual cycle we will estimate the length of the real seismic cycle and these estimations will be more and more realistic when l_i is closer to L.

10. FINAL EARTHQUAKE'S MAGNITUDE ESTIMATION

In the previous section we concluded that, by analyzing a virtual seismic cycle $\boldsymbol{V}_{\mathrm{i}}(l_{\mathrm{i}})$ the length of the real seismic cycle $L_{\mathrm{est}}(l_{\mathrm{i}})$ can be estimated using only the information found in the interval $l_{\mathrm{i}} = t_{\mathrm{i}} - t_0$ and the characteristic function.

For every virtual seismic cycle it can be constructed its loading function:

$$M_{\max}(t) = a_{\mathrm{i}} \times \log_{10}(b_{\mathrm{i}} \times t), \tag{28}$$

where a_{i} and b_{i} represent two constants obtained during the fitting operation. For every virtual seismic cycle it was estimated the length of the real cycle $L_{\mathrm{est}}(l_{\mathrm{i}})$. Supposing that the real seismic cycle will evolve on the same parameters until its end we would be able to estimate the magnitude of the final earthquake as follows:

$$M_{\mathrm{est}}(l_{\mathrm{i}}) = a_{\mathrm{i}} \times \log_{10}\left[b_{\mathrm{i}} \times L_{\mathrm{est}}(l_{\mathrm{i}})\right]. \tag{29}$$

The supposition that the cycle will evolve on the same parameters typically for the virtual seismic cycle $\boldsymbol{V}_{\mathrm{i}}(l_{\mathrm{i}})$ is not always fulfilled. But the failure to execute this supposition will introduce some small errors in the future estimations. These errors are not so big, as we can see in Tables 3, 5, 7, 9, 11 from section 11.

From the authors' experience it can be said that the estimations for the final earthquake's magnitude, $M_{\mathrm{est}}(l_{\mathrm{i}})$, are better than the estimations for the length of the seismic cycle.

11. EXAMPLES

In this section it can be found the analysis of five seismic cycles that generated large final earthquakes in different seismic areas.

For every seismic cycle there will be presented the followings:

- a map of the analysed area. On this map there are plotted all events having $M_S > 5.0$ beginning with 1973;
- a table containing the corner coordinates of the analysed area;
- a graph in which there are described the main seismic events occurred during the analysed cycle;
- a table containing the entire analysis for each seismic cycle;
- a graph in which the loading function is represented;
- a graph in which the forecast function is described;
- a comment regarding the evolution of the cycle and the quality of the analysis.

Every table containing the analysis for the seismic cycle will be structured as follows:

Column #1 current number;
Column #2 the moment t_i of the analysis;
Column #3 the length of the virtual seismic cycle: $l_i = t_i - t_0$;
Column #4 seismic potential estimation $M_{max}(t_i)$;
Column #5 status parameter ?(t_i);
Column #6 real seismic length estimation $L_{est}(t_i)$;
Column #7 the year and the month when the real seismic cycle is expected to be ended;
Column #8 final earthquake magnitude estimation $M_{est}(t_i)$.

Every row represents a virtual seismic cycle.

11.1. TAIWAN SEISMIC CYCLE ANALYSIS

On the 20th of September, 1999 a devastating earthquake (also known as *Chi – Chi* earthquake) struck Taiwan. Its magnitude was M_S = 7.7 (NEIC), M_W = 7.7 (HRV). At least 2,400 people were killed and over 8,700 were injured, 82,000 housing units were damaged and 100,000 people were left homeless. The damages were estimated at 14 billion USD.

In Fig. 5 it was represented the area under analysis with the earthquakes (M_S > 5.0) that have been recorded since 1973.

In order to analyse the seismic cycle, whose final earthquake was represented by the *Chi – Chi* event there was selected an area enclosed into a polygon with the following corner coordinates (Table 2):

Table 2

Seismic zone for *Taiwan* earthquake

No	Latitude	Longitude
1	23.2^0 N	119.8^0 E
2	26.0^0 N	122.1^0 E
3	25.1^0 N	123.5^0 E
4	23.8^0 N	122.6^0 E
5	22.7^0 N	120.4^0 E

The analysed seismic cycle started on the 14th of September, 1996, after an earthquake (M_S = 7.5) which ended the previous seismic cycle. In Fig. 6 there were represented the most important seismic events occurred during this cycle. Inside this cycle, unlike other seismic cycles, there were no significant recorded events.

The analyse of the seismic cycle can be found in Table 3.

The *loading* and the *forecast functions* are represented in Figs. 7, 8, respectively.

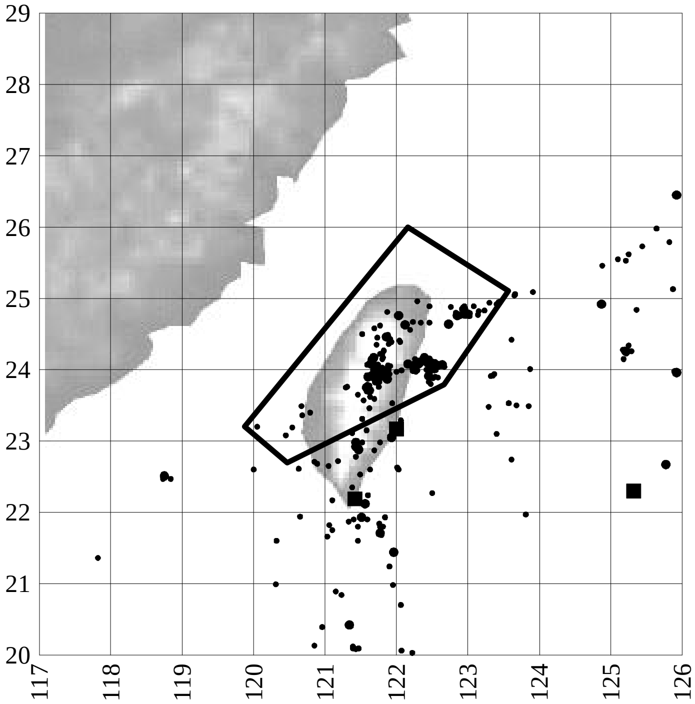


Fig. 5 – Taiwan seismic cycle. The map of the seismic area choosed for analysis; earthquakes with magnitudes $M_s > 5.0$ are also represented: ¦ M_s greater than 7.0, ? M_s greater than 6.0, ? M_s greater than 5.0.

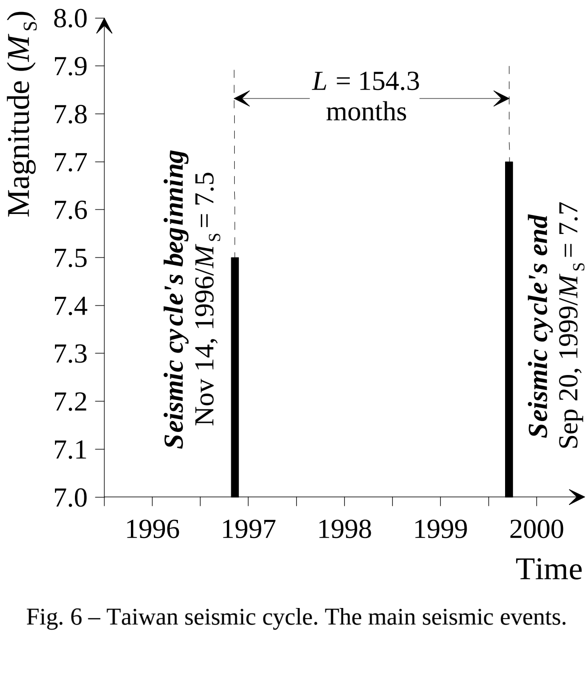


Fig. 6 – Taiwan seismic cycle. The main seismic events.

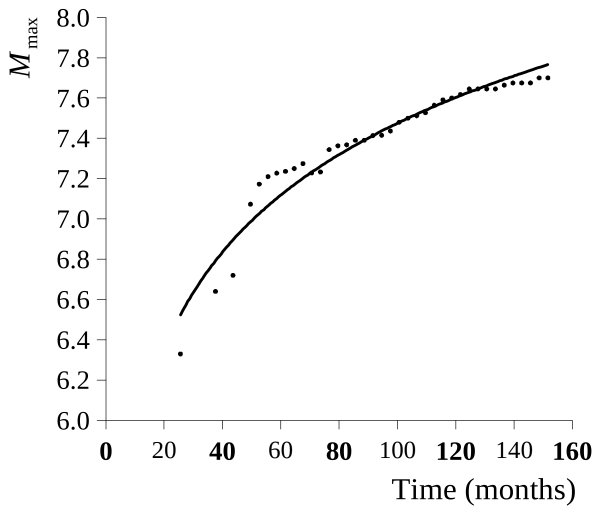


Fig. 7 – The loading function for the Taiwan seismic cycle.

Comments:

▪ The analysed cycle can be deemed as a calm seismic cycle. From Figure 6 it can be seen that no unexpected earthquakes disturbed the evolution of the cycle. As a result, the estimated values for the length of the real cycle are very close to each other. This calm feature of the cycle can be noticed also from Fig. 8 where the last part of the cycle could be described by a single function (exponential function).

▪ There are few seismic cycles in which the status parameter belongs to the *Group #2* of specific features, (23), section 8. This cycle is good example.

▪ The estimations made for the length of the cycle and for the final earthquake magnitude are very good. These very good estimations represent another result of the fact that the cycle's evolution was calm.

