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Analysis of earthquake prediction models to obtain the best model

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Abstract: Relevance. The science of studying the causes of earthquakes is rapidly developing. Each cause of an earthquake can be considered a precursor of an earthquake and using these precursors, predictive models can be built. To date, there are quite a few earthquake prediction models, which allow you to analyze these models to improve accuracy, that is, apply forecast data with higher probabilities. **Aim.** Analyze forecasting models and, based on the substantiation of existing forecasts, classify them into "necessary" and "sufficient" models, and define these terms. And also, to determine the algorithms for planning further actions to obtain much better forecasting models. It is "necessary" to develop algorithms that bring the "necessary" model to the "sufficient" one and vice versa. "necessary" forecasting models are models whose set of forecasts always includes a set of actually occurring events, and "sufficient" forecasting models are models whose forecasts always come true. **The research methodology** is to process the existing large data structures that are specified for further use in our algorithm. To calculate the probability of forecast accuracy, an algorithm with "parallel data" – "parallel probability" is used, which allows you to select those pairs of forecasting models (or triples, quadruples, etc.), whose "joint" probability of forecast accuracy gives a much better result than separately. **Results** were the formation of an author's approach to processing earthquake forecast models and obtaining a generalized model that gives forecasts with a higher probability due to the use of statistics from already existing forecast models and their further observation. Algorithms have been defined for a) when to analyze all available required models and obtain one best model by combining the appropriate number of required models and b) when to combine enough models closest to guessing all predictions so that their number is less than in other unions. Also exists an algorithm that determines the study to be carried out after the occurrence of each event – the calculation of the probability of justification for individual models, as well as paired and triple models. The problem of using these algorithms in a specific area – earthquake prediction is discussed, and the results of the work of the author's algorithm are shown.

Keywords: predictive models, necessary and sufficient models, earthquake prediction.

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Оригинальная статья

Анализ моделей прогнозирования землетрясений для получения наилучшей модели

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Резюме: Актуальность работы. Наука, изучающая причины землетрясений, стремительно развивается. Каждую причину землетрясения можно рассматривать как предвестник землетрясения, и, используя эти предвестники, построить модели прогнозирования. На сегодняшний день существует довольно много моделей прогнозирования землетрясений, что позволяет анализировать эти модели для повышения точности, то есть применять данные прогноза с более высокими вероятностями. **Целью работы** является анализ моделей прогнозирования, их классификация на основе существующих прогнозов на «необходимые» и «достаточные» модели, дать определение этим понятиям. Также целью является определение алгоритмов планирования дальнейших действий для получения гораздо более качественных моделей прогнозирования. Необходимо разработать алгоритмы, приводящие «необходимую» модель к «достаточной» и наоборот. «Необходимые» модели прогнозирования – это модели, набор прогнозов которых всегда включает набор реально происходящих событий, а «достаточные» модели прогнозирования – это модели, прогнозы которых всегда сбываются. **Метод исследования** заключается в обработке имеющихся больших структур данных, которые заданы для дальнейшего использования в нашем алгоритме. Для расчета вероятности точности прогноза используется алгоритм с «параллельными данными» – «параллельная вероятность», который позволяет выбрать те пары моделей прогнозирования (или тройки, четверки и т.д.), «совместная» вероятность точности прогноза которых дает гораздо лучший результат, чем по отдельности. **Результатами исследования** стали формирование авторского подхода к обработке моделей прогноза землетрясений и получение обобщенной модели, дающей прогнозы с большей вероятностью за счет применения статистики уже существующих моделей прогноза и их дальнейшего наблюдения. Алгоритмы были определены для вариантов: а) анализа всех имеющихся необходимых моделей и получения одной лучшей модели путем объединения соответствующего количества необходимых моделей, б) объединения достаточного количества моделей, наиболее близких к оцениванию всех прогнозов, чтобы их количество было меньше, чем в других объединениях. Также существует алгоритм, определяющий исследование, которое необходимо провести после наступления каждого события – расчет вероятности обоснования для отдельных моделей, а также парных и тройных моделей. Обсуждается задача использования этих алгоритмов в конкретной области – прогнозирование землетрясений и показаны результаты работы авторского алгоритма.

