Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022)
Edited by Maria Chiara Leva, Edoardo Patelli, Luca Podofillini, and Simon Wilson
©2022 ESREL2022 Organizers. *Published by* Research Publishing, Singapore.
doi: 10.3850/978-981-18-5183-4_S08-06-484-cd

Towards a new seismic short-term prediction methodology for critical service operators and manufacturing companies against earthquake

Vadim Bobrovskiy

Graduate School of Management, Politecnico di Milano, Italy. E-mail: Vadim.bobrovskiy@polimi.it

Paolo Trucco

Graduate School of Management, Politecnico di Milano, Italy. E-mail: Paolo.trucco@polimi.it

Alexey Kaplin

Cosmetecor UK Ltd, England. E-mail: Alexey.kaplin@cosmetecor.org

This paper is concerned with the novel short-term and operational-term seismic hazard assessment approach within the critical service operators and the manufacturing industry. The Cosmetecor earthquake prediction methodology has been tested and validated in the recent two decades. A prototype, Kuznetsov method, for exploring the Earth's interior has been used to create global monitoring network, which automatically detects spatial-temporal clusters and identifies electric potential anomalies. Research team developed the mathematical modelling of proton migration in terms of the fundamental Vlasov-Maxwell equation to convert original time series into visualization of electromagnetic wave. A 2-layer neural network model is used to fine-grained classification. Further, the statistical and scaling laws of seismicity have been exploited to present case of earthquake seasonality, i.e., a dataset of abnormal seismic scenarios for machine learning task. Finally, authors evaluated results in terms of reliability and accuracy of earthquake warnings at M5.2 threshold in Kamchatka: 17% of all warning represent missed alerts, and 83% represent correct alerts where events occurred in a 10-year time horizon. Common outcome in almost every case is mean lead time (time horizon) of $\mu(N)=11.62$ days. The dispersion is $\sigma(N)=6.7$ days. Further, a non-random sample of the Italian companies assessed new benefits of methodology during survey. The stakeholders confirmed that they will be able to activate business continuity plan to mitigate earthquake consequences in a specific time frame. It is anticipated the emergence of new risk management practices on the Cosmetecor-based high technology of the 21st century, and the replacement of the long-term, one-in-a-hundred-year return period, assessment with a short-term, seasonal, seismic risk assessment.

Keywords: Seismic Risk, Reinsurance, Seasonality, Risk management.

1. **Introduction**

Several academic studies addressed the complexity of how seismic events can affect businesses or an entire economy (McDonald, 2015, Lackner, 2018), and of the variety of risk measures that can be used to assess the vulnerability of infrastructure and the associated impacts (Calvi et.al., 2006; Sathurshan, 2022, Vatenmacher, 2022), in particular considering that critical infrastructure systems have become more complex and interdependent (Brown, 2004), and the dynamics of cascading failures is getting more difficult to predict and assess (Brunsdon, 2002; Pescaroli, 2018). A way to address this issue is the estimation of the downtime of infrastructure service after an earthquake (Zhang et.al., 2009). The downtime is the time required to achieve pre-event performance after a disastrous event (Tierney, 1997). Natural disasters, such as earthquakes, can be devastating also to businesses because of their vulnerability to capital, labour, suppliers, and markets. Businesses often report direct physical damages to buildings, equipment, and inventories. However, business organisations are dependent on external essential services (e.g. electricity, gas, and telecommunication) and are linked with other supply chain actors, such as suppliers. Thus, beside direct damages, companies are exposed to possible business interruptions contingent to the unavailability of critical infrastructure (Kammouh et.al., 2018) and suppliers (Pant, 2014).

So far, literature is more concentrated on repair and reconstruction costs, repair time, mobilization of resources and decision making in the reconstruction phase (Weng et.al., 2020). A major shortcoming of existing risk assessment approaches is that the recovery to their initial (pre-disaster) performance level is established on the basis of long-term post-disaster reconstruction estimations and fail to consider a recovery within a short period of time in the aftermath of the disaster. One reason is that given the number of expected annual earthquake occurrences and rare catastrophic events, long-term planning is the best risk reduction option. However, in the short time, after a seismic event, companies primarily rely on their limited recovery budgets and preparedness measures they have taken prior to the event.