Table 3

The analysis of Taiwan seismic cycle (L = 154.3 months, M_f = 7.7)

No.	The moment of the analysis	l (months)	M_{max}	?	L_{est} (months)	The estimated moment of the final earthquake occurrence	M_{est}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	31/12/1988	25.6	6.330				
2	31/12/1989	37.6	6.640				
3	30/06/1990	43.6	6.720				
4	31/12/1990	49.6	7.073				
5	31/03/1991	52.6	7.173				
6	30/06/1991	55.6	7.210				
7	30/09/1991	58.6	7.227				
8	31/12/1991	61.6	7.236				

Table 3 (continued)

9	31/03/1992	64.6	7.250				
10	30/06/1992	67.6	7.275				
11	30/09/1992	70.6	7.228				
12	31/12/1992	73.6	7.233				
13	31/03/1993	76.6	7.344				
14	30/06/1993	79.6	7.363				
15	30/09/1993	82.6	7.368				
16	31/12/1993	85.6	7.390				
17	31/03/1994	88.6	7.390				
18	30/06/1994	91.6	7.414				
19	30/09/1994	94.6	7.415				
20	31/12/1994	97.6	7.436				
21	31/03/1995	100.6	7.480				
22	30/06/1995	103.6	7.500				
23	30/09/1995	106.6	7.512				
24	31/12/1995	109.6	7.527	0.7949			
25	31/03/1996	112.6	7.564	0.8146			
26	30/06/1996	115.6	7.591	0.8301			
27	30/09/1996	118.6	7.600	0.8463			
28	31/12/1996	121.6	7.618	0.8607	151.5	June, 1999	7.8
29	31/03/1997	124.6	7.645	0.8713	153.6	September, 1999	7.8
30	30/06/1997	127.6	7.645	0.8844	154.9	October, 1999	7.8
31	30/09/1997	130.6	7.645	0.8991	155.2	October, 1999	7.8
32	31/12/1997	133.6	7.645	0.9150	154.8	October, 1999	7.8
33	31/03/1998	136.6	7.664	0.9284	154.5	September, 1999	7.8
34	30/06/1998	139.6	7.675	0.9407	154.4	September, 1999	7.8
35	30/09/1998	142.6	7.675	0.9539	154.3	September, 1999	7.8
36	31/12/1998	145.6	7.675	0.9676	154.1	September, 1999	7.8
37	31/03/1999	148.6	7.700	0.9779	154.2	September, 1999	7.8
38	30/06/1999	151.6	7.700	0.9887	154.2	September, 1999	7.8

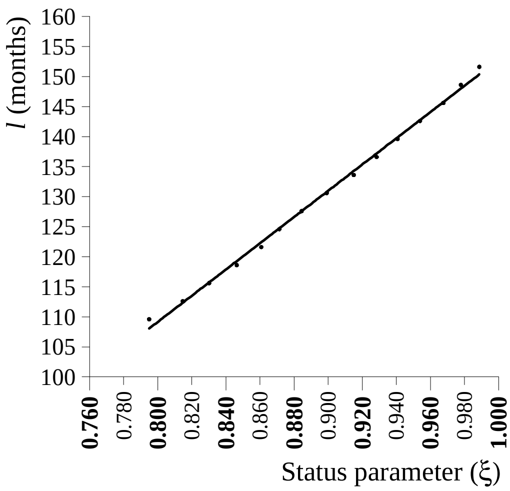


Fig. 8 – The forecast function for the Taiwan seismic cycle.

11.2. EL SALVADOR SEISMIC CYCLE ANALYSIS

On the 13th of January 2001 a large earthquake struck El Salvador. Its magnitude was M_S = 7.7(NEIC), M_S = 7.8 (BRK), M_W = 7.7 (HRV). At least 844 people were killed, over 4,723 were injured, 108,226 housing units were damaged and 150,000 were left homeless.

In Fig. 9 we may find the area under analysis and all earthquakes with magnitudes $M_S > 5.0$.

In order to analyse the seismic cycle ended by this earthquake we will examine the seismic activity from the area enclosed into a polygon with corner coordinates given in Table 4.

Table 4

Seismic zone for El Salvador earthquake

No.	Latitude	Longitude
1	15.0^0 N	95.0^0 W
2	20.0^0 N	95.0^0 W
3	20.1^0 N	90.0^0 W
4	13.8^0 N	83.0^0 W
5	10.7^0 N	87.2^0 W

On this area, the analysed seismic cycle started on February 4th, 1976, after the earthquake of magnitude M_S = 7.5 that ended the previous cycle. In Fig. 10 there were represented the main seismic events occurred during the analysed seismic cycle.

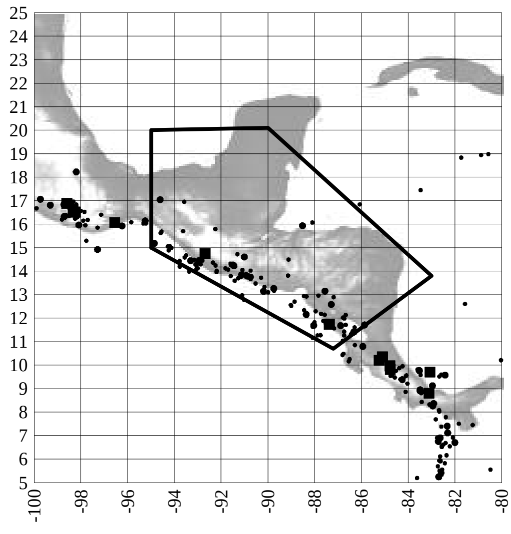
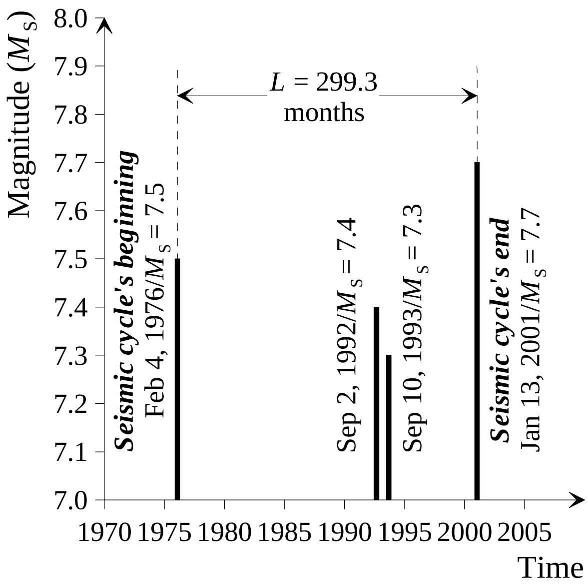


Fig. 9 – El Salvador seismic cycle. The map of the seismic area choosed for analysis; earthquakes with magnitudes $M_s > 5.0$ are also represented: ¦ M_s greater than 7.0, ? M_s greater than 6.0, ? M_s greater than 5.0.



Figu. 10 – El Salvador seismic cycle. The main seismic events.

The analysis of this cycle can be found in Table 5. In Figs. 11, 12 we may find the *loading function* and the *forecast function* for the analysed seismic cycle, respectively.

Comments:

▪ The status parameter ? verifies the Group #1 of specific features, (22), section 8.

▪ Estimations made for the lengths of the cycle show that the final earthquake can occur in the last part of 2000 – the beginning of 2001 (at least in the last 5 years of the cycle's evolution). Indeed, since 31/12/1995 (Table 5, row #32) the analysis shows us this. Estimations made for the magnitude of the final earthquake were good enough.

▪ This cycle presents a very interesting situation that will be encountered in many other cycles. From Fig. 10 we may observe that some large earthquakes may occur during the cycle's evolution, but it is not necessary to be final earthquakes. On September 2nd, 1999 a large earthquake (M_S = 7.4) occurred. From Table 5 we may find at row #25 that on 30/06/1992 the accumulated energy would have been enough for an earthquake of magnitude M_S = 7.57. So, if the cycle had ended in 30/06/1992, it would have ended by an earthquake of magnitude M_S = 7.6 and not M_S = 7.4. Much more, the status parameter has still a big value as against its inferior limit ? = 1.2932. In other words, the earthquake occurred on September 2nd, 1999 discharged only a small amount of the energy accumulated until its occurrence. We will come to the same conclusions analysing the earthquake from

September 10th, 1993. So, neither the first nor the second of these earthquakes may be considered as final earthquakes. In many cycles, the appearance of such large earthquakes, especially in the last part of the cycle's evolution changes its evolution, sometimes dramatically. These earthquakes can occasionally accelerate the process of energy accumulation or, in other cases can decelerate it.

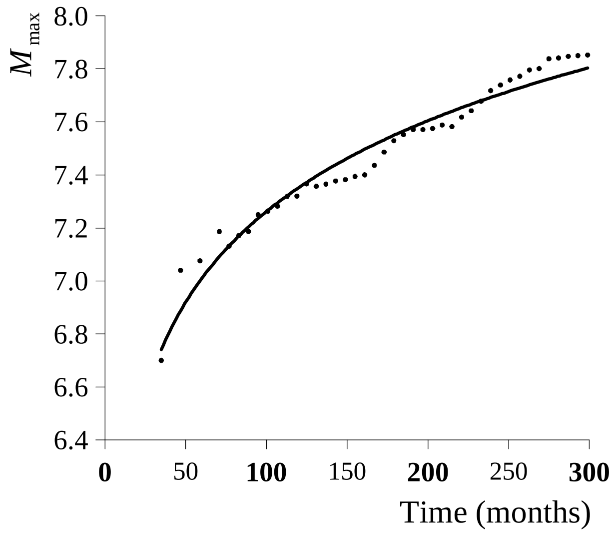


Fig. 11 – El Salvador seismic cycle. The loading function.