Ключевые слова: прогностические модели, необходимые и достаточные модели, прогноз землетрясений.

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Introduction

The scope of predictive modeling is vast and includes the tasks of predicting natural phenomena: earthquakes, landslides, tsunamis, floods, etc., as well as the tasks of predicting the economy (business, macroeconomics), political events (elections, distribution of political power), medicine and other fields.

Geoinformatics: A scientific and technical direction that combines both the theory of modeling a subject area using spatial data and technologies for creating and using geographic information systems[Ivannikov et al., 2001]. As you know, the main tasks of geoinformatics:

1. Creation of geodatabases (geocoding) and their management;
2. Analysis and modeling of geodata;
3. Software development for the first two tasks [Khokhryakova, 2001].

In this article, we will outline the modeling task and create algorithms to improve the modeling process, which makes this task relevant.

Science is rapidly developing to study the causes of earthquakes. Of particular note are [Guglielmi et al., 2022; Zavyalov, Zotov, 2021; Kachakhidze et al., 2015; Kereselidze et al., 2012] where both the main causes of earthquakes and the earthquake prediction models built on their basis are discussed. Scientists do temporal and Spatial Geophysical Data Analysis for the Issues of Natural Hazards and Risk Assessment [Matcharashviliet al., 2015; Melkov et al., 2022]. Scientists study correlation between the value of macroseismic intensity and the indicators of instrumental records [Chelidze et al., 2019; Zaalishvili et al., 2014a, b, 2016, 2022] and also process some new data on the influence of various soil conditions on probabilistic seismic hazard assessment of territories [Chernov et al., 2022]. In the course of the study, the works of a number of authors were studied: [Yaitskaya, Brigida, 2022; Kerimov, Ezirbaev, 2022; Lipilin, Evtushenko, 2022; Tsiramua et al., 2009; Matcharashvili et al., 2016; Basheleishvili et al., 2019], who solve various problems of geoinformatics, including the problem of modeling.

Methodology

To solve the tasks set, a complex research method was used, which consisted in assessment of the probability of success.The research methodology is to process the existing large data structures that are specified for further use in our algorithm [Gasitashvili et al., 2019, 2021; Phkhovelishvili et al., 2019]. To calculate the probability of forecast accuracy, an algorithm with "parallel data" – "parallel probability" [Gasitashvili et al., 2019] is used, which allows you to select those pairs of forecasting models (or triples, quadruples, etc.), whose "joint" probability of forecast accuracy gives much better result than individually.

Earthquake prediction models have been studied by the authors of this article and their co-authors, and some results have been obtained, which are presented in various papers [Gasitashvili et al., 2019, 2021; Phkhovelishvili et al., 2019].

Based on the substantiation of existing forecasts, the article considers their division into "necessary" and "sufficient" models. About the best couples, trios, etc. the discussion will go on. Selection algorithms that will make it much easier for less developed countries to make better forecasts. Because in such countries it is impossible to have the appropriate equipment for a large number of models and observe them. With our current algorithm, fewer models can be used to get more probabilistic predictions.

The results of the work and their discussion

Each cause can be considered a precursor of an earthquake and based on these precursors, predictive models can be built. To date, there are quite a few earthquake prediction models, which makes it possible to analyze them, which determines the relevance of the topic under discussion.

For predictive modeling, definitions of the concepts of "necessary" and "sufficient" models are introduced.

Definition: "necessary" predictive models are those models whose set of predictions always includes a set of actually occurred events. Obviously, such models often give incorrect predictions, but they predict every event that occurs.

Definition: "sufficient" predictive models are models whose predictions are always correct, even though they cannot predict all events that occur.