Earthquake warning systems (EEW) can help companies mobilize resources and make informed decisions (Cremen et.al., 2022). They are designed to issue alerts based on magnitude thresholds calibrated on damage-to-loss relationships of the built environment. Thus, the current EEW methodology (Guenan et. al., 2016) only works for binary actions when the end-users receive an alarm on seismic hazard in real-time. Furthermore, the EEW benefit is limited to the available lead (or warning) time between the alarm notification and the onset of strong shaking, which is typically tens of seconds only. This very limited time window strongly influences the ability of business organisations to implement articulated response actions or activate business continuity plans along with the automatic sirens to evacuate people from buildings, the automatic shutdown systems for nuclear power plants (Cauzzi, 2016) or the sudden speed reduction of high-speed trains (Minson, 2021). The activation of a business continuity plan in case of an earthquake would require much more time to be effective.

The aim of this study is to develop and validate a novel seismic short-term prediction methodology whose characteristics enable the decision maker to implement specific preparedness actions or activate the company business continuity plan.

The proposed methodology was built and validated relying on data collected from the Cosmetecor platform. The platform is an information management system based on global station network and software modules to enhance integrity throughout the machine learning pipeline in a cloud based system.

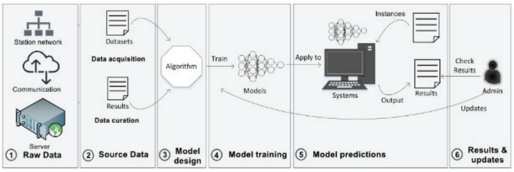

Fig. 1. Cosmetecor platform architecture integrating machine learning pipeline (adopted from Witando, 2022).

The rest of the paper is organised as follows. The proposed methodology its phases are reported in Section 2, which specifically details how methodology is developed in the context of risk-driven EEW to provide more reliable and anticipated predictions. Section 3 involves an application of the methodology to seismic risk prediction in Kamchatka (Russia). The Discussion section highlights the degree of alignment between the prediction performance of the novel methodology and business stakeholder's needs when it comes with the proactive management of seismic catastrophes. The concluding section draws the main implications for research and practice stemming from the design and validation of the proposed seismic short-term prediction methodology across events and across time horizons for a single event.

2. Methodology

The methodology is developed on leveraging and implementing existing tools, i.e. mathematical modelling of proton migration in Earth mantle (Hou et.al., 2021, Bobrovskiy et.al., 2022), a prototype of the Cosmetecor global station network (Bobrovskiy et.al., 2017), diagnostic algorithms for temporal electric anomalies and methodology for the occurrence frequency of seismic activity and magnitude exceedance over short-term (less than 1 year), within a next-generation framework. The methodology specifically combines 1) the statistical and scaling laws of seismicity (Unified Scaling Law for Earthquakes) which, unlike the Poisson model, describe dependent events, and this approach was previously applied to seismicity variations in six-years long time window (Nekrasova, 2021 and references within); 2) machine learning (ML) methods to define number of feature objects by contrasting and analysing the relationship between the anomalies in electric potential and seismic scaling law statistics.

The overall methodology is articulated into 3 steps, as reported in the following.

Step 1: Develop a time diagnostics matrix (ALGO_ELAnomaly).
At the first step, we collect electric potential data over time over multiple locations on the planet - ***ε(t, i),*** where *ε* - is the potential (electromotive force), **t** - time and **i** - location. Then we run a ML-based anomaly detection algorithm to obtain an anomaly function:

$$A(t,i) = ALGO\_ELAnomaly(\varepsilon(t,i))$$

Step 2: Establish a correlation between diagnostic matrix and earthquakes events.
ALGO_COR - is an algorithm, that converts an anomaly function ***A(t, i)*** into a prediction function for a specific time horizon ($t_{HORIZON}$) and lead time ($\boldsymbol{lead_{time}}$).

$$\boldsymbol{C\_h}(\boldsymbol{t}, \boldsymbol{lead_{time}}, \boldsymbol{t_{HORIZON}})$$

$$\Rightarrow \boldsymbol{ALGO\_COR}(A(t,i), \boldsymbol{t_{HORIZON}}, \boldsymbol{lead_{time}})$$

where C_h - is a predictive function for a number of events during the next period (days/year/month).