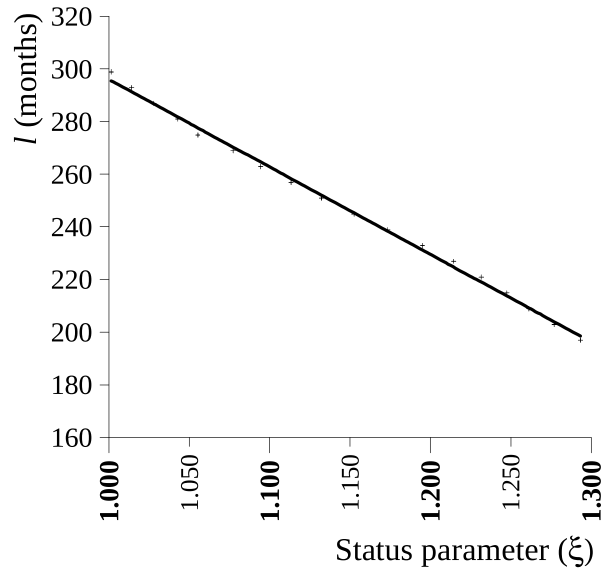


Fig. 12 – El Salvador seismic cycle. The forecast function.

Table 5

The analysis of El Salvador seismic cycle (L = 299.3 months; M_f = 7.7)

No.	**The moment of the analysis**	$\boldsymbol{l}$ **(months)**	$\boldsymbol{M_{max}}$	?	$\boldsymbol{L_{est}}$ **(months)**	**The estimated moment of the final earthquake occurrence**	$\boldsymbol{M_{est}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	31/12/1978	34.9	6.700				
2	31/12/1979	46.9	7.040				
3	31/12/1980	58.9	7.076				
4	31/12/1981	70.9	7.186				
5	30/06/1982	76.9	7.131				
6	31/12/1982	82.9	7.171				
7	30/06/1983	88.9	7.186				
8	31/12/1983	94.9	7.250				
9	30/06/1984	100.9	7.263				
10	31/12/1984	106.9	7.282				
11	30/06/1985	112.9	7.319				
12	31/12/1985	118.9	7.320				
13	30/06/1986	124.9	7.366				
14	31/12/1986	130.9	7.357				
15	30/06/1987	136.9	7.365				
16	31/12/1987	142.9	7.377				
17	30/06/1988	148.9	7.382				
18	31/12/1988	154.9	7.394				
19	30/06/1989	160.9	7.400				
20	31/12/1989	166.9	7.436				
21	30/06/1990	172.9	7.486				
22	31/12/1990	178.9	7.529				
23	30/06/1991	184.9	7.552	1.3363			
24	31/12/1991	190.9	7.571	1.3122			
25	30/06/1992	196.9	7.571	1.2932	277.9	April, 1999	7.7
26	31/12/1992	202.9	7.575	1.2771	297.2	November, 2000	7.8
27	30/06/1993	208.9	7.588	1.2614	301.5	February, 2001	7.8
28	31/12/1993	214.9	7.582	1.2475	306.2	August, 2001	7.8
29	30/06/1994	220.9	7.618	1.2317	308.2	October, 2001	7.8
30	31/12/1994	226.9	7.643	1.2145	307.7	September, 2001	7.8
31	30/06/1995	232.9	7.678	1.1951	305.7	July, 2000	7.8
32	31/12/1995	238.9	7.718	1.1735	295.7	September, 2000	7.8
33	30/06/1996	244.9	7.739	1.1525	293.3	July, 2000	7.8
34	31/12/1996	250.9	7.758	1.1323	292.1	June, 2000	7.8
35	30/06/1997	256.9	7.772	1.1133	291.8	May, 2000	7.8
36	31/12/1997	262.9	7.796	1.0944	291.8	May, 2000	7.8
37	30/06/1998	268.9	7.801	1.0773	292.2	June, 2000	7.8
38	31/12/1998	274.9	7.838	1.0553	292.6	June, 2000	7.8
39	30/06/1999	280.9	7.841	1.0429	293.7	July, 2000	7.8
40	31/12/1999	286.9	7.847	1.0279	297.0	November, 2000	7.8
41	30/06/2000	292.9	7.850	1.0141	299.0	January, 2001	7.8
42	31/12/2000	298.9	7.852	1.0014	299.3	January, 2001	7.8

11.3. PERU SEISMIC CYCLE ANALYSIS

On the 23rd of June, 2001, a large earthquake (M_S = 8.2, M_W = 8.4) occurred in Peru. There were 74 death tolls, 2,689 injured people, 17,584 housing units damaged and 35,601 homeless people. In Fig. 13 we may find a map with the main seismic events occurred in in the analysed area.

In order to analyse the seismic cycle ended by this earthquake we will study the seismicity from an area enclosed into the rectangle defined by its corner coordinates (Table 6).

Table 6

Seismic zone for Peru seismic cycle

No.	Latitude	Longitude
1	10.0^0 S	80.0^0 W
2	10.0^0 S	68.0^0 W
3	18.0^0 S	68.0^0 W
4	18.0^0 S	80.0^0 W

The seismic cycle, whose final earthquake occurred on the 23rd of June, 2001 started in October 3rd, 1974, after the earthquake with the magnitude M_S = 7.6, earthquake that ended the previous cycle. In Fig. 14 we may find the main seismic events occurred during the analysed cycle. In Table 7 we may find the analysis of this cycle.

The *loading function* and the *forecast function* are represented in Figs. 15, 16, respectively.

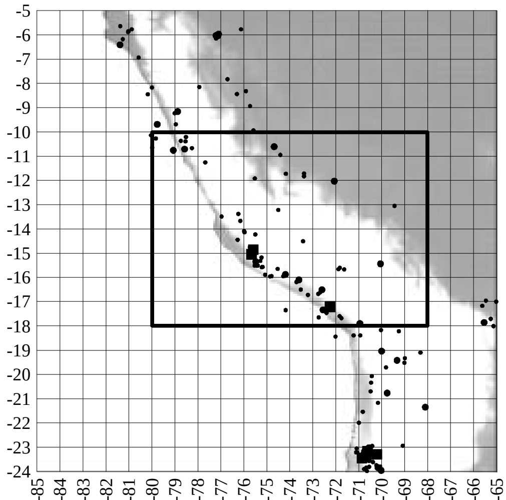


Fig. 13 – Peru seismic cycle. The map of the seismic area choosed for analysis. earthquakes with magnitudes M_s > 5.0 are also represented. ¦ M_s greater than 7.0, ? M_s greater than 6.0, ? M_s greater than 5.0.

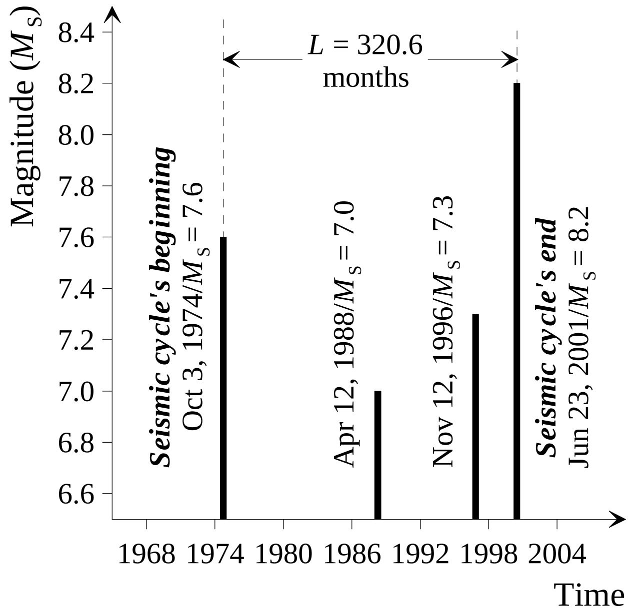


Fig. 14 – Peru seismic cycle. The main seismic events.

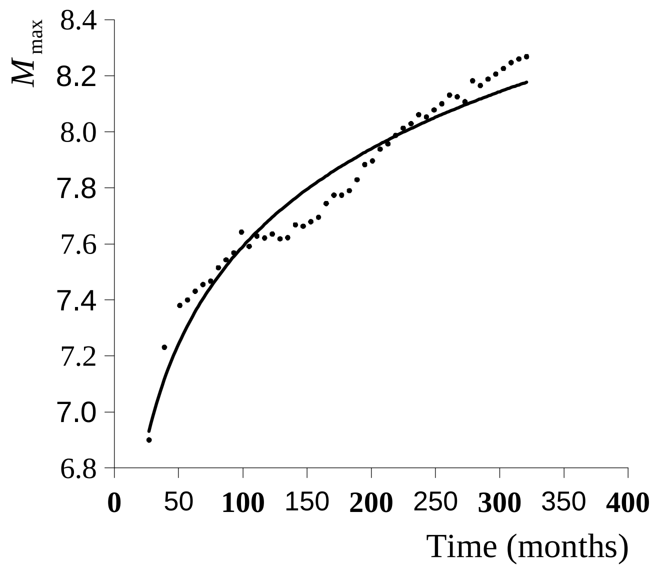


Fig. 15 – Peru seismic cycle. The loading function.