If "sufficient" models predict that a particular event will occur, that event will definitely occur. However, other events were not predicted by "sufficient" models. In practice, there may be too few such models (for example, in earthquake prediction) or too many of them (for example, in economics).

A. Necessary predictive models

Suppose there are models $A_{1,} A_2, \ldots, A_n$ for predicting a particular event. Each of these models is necessary, which means that the event in question has the necessary antecedents for which these models are developed. n is the number of antecedents under consideration. These models do not consider models that take into account unnecessary antecedents, which is why they could not predict the occurred event. As demonstrated [Prangishvili et al., 2022], the necessary predictive modeling requires the calculation of "true prediction probabilities".

The true prediction probability of the model A_i is the ratio of the number of occurrences of an event to the number of occurrences of an event predicted by the antecedent of this model, expressed as a percentage, i.e. the probability of the A_i model's true prediction K_i is equal to:

$$K_i = \frac{m}{p_i}100\%,$$

Where m – is the number of events that occurred, and P_i – is the number of occurrences of the event according to the A_i model, which was based on a_i n antecedent.

For cases where we have a large number of necessary predictive models, we may arrange them according to the prediction time. In the beginning, we put the model that predicts the earliest (M_1), etc., and the last model predicts an event (Mn) before the occurrence of (t_v) event. Fig. 1 illustrates such distributed models that allow for the possibility of the timely response of the corresponding services. These are predictions that allow to management the relevant institutions and organizations.

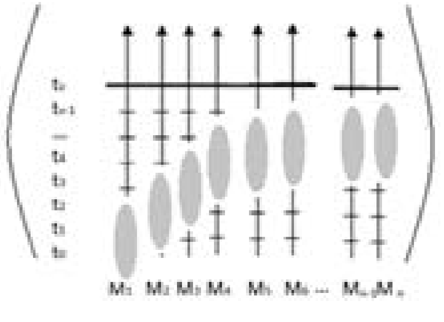

Fig. 1. Predictive models ordered by time

We discussed combinations of models (two, three, etc.) and estimated the probability of their combined correct prediction. Estimation and selection of combinations are made according to the definition of “parallel probabilities” [Gasitashvili et al., 2019]. It has been proven that when predicting events, if pairs of models are selected for which the number of “coincidences” of incorrect predictions of a given event is the smallest, but the presence of correct predictions for each of them is a necessary condition, then the true prediction probability calculated for such a best pair is always greater than or equal to the true prediction probability of the best model among all models (Fig. 2).

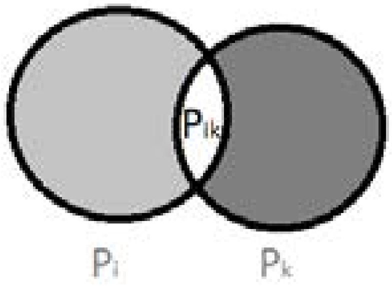

Fig. 2. Graphical illustration of two-model set case in an Euler-Venn diagram

This is an interesting metamorphosis – one may find a couple of models that individually often give incorrect predictions, but the intersection of their predictions gives the best results.

In addition, in case of the necessary models, it demonstrates that the more predictive model intersections we take, the better the prediction. For example, the best three – a combination of three predictions (Fig. 3) gives better results than the best pair of predictions (two), the best four give better results than the best three, etc. Thus, it makes sense to discuss the necessary sets of models.

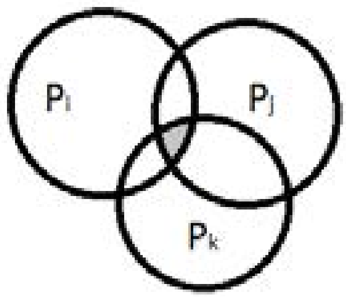

Fig. 3. Graphical representation of three-model set case in an Euler-Venn diagram

In necessary modeling, we do not consider unnecessary models, although the Bayesian approach does not make such a distinction [Stoltz et al., 2021]. On the contrary, all existing models are used to answer the question of whether a given event will occur or not. Depending on the predominance in terms of quantity or other characteristics (yes or no), an answer is given to the question of whether this or that event will occur at a given time.