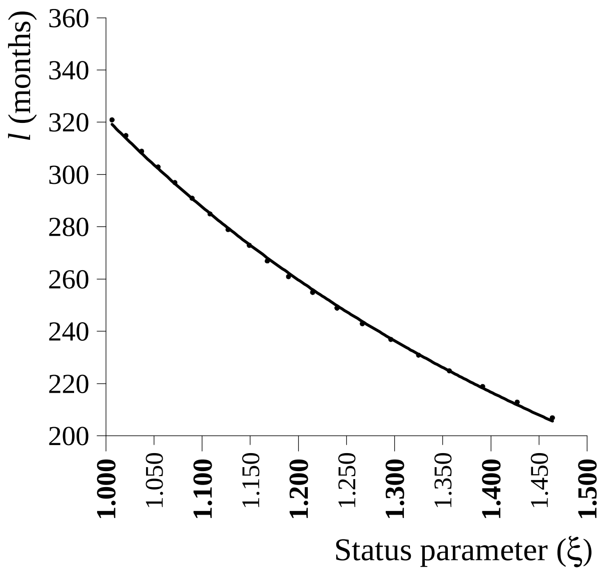


Fig. 16 – Peru seismic cycle. The forecast function.

Comments:

- The status parameter ? verifies the *Group #1* of specific features, (22), section 8.
- Estimations made for the length of the seismic cycle show us that the analysed cycle will be ended in the first part of 2001.
- Estimations made for the magnitude of the final earthquake were good enough (M_f = 8.1 – 8.2) in the last 6 years of the cycle's evolution.
- We may also note that in this cycle a large earthquake occurred during its evolution without being a final earthquake (1996/11/12 M_S = 7.3). This earthquake, probably slowed down the evolution of the cycle. This slowing down of the cycle's evolution can be realized from Table 7 (the estimations of the length of the cycle become bigger and bigger) and from the forecast function (Fig. 16) which can be approximated by a power function as the best fit function. The forecast function also put into evidence that the cycle's evolution can be considered as being calm.

Table 7

The analysis of Peru seismic cycle (L = 320.6 months; M_f = 8.2)

No.	**The moment of the analysis**	***l* (months)**	M_{max}	?	L_{est} **(months)**	**The estimated moment of the final earthquake occurrence**	M_{est}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	31/12/1976	26.9	6.900				
2	31/12/1977	38.9	7.231				

Table 7 (continued)

3	31/12/1978	50.9	7.380				
4	30/06/1979	56.9	7.400				
5	31/12/1979	62.9	7.431				
6	30/06/1980	68.9	7.455				
7	31/12/1980	74.9	7.467				
8	30/06/1981	80.9	7.515				
9	31/12/1981	86.9	7.543				
10	30/06/1982	92.9	7.568				
11	31/12/1982	98.9	7.624				
12	30/06/1983	104.9	7.591				
13	31/12/1983	110.9	7.628				
14	30/06/1984	116.9	7.621				
15	31/12/1984	122.9	7.635				
16	30/06/1985	128.9	7.618				
17	31/12/1985	134.9	7.622				
18	30/06/1986	140.9	7.668				
19	31/12/1986	146.9	7.663				
20	30/06/1987	152.9	7.679				
21	31/12/1987	158.9	7.695				
22	30/06/1988	164.9	7.744				
23	31/12/1988	170.9	7.774				
24	30/06/1989	176.9	7.774				
25	31/12/1989	182.9	7.790				
26	30/06/1990	188.9	7.829				
27	31/12/1990	194.9	7.883				
28	30/06/1991	200.9	7.896				
29	31/12/1991	206.9	7.938	1.4639			
30	30/06/1992	212.9	7.957	1.4273			
31	31/12/1992	218.9	7.987	1.3914			
32	30/06/1993	224.9	8.013	1.3568			
33	31/12/1993	230.9	8.029	1.3248			
34	30/06/1994	236.9	8.061	1.2960			
35	31/12/1994	242.9	8.053	1.2664	315.3	January, 2001	8.1
36	30/06/1995	248.9	8.078	1.2401	315.8	January, 2001	8.1
37	31/12/1995	254.9	8.100	1.2148	316.3	February, 2001	8.1
38	30/06/1996	260.9	8.131	1.1897	316.5	February, 2001	8.1
39	31/12/1996	266.9	8.125	1.1677	317.0	March, 2001	8.1
40	30/06/1997	272.9	8.107	1.1490	318.0	April, 2001	8.1
41	31/12/1997	278.9	8.182	1.1270	318.5	April, 2001	8.1
42	30/06/1998	284.9	8.165	1.1082	319.1	May, 2001	8.1
43	31/12/1998	290.9	8.188	1.0896	319.7	May, 2001	8.1
44	30/06/1999	296.9	8.206	1.0717	320.2	June, 2001	8.2
45	31/12/1999	302.9	8.226	1.0542	320.6	June, 2001	8.2
46	30/06/2000	308.9	8.247	1.0371	320.9	June, 2001	8.2
47	31/12/2000	314.9	8.260	1.0208	321.2	July, 2001	8.2
48	23/06/2001	320.9	8.268	1.0063	321.5	July, 2001	8.2

11.4. FIJI SEISMIC CYCLE ANALYSIS

On August 19th, 2002 in a seismic area close to Fiji Islands occurred two large earthquakes at an interval of time of only 8 minutes having the magnitudes M_S = 7.6 and M_S = 7.7. In Fig. 17 we may find a map with the main seismic events occurred in in the analysed area. In order to analyse the seismic cycle that generated these two earthquakes it was selected a seismic area enclosed into a rectangle whose corner coordinates are given in Table 8.

The analysed cycle started on December 19th, 1982 after the earthquake of magnitude M_S = 7.7 that ended the previous seismic one. In Fig. 18 we may find the main seismic events occurred during the cycle's evolution.

The analysis for Fiji seismic cycle is shown in Table 9.

The *loading function* and the *forecast function* are represented in Figs. 19, 20, respectively.

Table 8

Seismic zone for Fiji Islands seismic cycle

No.	Latitude	Longitude
1	21.5^0 S	180.0^0 W
2	21.5^0 S	172.0^0 W
3	26.0^0 S	180.0^0 W
4	26.0^0 S	172.0^0 W

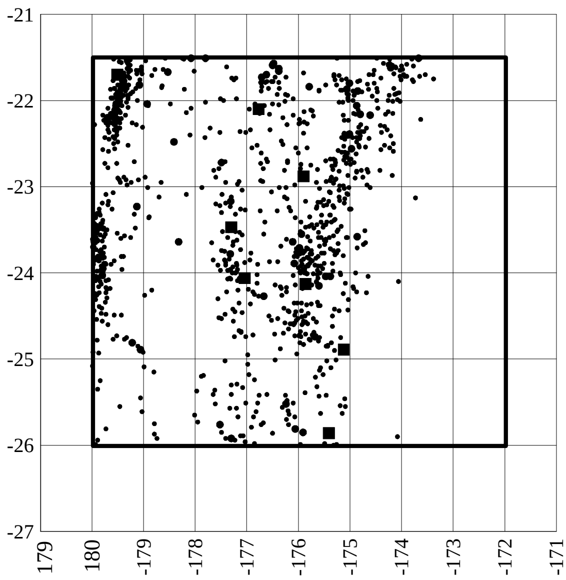


Fig. 17 – Fiji seismic cycle. The map of the seismic area choosed for analysis; earthquakes with magnitudes M_s > 5.0 are also represented: ¦ M_s greater than 7.0, ? M_s greater than 6.0, ? M_s greater than 5.0.

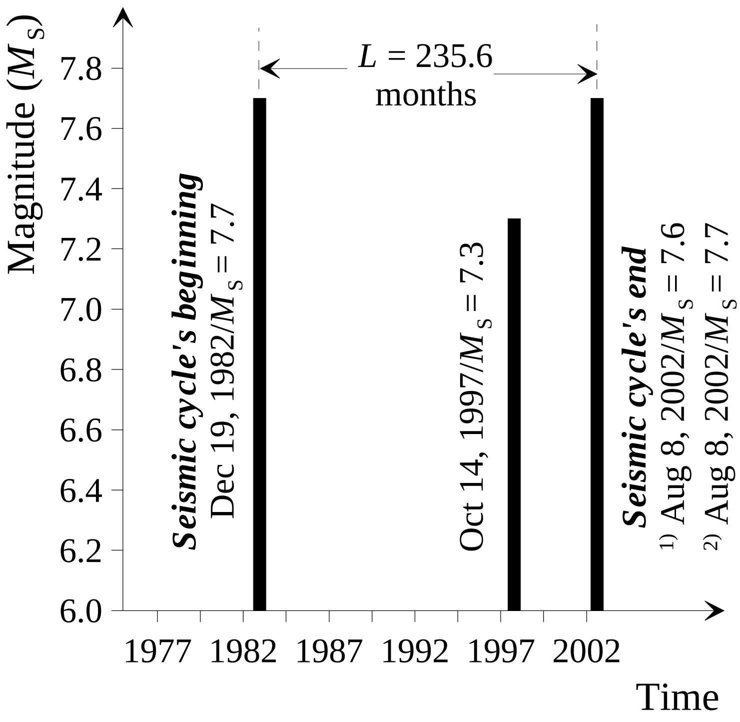


Fig. 18 – Fiji seismic cycle. The main seismic events.

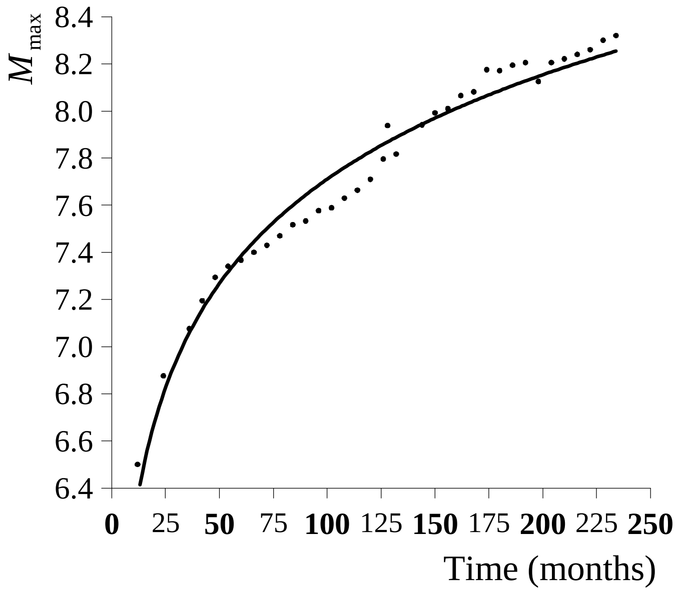


Fig. 19 – Fiji seismic cycle. The loading function.

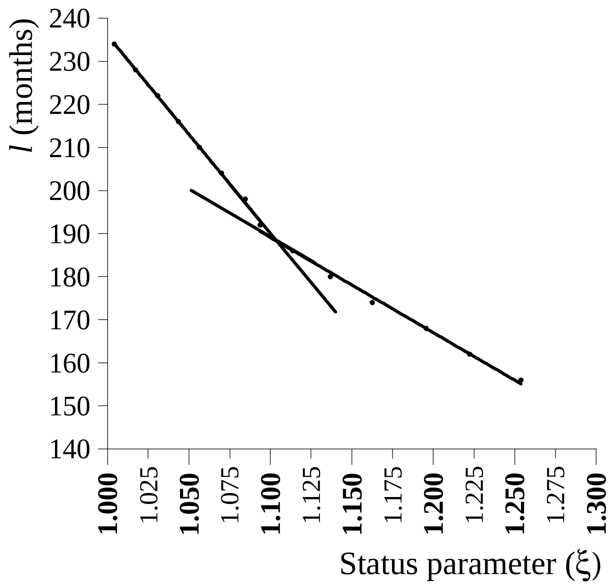


Fig. 20 – Fiji seismic cycle. The forecast function.

Table 9

The analysis of Fiji seismic cycle (L = 235.6 months; M_f = 8.3)

No.	**The moment of the analysis**	***l* (months)**	M_{max}	?	L_{est} **(months)**	**The estimated moment of the final earthquake occurrence**	M_{est}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	31/12/1983	12.0	6.500				
2	31/12/1984	24.0	6.876				
3	31/12/1985	36.0	7.076				
4	30/06/1986	42.0	7.195				
5	31/12/1986	48.0	7.294				
6	30/06/1986	54.0	7.341				
7	31/12/1987	60.0	7.367				
8	30/06/1988	66.0	7.400				
9	31/12/1988	72.0	7.430				
10	30/06/1989	78.0	7.470				
11	31/12/1989	84.0	7.517				
12	30/06/1990	90.0	7.533				
13	31/12/1990	96.0	7.577				
14	30/06/1991	102.0	7.589				
15	31/12/1991	108.0	7.630				
16	30/06/1992	114.0	7.664				

Table 8 (continued)

17	31/12/1992	120.0	7.710				
18	30/06/1993	126.0	7.796				
19	31/12/1993	132.0	7.817				
20	30/06/1994	138.0	7.938	1.3525			
21	31/12/1994	144.0	7.941	1.3174			
22	30/06/1995	150.0	7.992	1.2818			
23	31/12/1995	156.0	8.010	1.2538	201.3	October, 1999	8.1
24	30/06/1996	162.0	8.065	1.2223	202.8	November, 1999	8.1
25	31/12/1996	168.0	8.081	1.1956	204.6	January, 2000	8.1
26	30/06/1997	174.0	8.175	1.1626	205.1	February, 2000	8.1
27	31/12/1997	180.0	8.171	1.1368	206.0	February, 2000	8.1
28	30/06/1998	186.0	8.194	1.1137			
29	31/12/1998	192.0	8.205	1.0937			
30	30/06/1999	198.0	8.125	1.0846	230.4	March, 2002	8.2
31	31/12/1999	204.0	8.205	1.0701	233.0	June, 2002	8.2
32	30/06/2000	210.0	8.221	1.0565	234.0	July, 2002	8.2
33	31/12/2000	216.0	8.240	1.0435	234.7	July, 2002	8.2
34	30/06/2001	222.0	8.260	1.0308	235.2	August, 2002	8.2
35	31/12/2001	228.0	8.300	1.0172	235.4	August, 2002	8.2
36	30/06/2002	234.0	8.320	1.0041	235.6	August, 2002	8.3

Comments:

- From Table 9 it results that on August 2002 it ought to occur a final earthquake of magnitude M_S = 8.3. On August 19th, 2002 (11:01:01) an earthquake of magnitude M_S = 7.6 occurred. It is obvious that the accumulated energy was not entirely discharged. It results that a new earthquake with a magnitude comparable with the previous one must occur in the next days/weeks. Indeed, eight minutes later a new earthquake of magnitude M_S = 7.7 struck the region ending the cycle's evolution.
- This seismic cycle presents a very interesting situation because a large quantity of energy is discharged not only by a single shock. As we can see, the geostatistics can emphasize these special situations warning about the imminence of a new large earthquake.
- On October 14th, 1997 an earthquake of magnitude M_S = 7.3 changed drastically the evolution of the cycle. As we can see from Table 9 and also from Fig. 20, the cycle's behaviour was calm before this earthquake, going toward a final earthquake of M_S = 8.1 which ought to occur somewhere in the first months of the year 2000 (rows #25, #26, #27). The occurrence of this earthquake slowed down the evolution of the cycle, thus it become longer (L_{est} = 235.6 months, row

#36) by comparison with the former length (L_{est} = 206.0 months) and more dangerous (M_{est} = 8.3 versus M_{est} = 8.1). Also, the forecast function can grasp the change in the cycle's evolution. In Fig. 20 one can easily observe a change in the slope of the forecast function which denotes that the cycle will be longer after this earthquake.

▪ As a conclusion this seismic cycle presents two different features which will impose a special kind of analysis in the future.

1. A large earthquake is able to change drastically the evolution of a cycle. It results that the analysis of every seismic cycle must be done for the whole evolution of the cycle in order to interpret every possible change in its evolution.

2. There are cycles in which the accumulated energy is discharged by two or more shocks. It results that the monitoring of the cycle's evolution must continue until the end of the cycle, warning the scientific community about a new large earthquake occurrence.

If a seismic cycle, like the Fiji one, will evolve in a densely populated area this warning of a new large earthquake can be crucial in the final bill that must be paid by the nation affected by this type of seismic cycles.

11.4. KURIL ISLANDS SEISMIC CYCLE ANALYSIS

On October 4th, 1994 a large earthquake (M_S = 8.1) ended a seismic cycle developped in Kuril Islands seismic region.

The seismic area including all major earthquakes occurred inside it during the interval of time starting with 1973 up to 1995 was represented in Fig. 21.

In order to analyse this seismic cycle it was selected an area enclosed in the polygon defined by the coordinates given in Table 10.

Table 10

Seismic zone for Kuril Islands seismic cycle

No.	Latitude	Longitude
1	44.4^0 N	145.0^0 E
2	47.1^0 N	152.0^0 E
3	44.2^0 N	152.0^0 E
4	41.5^0 N	145.0^0 E

The analysed cycle started on February 23rd, 1980 after the earthquake of magnitude M_S = 7.0 that ended the previous seismic cycle. In Fig. 22 we may find the main seismic events occurred during the cycle's evolution.

The entire analysis for this seismic cycle is shown in Table 11.

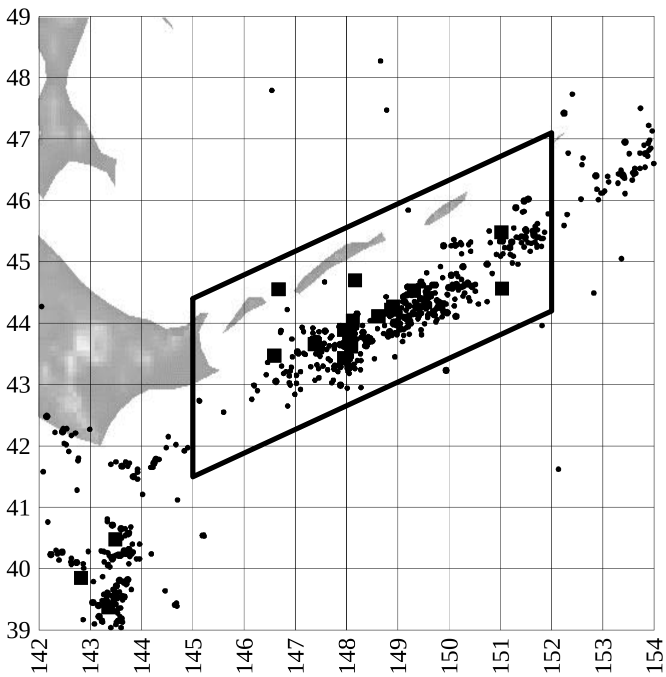


Fig. 21. Kuril Islands seismic cycle. The map of the seismic area choosed for analysis. earthquakes with magnitudes $M_s > 5.0$ are also represented. ¦ M_s greater than 7.0, ? M_s greater than 6.0, ? M_s greater than 5.0.