B. Sufficient predictive models

In practice, when there are very few sufficient models and there is no single universal model that predicts all events, the question arises whether these sufficient models can be used in such a way that their combination predicts all events, that is Necessary predictive models, that is, the combination of models become sufficient.

For example, let us consider the history of a predictable event that has occurred *n* times over a period of time, such as one year or ten years. Suppose one of the predictive models predicts that a certain event will occur *k* times, the second – *p* times, and the third – *q* – times. If $k<n$ *or* $p<n$ *or* $q<n$, then this means that none of the models individually will be sufficient, but if we consider a combination of all three models, then together they may predict *n* number of events. It follows that having considered a combination of these three models in combination, we may get a sufficient model (see Fig. 4):

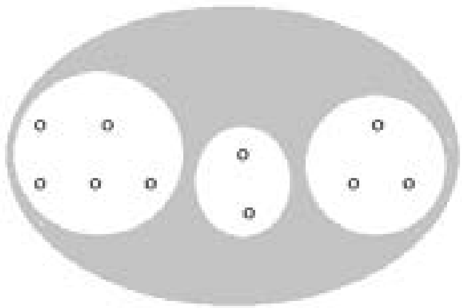

Fig. 4. A sufficient model built by combining three models

The figure considers three models. One predicted the event five times, the second model – 2 times (different from the first), and the third model – 3 times. Jointly, the three models predicted ten events, that is, exactly as many events as occurred, which means that their combination can be considered a “sufficient” model.

Algorithm for selecting pairs of the best models: when we considered the necessary models, then we should consider the intersection of the forecasts of these models as pairs of models, and in the set of sufficient models, we consider it necessary to consider their combination (not the intersection) and those models should be selected that, as far as possible, fully cover all possible events in the set. For example, if there were seven earthquakes, and one model predicted 3 of them, another predicted two others, and the third predicted two more, then together, that is the combination of all three models predicted all seven earthquakes.

Such models are “sufficient”, that is, they do not make predictions that do not come true. The “necessary” models are not “sufficient”, but the combination of these “sufficient” ones results in the “necessary” model, that is, we completely cover the set of all events that have occurred, so in this case, we are trying to get the most complete prediction of all occurred events. It may not be 100%, but in the end, after combining a “sufficient” number of models, it will be close to 100%, and also, obviously, here we combine antecedents and narrow down identical, repeating antecedents to a single antecedent. Here too we can consider which antecedent results from which of these antecedents.

The main objective is to bring the probability of guessing such a combination as close as possible to 100%. For example, if the probability of guessing is 90%, that means that combining enough models will cover 90% of the events, which will be a very good result.

The question is when the best models should be obtained from the “necessary” models and also when the best combination of best models should be identified. Obviously, the algorithm that was created first will analyze all existing models and existing data and obtain the appropriate number of required models, the intersection of which gives the best result. Also, from these models, a combination of "sufficient" models is obtained, which will be closest to the correctness of all forecasts, while their number is less compared to other combinations.

Model classification update algorithm for "necessary" models: Obviously, after each event, it may turn out that we already have new models, or some of the old "necessary" models may turn out to be un "necessary", which means that they could not predict the event that has occurred, in which case such models are discarded, and we will need to look for new pairs.

Model classification update algorithm for "sufficient" models: As for "sufficient" models, after each event, it may turn out that some "sufficient" models from the penultimate to the last event gave an incorrect prediction. In this case, such "sufficient" models are also discarded, and if a new "sufficient" model is introduced, then it is also processed to identify new and old "sufficient" models that cover events as fully as possible.