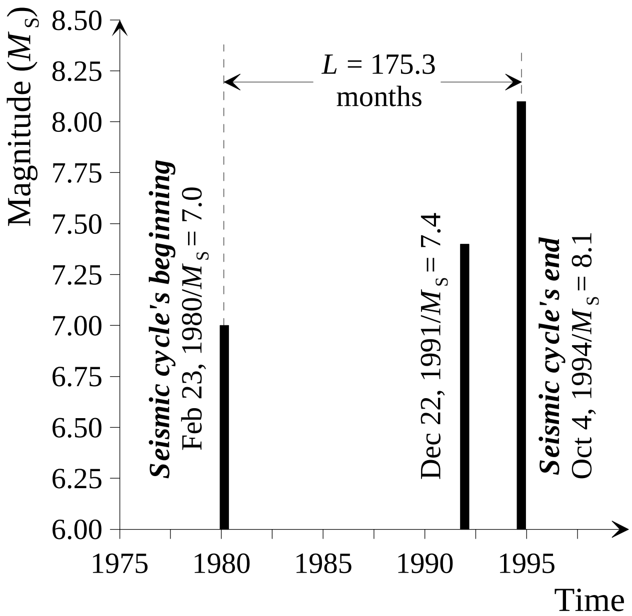


Fig. 22 – Kuril Islands seismic cycle. The main seismic events.

Table 11

The analysis of Kuril Islands seismic cycle (L = 175.3 months; M_f = 8.1)

No.	The moment of the analysis	l (months)	M_{max}	?	L_{est} (months)	The estimated moment of the final earthquake occurrence	M_{est}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	31/12/1981	22.2	6.793				
2	31/12/1982	34.2	7.060				
3	30/06/1983	40.2	7.150				
4	31/12/1983	46.2	7.229				
5	31/03/1984	49.2	7.314				
6	30/06/1984	52.2	7.314				
7	30/09/1984	55.2	7.326				
8	31/12/1984	58.2	7.378				
9	31/03/1985	61.2	7.396				
10	30/06/1985	64.2	7.400				
11	30/09/1985	67.2	7.414				
12	31/12/1985	70.2	7.414				
13	31/03/1986	73.2	7.424				
14	30/06/1986	76.2	7.478				
15	30/09/1986	79.2	7.492				
16	31/12/1986	82.2	7.506				
17	31/03/1987	85.2	7.522				
18	30/06/1987	88.2	7.539				
19	30/09/1987	91.2	7.563				
20	31/12/1987	94.2	7.570				
21	31/03/1988	97.2	7.581				
22	30/06/1988	100.2	7.621				
23	30/09/1988	103.2	7.637				
24	31/12/1988	106.2	7.642				
25	31/03/1989	109.2	7.663				
26	30/06/1989	112.2	7.686	1.4501			
27	30/09/1989	115.2	7.723	1.4314			
28	31/12/1989	118.2	7.761	1.4090			
29	31/03/1990	121.2	7.792	1.3838			
30	30/06/1990	124.2	7.796	1.3648	174.1	August, 1994	8.0
31	30/09/1990	127.2	7.800	1.3505	177.2	November, 1994	8.0
32	31/12/1990	130.2	7.820	1.3357	180.3	March, 1995	8.0
33	31/03/1991	133.2	7.850	1.3182	182.2	April, 1995	8.0
34	30/06/1991	136.2	7.875	1.2996	183.5	June, 1995	8.0
35	30/09/1991	139.2	7.900	1.2804	184.0	June, 1995	8.0
36	31/12/1991	142.2	8.000	1.2462	181.8	April, 1995	8.0
37	31/03/1992	145.2	8.061	1.2079	178.2	December, 1994	8.0
38	30/06/1992	148.2	8.074	1.1748	175.2	October, 1994	8.0
39	30/09/1992	151.2	8.115	1.1418	172.8	July, 1994	8.0
40	31/12/1992	154.2	8.135	1.1121	171.0	May, 1994	8.0
41	31/03/1993	157.2	8.100	1.0924	170.3	May, 1994	8.0
42	30/06/1993	160.2	8.105	1.0759	170.1	April, 1994	8.0
43	30/09/1993	163.2	8.110	1.0618	170.3	May, 1994	8.0

Table 11 (continued)

44	31/12/1993	166.2	8.111	1.0504	170.7	May, 1994	8.0
45	31/03/1994	169.2	8.116	1.0406	171.4	June, 1994	8.1
46	30/06/1994	172.2	8.133	1.0310	172.1	June, 1994	8.1
47	04/10/1994	175.2	8.168	1.0195	173.0	July, 1994	8.1

The *loading function* and the *forecast function* for the analysed cycle were represented in Figs. 23, 24, respectively.

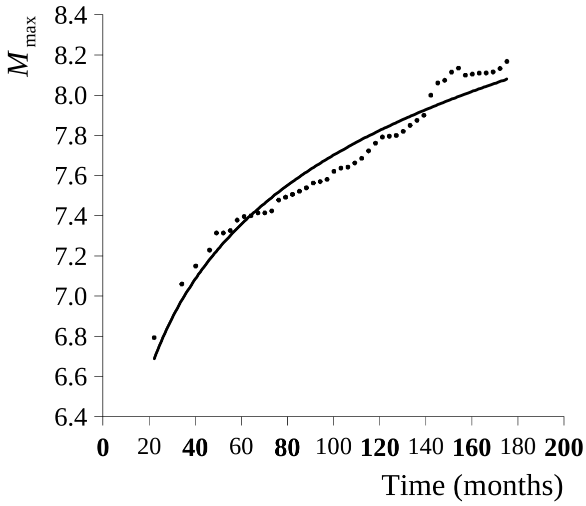


Fig. 23 – Kuril Islands seismic cycle. The loading function.

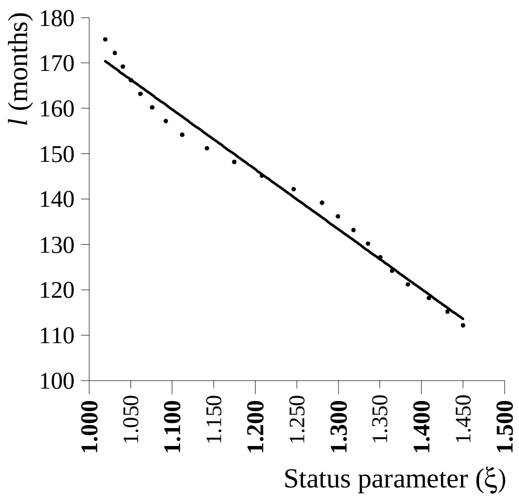


Fig. 24 – Kuril Islands seismic cycle. The forecast function.

Comments:

• From the analysis presented in Table 11, the cycle's evolution ought to be ended by a final earthquake of magnitude M_S = 8.1 which had to occur in July, 1994. In fact, the cycle was ended by a final earthquake of magnitude M_S = 8.1 (good estimation) occurred in October, 1994 (L = 175.3 months, the real seismic cycle's length related to L = 173.0 months as it results from the analysis).

• The *forecast function* for this cycle (Fig. 24) is represented by a straight line. In such situations, the mean value for the estimations of the cycle's length (L_{est}) will give us more realistic results regarding to the accurate value of the real seismic cycle's length. In Table 12 we rewrote the last part of the analysis in which the estimations of the cycle's length represent the mean values of the previous ones.

Table 12

The new analysis of Kuril Islands seismic cycle

No.	**The moment of the analysis**	L_{est} **(months)**	$\overline{L_{est}}$ **(months)**	**The estimated moment of the final earthquake occurrence**
(1)	(2)	(3)	(4)	(5)
30	30/06/1990	174.1		
31	30/09/1990	177.2	175.7	October, 1994
32	31/12/1990	180.3	177.2	November, 1994
33	31/03/1991	182.2	178.5	January, 1995
34	30/06/1991	183.5	179.5	February, 1995
35	30/09/1991	184.0	180.2	February, 1995
36	31/12/1991	181.8	180.4	March, 1995
37	31/03/1992	178.2	180.2	Febryary, 1995
38	30/06/1992	175.2	179.6	February, 1995
39	30/09/1992	172.8	178.9	January, 1995
40	31/12/1992	171.0	178.2	December, 1995
41	31/03/1993	170.3	177.6	December, 1994
42	30/06/1993	170.1	177.0	November, 1994
43	30/09/1993	170.3	176.5	November, 1994
44	31/12/1993	170.7	176.1	October, 1994
45	31/03/1994	171.4	175.8	October, 1994
46	30/06/1994	172.1	175.6	October, 1994
47	04/10/1994	173.0	175.5	October, 1994

In this way we may observe from Table 12 that the estimations for the real seismic cycle's length have already been improved very much.

12. AFTERSHOCK ACTIVITY

In the previous sections we concluded that a seismic cycle is ended by a final earthquake (a main or two almost equal shocks) which discharges the whole energy accumulated during the cycle's evolution.

The final earthquake ends a cycle's evolution but it also starts a new process accumulation called aftershock activity.

The term aftershock refers to the big number of moderate earthquakes that occur after a final earthquake. This high seismicity which is developed in an affected area after the final earthquake occurred, seismicity that may last for a few weeks / months can be called *aftershock activity*. The huge frequency of the aftershock occurrence shows a violent process of energy accumulation that is developing in the affected area.

It is easy to explain this process; let us consider a given seismic area in which a final earthquake discharged the energy accumulated during a cycle's evolution. Before the final earthquake's occurrence equilibrium in the state of stress between different volumes from the analysed region was established.

The final earthquake will discharge a huge quantity of energy affecting a volume, bigger or smaller as a function of the earthquake's magnitude. In the affected volume, the state of stress will vanish. In this moment a lack of poise between the state of stress from the affected volume and the state of stress from the neighboring volumes will be established. In order to cancel this lack of poise, a large quantity of energy will be transferred from the unaffected volumes towards the affected ones. As a result a violent process of charging in the affected volume will take place. Therefore, a large number of earthquakes will occur, earthquakes known as *aftershocks*. So, the lack of poise in the state of stress between the affected and the unaffected volumes diminishes and the loading process becomes a more and more calm one and the frequency of the aftershocks evidently decreases.

It is very interesting to note that this violent process of accumulation is ended by a large earthquake that can affect the already weakened structures by the final earthquake. So, the study of this kind of accumulation process would be useful from a practical point of view. In fact, in the affected volume a new kind of seismic cycle is established. A very violent, a very short seismic cycle, but a seismic cycle after all. In order to estimate the magnitude and the moment of its "final earthquake" we will use the same methodology described in the previous sections. A problem appears here, regarding the characteristic function (section 7) that does not allow the analyse of such short cycles, because it was constructed using longer and not so violent cycles. Thus, a new characteristic function must be built in order to be able to analyse such kind of cycles. Such new characteristic functions are not available until now, but they will be constructed in the next few years.

In the absence of a suitable characteristic function for such cycles we will only estimate the seismic potential, $M_{\max}(t)$, and build the loading function. In this way, we will be able to have interesting information about the magnitude of the "final earthquake" due to aftershock activity.

To exemplify, we will analyse the aftershock activity occurred after the final earthquake of M_S = 8.1 magnitude from *Kuril Islands* seismic region. In Table 13 we shall find the estimations of the seismic potential after the final earthquake of M_S = 8.1 magnitude from Kuril Islands (section 11.5) and in Fig. 25 we shall find the loading function of the aftershock seismic cycle.

Table 13

Aftershock seismic cycle's analysis – Kuril Islands (1994 – 1995)

No.	**The moment of the analysis**	***l* (days)**	**M_{max}**	**No.**	**The moment of the analysis**	***l* (days)**	**M_{max}**
(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
1	19/10/1994	15	7.392	16	01/06/1995	240	7.717
2	03/11/1994	30	7.475	17	16/06/1995	255	7.722
3	18/11/1994	45	7.507	18	01/07/1995	270	7.722
4	03/12/1994	60	7.500	19	16/07/1995	285	7.733
5	18/12/1994	75	7.538	20	31/07/1995	300	7.739
6	02/01/1995	90	7.559	21	15/08/1995	315	7.768
7	17/01/1995	105	7.520	22	30/08/1995	330	7.774
8	01/02/1995	120	7.589	23	14/09/1995	345	7.744
9	16/02/1995	135	7.607	24	29/09/1995	360	7.744
10	03/03/1995	150	7.644	25	14/10/1995	375	7.758
11	18/03/1995	165	7.627	26	29/10/1995	390	7.763
12	02/04/1995	180	7.644	27	13/11/1995	405	7.763
13	17/04/1995	195	7.663	28	28/11/1995	420	7.795
14	02/05/1995	210	7.694	29	03/12/1995	425	7.892
15	17/05/1995	225	7.706				

On December the 3rd, 1995 an earthquake of M_S = 7.9 magnitude ended this evolution.

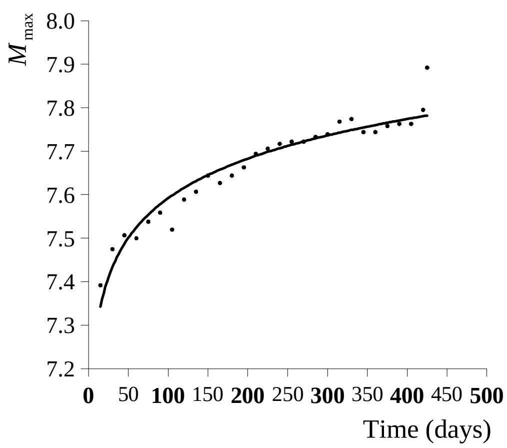


Fig. 25 – Kuril Islands. The loading function of the aftershock seismic cycle, 1994–1995.

Comments:

• In order to understand what a violent seismic cycle means we must compare the values from Table 13 with those from Table 11, which describe the evolution of a classic seismic cycle. We may observe that in the first 15 days (row #1, Table 13) the same quantity of energy has accumulated as in the first 61.2 months from a classic seismic cycle (row #9, Table 11), in the first 30 days of the aftershock seismic cycle's evolution the accumulated energy was similar to the one from the first 76.2 months from the classic seismic cycle and so on.

• Much more, a comparison between this aftershock seismic cycle and the other classical cycles will better emphasize the violent character of this kind of cycles.

• We may observe from Table 13 that beginning with 17/05/1995 (row #15, Table 13), the process of accumulation has entered into a saturation stage. It can be concluded that the final earthquake of this aftershock cycle will have a magnitude about M_S = 7.7 – 7.8. We may wonder now: *when will this final earthquake occur?*. We will be able to answer this question only when the characteristic function for such special cycles will be built.

13. ANOTHER LARGE EARTHQUAKE?

It is interesting to talk over a typical situation that appears in almost all densely populated countries after the occurrence of a large earthquake.

Suddenly, a wave of panic will overcome the whole population who lives in the affected area. Many damaged structures, a lot of people caught under these structures, many of them already deceased, other only injured waiting to be rescued, a crowd of people trying to help the rescue teams and so on.

Many accusations against government *which makes nothing to help the people*, a lot of people leaving their homes to settle in parks, gardens waiting, waiting, waiting… Waiting for what?

It is well known that on this common hubbub a question very often appears: *will it be another large earthquake?* Everyone wants to know if another large or even larger earthquake will affect in the near future their own lives and their families. They feel that a new large earthquake can crash their already weakened houses, can destroy all their fortune accumulated in a lifetime or, worst, can kill them. Everyone expects an answer to this question, but everyone hopes that this answer will be clear: *no large earthquake is likely to occur*. A new kind of madness is going to be installed. Some "specialists" in seismic forecast will state in mass media either a new large earthquake is impossible to appear or, on the contrary, a new large earthquake is now impeding, increasing the already installed confusion. Every seismologist who experienced such a situation knows how difficult is to answer this question.

The geostatistical analysis can help the seismologists in these hard moments giving them a few useful elements in order to guide them in their future decisions.

So, this section will analyse the possibility that a new large earthquake is possible to happen after an already occurred large one.

13.1. In many seismic cycles, a few years before the final earthquake's occurrence one or two large earthquakes strike the respective region. These *checking earthquakes* are larger than any ordinary earthquakes from that area but smaller than the final earthquake. As an example, we may note the following events, already exposed in Section 11:

1992/09/02	$M_S = 7.4$	*El Salvador* seismic cycle	Figure 10
1993/09/10	$M_S = 7.3$	*El Salvador* seismic cycle	Figure 10
1996/11/12	$M_S = 7.3$	*Peru* seismic cycle	Figure 14
1997/10/14	$M_S = 7.3$	*Fiji* seismic cycle	Figure 18
1991/12/22	$M_S = 7.4$	*Kuril* seismic cycle	Figure 22

All these earthquakes are large enough to create panic in the affected region. Considering these examples, the answer to the question if a new large earthquake will occur is unfortunately *yes, a new larger earthquake is going to occur*. Why? Because these earthquakes do not end the seismic cycle. So, a final earthquake, larger than these already produced is expected to strike the area later. The analysis of these cycles will show us the magnitudes and the periods of time when the final earthquake will occur (Tables 5, 7, 9, 11).

It is interesting to mention that there are seismic cycles in which such earthquakes do not occur. For example, in the *Taiwan* seismic cycle, no large earthquake occurred before the final earthquake (Fig. 6).

13.2. The second situation in which a large earthquake creates panic is represented by the final earthquake itself, single shock. We can find these situations in section 11.1 (*Taiwan* seismic cycle, 1999/09/20, $M_S = 7.7$), section 11.2 (*El Salvador* seismic cycle, 2000/01/13, $M_S = 7.7$), section 11.3 (*Peru* seismic cycle, 2001/06/23, $M_S = 8.2$), section 11.5 (*Kuril Islands* seismic cycle, 1994/10/4, $M_S = 8.1$).

In these situations the answer will be *no larger earthquake will occur in the near future*. After all these final earthquakes there will follow an aftershock activity in which a big number of moderate earthquakes will occur. In fact, there will develop one or two aftershock seismic cycles and the "final earthquakes" of these short cycles will be in any case smaller than the final earthquake of the exhausted main cycle.

In many cases these "final earthquakes" of the aftershock cycles can be large enough to create damages (*Kuril Islands* aftershock cycle, Table 13). So, we need to analyse the aftershock cycles in order to know the magnitudes of their "final earthquakes".