C. The example

To demonstrate the presented algorithms, consider a concrete example of earthquake prediction. Table 1 shows the latest earthquakes in or near Tbilisi City, Georgia, in the past 30 days (20.12.2022-20.01.2023), whose magnitude is from 3 to 5 [https://www.volcanodiscovery.com/place/7999/earthquakes/tbilisi-past30days.html]. We have taken earthquake magnitude, date of occurrence, time and name of the epicenter as characteristics of each earthquake. The table 1contains a list of earthquakes in descending order of magnitude.

Table 1

Latest quakes in or near Tbilisi City, Georgia

No	Magnitude	Date	Time	Epicenter
1	4.5	Jan 14, 2023	11:36 am	Dagestan, Russia, 44 km north of Zaqatala, Azerbaijan
2	3.8	Jan 9, 2023	11:55 pm	48 km east of Kutaisi, Imereti, Georgia
3	3.7	Dec 26, 2022	2:47 pm	4.6 km north of Oni, Racha-Lechkhumi and Kvemo Svaneti, Georgia
4	3.3	Dec 28, 2022	10:15 pm	68 km south of Grozny, Chechen Republic, Russia
5	3.2	Dec 29, 2022 11:41 am	Dec 29, 2022 11:41 am	Azerbaijan, 89 km southeast of Tbilisi, K'alak'i T'bilisi, Georgia
6	3.0	Dec 30, 2022	12:00 am	43 km east of Telavi, Kakheti, Georgia

Let us review several models of earthquake prediction specifically for Tbilisi City. Designate the earthquake prediction models as Mod_1, Mod_2, ..., etc. which provide some predictions through their predecessors (for example, for when it would occur, at which location and with which magnitude). We must choose only those models, which satisfy the necessary condition, i.e. intersection of the set of model predictions with the set of actual events should result in the set of actual events. We call this condition a "necessary" condition for choosing a prediction model. This condition in the case of earthquake means the following: If during the time T there occurred, for example, 6 earthquakes (as in our example), only those models should be considered that predicted all these twelve earthquakes. Assume that such are the following models: $Mod_1, Mod_2, \dots, Mod_n$. In our case it is not essential, what specifically is each model and based on which predecessors of the earthquake it makes the prediction.

The numbers of predictions, the numbers of successful and failed predictions must be calculated for each model and calculated the probability of success for each model. It is obvious in this that the sum of successful and failed predictions is equal to the total number of predictions. As for the probability of success, it is calculated for each model and determines, how many times earthquake prediction was made and how many times an actual earthquake occurred. The following Table 2 shows the obtained results:

Table 2

Calculation of justification probabilities for individual models

Model	Number of predictions	Successful number of predictions	Failed number of predictions	Probability of success (%)
Mod_1	92	6	86	6,52
Mod_2	80	6	74	7,50
Mod_3	81	6	75	7,41
Mod_4	97	6	91	6,19
Mod_5	82	6	76	7,32

Assume that in total for 5 models there is calculated probability success and these values are: 6.52, 7.5, 7.41, 6.19, 7.32.

Author of each model of earthquake prediction claims that their model is best and argues that their model predicted each actually occurred earthquake. Neither of them provides number of wrong predictions, and, therefore, do not calculate success probability, which is quite low values. The success probability for a model might be low, but it is possible to find another model for this model, with which a combined possibility of success ensures the best result. We will show the correctness of this for our example.

We should consider pairs of models as a next step for the algorithm. In total there will be 10 pairs: M1, M2,…,M10, where M1=$Mod_1 \cap Mod_2$; M2= $Mod_1 \cap Mod_3$; M3= $Mod_1 \cap Mod_4$; M4=$Mod_1 \cap Mod_5$; M5= $Mod_2 \cap Mod_3$; M6= $Mod_2 \cap Mod_4$; M7= $Mod_2 \cap Mod_5$; M8= $Mod_3 \cap Mod_4$; M9= $Mod_3 \cap Mod_5$; M10=$Mod_4 \cap Mod_5$. For each model, we should calculate the numbers of predictions made, the numbers of successful and not successful predictions and, also, calculate the success possibilities for each pair. The following table calculates these values for pair models (Table 3):