13.3. There are some seismic cycles in which the accumulated energy is discharged not only by a single shock but also by two or even three shocks having almost the same magnitude. The geostatistical analysis is able to emphasize this situation (*Fiji* seismic cycle, 2002/08/19, Table 9). It is obvious that after the first shock the population must be warned about a second large earthquake that may occur in the next few minutes/hours/days later.

13.4. After the final earthquake(s) occurred in any area, it is necessary to analyse the aftershock activity because large and at the same time dangerous earthquakes can occur during this aftershock activity (*Kuril Islands* aftershock seismic cycle, Table 13).

14. SEISMIC CYCLES CLASSIFICATION

In section 6 we introduced the concept of *mean rate of energy accumulation* – S_a as a parameter that characterizes the seismic cycle from a dynamic point of view. In section 7 we established that this parameter is strongly correlated with the cycle's length L by the so called *characteristic function*. The mean rate of accumulation S_a divides the entire number of seismic cycles into three different categories:

14.1. ***V**ery **L**ong **S**eismic **C**ycles* (**VLSC**). These cycles always have $L > 500$ months, are also very slow (S_a very small) and as a general rule, they are very calm. It is interesting to mention that such cycles are encountered especially in areas where the accumulation process is managed by strike – slip faults. It is often very difficult to analyse many of these cycles because it is almost impossible to find suitable input data covering such long intervals of time (a complete and homogenous earthquake catalog, as it will be shown in section 15).

14.2 ***M**oderate **S**eismic **C**ycles* (**MSC**). These cycles have the length L included in the interval $L(\text{months}) \in [30, 500]$. As a general rule such kind of cycles are encountered in areas where the energy accumulation is managed by subduction phenomena. They are presented in the most cases of the world seismic regions and are characterized by a very high diversity factor. They can be either calm or violent, disturbed or not by large earthquakes occurred inside their evolution.

14.3 ***V**ery **S**hort **S**eismic **C**ycles* (**VSSC**). These peculiar seismic cycles always occur in the so called *aftershock activity*. These cycles are extremely violent (S_a very big), lasting from a few weeks at most to a few months. Many of them are very dangerous because large earthquakes can often end this special type of seismic cycles.

The method presented in this paper can be used in order to analyse the cycles from every category. Unfortunately, for every category of seismic cycle we have to build its own characteristic function and also to set in an adequate way the computer programs.

The computer software used by the authors is set at this time to work properly with **MSC** and the characteristic function is able to help in the forecast activity only for this type of seismic cycles.

In the next years it will be necessary to adjust the programs in order to be able to work also with **VLSC** and **VSSC**. It will be also necessary to build the characteristic functions for these special types of seismic cycles. Even if these operations are not so difficult but a real time checking may last at least a few years.

15. INPUT DATA

In every branch of science, when a method of analysis is used in order to interpret some recorded data, the guarantee that the output results are realistic is given by the quality of the method itself and also by the quality of the input data. We will discuss in this section what means the quality of the input data in the frame of the geostatistical analysis.

Geostatistics, as a method of analysis of the accumulation process demonstrated that the seismology is a world's science. Indeed, in the stage of characteristic function's building for a category of seismic cycles (as it was shown in section 7), the scientists have to analyse as many exhausted cycles as possible, cycles which occur in different seismic areas of the world.

To be sure that the results are comparable, the scientists need to use the same method of analysis (the same computer programs) and the same quality of input data. The first condition (singleness of the computer software) is entirely respected. With regard to the second condition (the quality of the input data) there are some problems which require to be further discussed.

For this kind of analysis, a set of input data always means a catalog of earthquakes occurred in the area under study. Magnitudes of these earthquakes are more important. Or, it is well known that in the field of the seismology there is no standardization in the magnitudes' computing of the occurred earthquakes. As a general rule, the magnitudes of small earthquakes ($M < 4.0$) are computed in the terms of local magnitudes (M_L, M_D, m_{GR}), the magnitude of a moderate earthquakes ($4.0 < M < 6.5$) are computed as body and surface magnitudes (m_b, M_S but also as M_L) and the magnitudes of large earthquakes are computed as M_S, M_W, M_L.

Knowing that every scale of magnitudes describes only a part of the discharged energy spectrum, it is easy to understand that a catalog of earthquakes which contains two or more scales of magnitudes represents in fact a mixture of distinct populations. Such kind of input data cannot provide realistic results. To complicate this matter we have to say that in computing of the magnitudes every agency uses some different correction factors, depending on the chosen agency. So, it results a very chaotic medium in which the seismologists must navigate.

In order to understand how the authors managed these problems, we have to say that all input data for this special kind of analysis must respect two conditions:

a) to be *homogeneous* on the whole length of the analysed seismic cycle;

b) to be *complete* on the whole length of the analysed seismic cycle.

a) A *homogenous* set of input data means a catalog of earthquakes for the analysed cycle in which the magnitudes were computed using the same scale. This condition is fulfilled for some seismic countries, in different intervals of time. Problems appear when we need to analyse similar seismic cycles from other countries where the catalog of earthquakes is computed in other scale(s) of magnitudes.

To avoid these problems the authors decided to use a single worldwide catalog created by a single agency. From this unique catalog there were extracted the catalogs of earthquakes occurred in the analysed area, catalogs that represented the input data for the analysis. The authors selected the worldwide catalog created by the *National Earthquake Information Center* (NEIC) that fulfill good enough the requirements of homogeneousness. In case of doubts regarding some magnitudes the authors resorted to another very good worldwide catalog computed by the *International Seismological Center* (ISC). From these two catalogs the authors extracted the subcatalogs for the analysed areas in which the magnitudes are computed in m_b scale only. The computer software that is currently used, is set in such a manner that it will only accept a catalogue computed in m_b scale as input data and the results are always obtained in M_S scale of magnitudes. The authors admit that the existence of these two worldwide catalogs (NEIC and ISC) allowed the evolution of this method. The authors deeply appreciate the work of the scientists from these two agencies.

b) The *degree of completitude* of any catalog of earthquakes is given by the rate of recorded earthquakes from the catalog versus the occurred earthquakes. It is interesting to notice that this parameter depends on many subjective and objective factors. It depends on the density of seismographs in a given seismic area but also, on the type of seismicity from the same area. Every combination of these factors:

- deep seismicity and dense seismic network,
- shallow seismicity and dense seismic network,
- shallow seismicity and scarce seismic network,
- deep seismicity and scarce seismic network,

will finally give different values of this *degree of completitude*. Much more, for a given seismic area, this parameter becomes better and better as the networks become more densely.

It results that this parameter has different values depending on the chosen seismic region and inside the same seismic area it is not constant in time. Using such different catalogs as input data might be very dangerous for the final results. In order to avoid these problems the authors forced the computer programs to accept only magnitudes $m_b = 4.0$ as input data sets.

The authors thought that the two worldwide catalogs (NEIC and ISC) present a very high degree of completitude in the range of magnitudes $m_b = 4.0$ for almost every seismic area from the world.

16. CONCLUSIONS

If we look at the succession of earthquakes from a given seismic area (which is generic called as seismicity of the area under analysis) we will have an impression that this seismicity represents a permanent phenomenon which started a few millions of years ago and lasts for other millions of years from now on.

In the frame of this permanent seismic activity, from time to time a large earthquake struck the area making some damages, after that everything entering into normality.

On this permanent seismic activity, the occurrence of an earthquake seems to be a random phenomenon that is not managed by any physical law. This sensation of permanent activity generates the types of methods of analysis developed in the last years.

Geostatistics changed this philosophy by quantifying this apparent seismic activity. There were defined independent, successive units, called seismic cycles. From the geostatistics point of view, the seismicity of a given seismic area represents a succession of independent seismic cycles having their own evolution limited in time. According to this new philosophy a large earthquake represents a logical and necessary phenomenon that discharges the energy accumulated during the evolution of any seismic cycle. It results that the occurrence time and the magnitude of this final earthquake is strongly managed by physical laws. The fact that these physical laws cannot be described by mathematical equations yet does not entirely obstruct the seismic monitoring and forecast of large earthquakes.

Attaching to every seismic cycle a *computed parameter*, S_a, or a *computed function* (the loading function) we will be able to compare different seismic cycles from the same area or from dissimilar seismic areas. Comparing different seismic cycles from the same area we will be able to evaluate the seismicity evolution in large intervals of time. Comparing different seismic cycles from different seismic areas we will be able to distinguish between various kinds of seismicity:

- seismicity generated by *strike – slip faults*;
- seismicity generated by *subduction processes*;
- *aftershock* seismic activity.

Changing the philosophy over the seismicity of a given seismic area, we will change also the methods of analysis. Forecasting the occurrence time and the magnitude of a final earthquake it is possible to change the way of monitoring the seismicity in a given seismic area, especially in the last part of a seismic cycle.

In fact, every seismic analysis of an evolving seismic cycle emphasizes a final earthquake that will occur in the end of the cycle. It results that every final earthquake will become an *expected large earthquake*.

So, before the occurrence of this expected large earthquake the seismic area can be covered with networks consisting of high sensitive sensors in order to record the next large earthquake as precise as possible. Moreover, inside this final part of a seismic cycle one can test different methods of earthquake prediction, knowing that the final earthquake will undoubtedly occur.

As a conclusion, an expected large earthquake will generate an extensive research activity in the analysed area because it represents more than a large earthquake that surprisingly occurs.

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