Table 3

Calculation of justification probabilities for pairs models

Model	Number of predictions	Successful number of predictions	Failed number of predictions	Probability of success (%)
M_1	14	6	8	42,86
M_2	8	6	2	75,00
M_3	26	6	20	23,08

M_4	11	6	5	54,55
M_5	23	6	17	26,09
M_6	10	6	4	60,00
M_7	8	6	2	75,00
M_8	17	6	11	35,29
M_9	9	6	3	66,67
M_{10}	18	6	12	33,33

Let us analyze the obtained table by the corresponding diagram (see Fig. 5), where we see that the best result is obtained from M_2 – combination of two models Mod_1 and Mod_3 and M_7 – combination of two models Mod_2 and Mod_5.The combined probability of success for them is increased up to 75%. Despite the fact that separately these models have significantly lower rates of success: 6.52% and 7.41%. For the considered examples, it is possible that two pairs of the models show the same result. In such a case, an expert should decide, which one of them should be used.

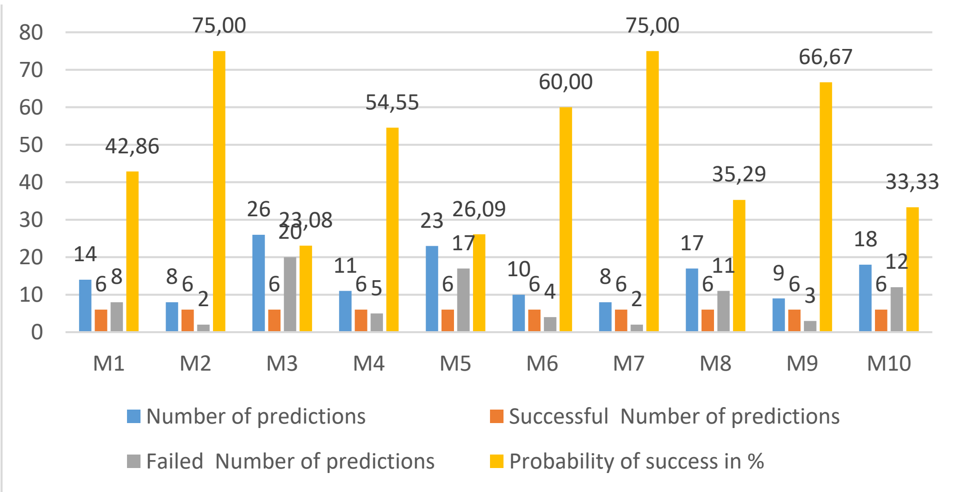

Fig. 5. The characteristics of the "necessary models" for pairs

Obviously, this applies not only to prediction of earthquakes, but to prediction of any other event, including static (most often these are problems of natural disaster prediction), and dynamic prediction, such as economic problems.

Summary

We have explained what necessary and sufficient models are. For the necessary models, an algorithm was proposed for choosing the intersection of two or more models, which in combination give a more probabilistic forecast. We have also discussed sufficient models and an algorithm for choosing sufficient models whose combination completely covers all occurred events. That is, there is also a need to combine such sufficient models. Thus, it is possible to obtain a sufficient or almost sufficient prediction model by intersecting the necessary models and by combining sufficient models to obtain the necessary or close to the necessary model.

In the algorithm proposed by us, unnecessary models are not taken into account when using the necessary models. If there are models that cannot predict the event (but are not sufficient models either), then such models are discarded from our database. Similarly, when considering sufficient models, where an excess forecast of an event is given, such a model can be excluded from the database of sufficient models.

Thus, we have explained what is necessary and sufficient models for predicting events, how to derive necessary models from sufficient ones, and determined how to derive sufficient models from necessary ones.

From sufficient models, we derive the necessary model, which will be both sufficient and necessary at the same time. In addition, we combine such sufficient models to obtain the necessary model.

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