Then we run an optimization to obtain the best match over all possible $t_{HORIZON}$. We consider $\boldsymbol{lead_{time}}$ to be equal to 1, 2, 3, 4, 5, 6, … 12 months. Thus, $t_{HORIZON}$ is defined similar to $\boldsymbol{lead_{time}}$ from 1 to 12 months.

The optimal prediction function C(t) is selected for specific **lead_time**. To indicate the quality of a prediction model we compare it with a statistical prediction based on a historical earthquake frequencies alone.

Additionally, this model can be applied to the entire planet as well as to certain regions. We used USGS catalogue put forward a historical data of earthquakes with epicenters distributed across Kamchatka (between 48...60 North and between 150...168 East).

Step 3: Apply prediction function for decision making.
The risk assessment (VaR) comes from an estimate of a fractile value on a seismic loss curve corresponding to a selected probability level. VaR is a mathematical measure used in CAT-modelling to represent a risk profile. By improving this estimate over the short-term, we can reduce the cost of pay-outs and, as a result, easing the capital solvency requirements for the insurance portfolio.

Traditionally, synthetic earthquake catalogues (stochastic event sets) are generated over a centuries-wide time horizon drawing on historical data. However, this model approach has the disadvantage of a spread between real events and their uniform stochastic estimate in the short-term. For realistic calculations, frequency (inter-event time variability) and clustering of events in space, time, and size are needed (Bak & Tang 1989; Christensen et.al. 2002; Zaliapin, 2008; Vidale and Shearer, 2006).

The correct estimate of insured events clustering in time is used to avoid total loss (exhaustion) , after refinement of the frequency prediction of the insured event. Our research finds that the methodology presented in the paper can be used to employ models similar to those used in "seasonal" insurance markets.

3. Application: forecasting seismic events in Kamchatka (Russia)

The proposed methodology is demonstrated, using a timeseries collected through the network of Cosmetecor stations located in Kamchatka (between 48...60 North and between 150...168 East). The forecasting is for a 10-year interval from 01-st July 2006 to 30-th January 2016. The examined 10 years interval reflects the diversity of seismic activity under Kamchatka at various distances from the reference point, including large and deep-focus M8.3 earthquake beneath the Sea of Okhotsk, west of the Kamchatka peninsula, a number of earthquakes of M7+ and of M5.2+, and a total number of 156 events in the period. The choice of location is on purpose, given that Kamchatka had experience since the beginning of '90th to benefit from short term warnings for large M6.9+ earthquakes issued by the Cosmetecor system and model (e.g., Bobrovskiy, 2017).

Up to date, this system combines non-seismic algorithmic estimates, to forecast an impending earthquake with estimated magnitudes of at least 5.2 and located no more than 100 km from the reference point at 53.05° North 158.65° East. This reference point is located in Petropavlovsk-Kamchatski city, regional center. The large earthquake on 30-th January 2016, was the single largest event that occurred 100-km from the reference point 53.05° 158.65 in a 10-year interval from 01-st July 2006 to 30-th January 2016 (Fig. 2).

The heat map (fig. 2) shows how the prototype station network allows Cosmetecor to deduce the variable process in the earth's mantle by observing non-stationary changes of electric potential and their relation to the major seismic events that accompany subduction of the Pacific plate under Kamchatka. The computation for a group of four stations located 0-5-10-25 km from the reference point revealed the contrast spatial localization of the electric potential before impending ground motion on 30-th January 2016, M7.2.

Most of the time, the user experiences a correct warning 30 days in advance in the proximity of business location. The warning reflects impending ground motion close to the user's location that coincides with 100-km from the reference point 53.05° 158.65. (Fig. 2).

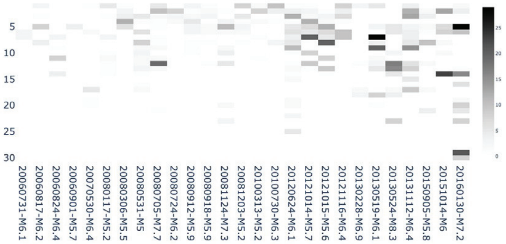

Fig. 2. The plots are for a 10-year interval from 01-st July 2006 to 30-th January 2016. The OY axis on the left denotes the number of days during which the changes in the electrical potential were recorded before each earthquake. The OY axis on the right is the aggregated intensity of the signals vs stations. The aggregated sum of the electric potential is maximum before earthquake M7.2 on 30-th January 2016, details in Bobrovskiy et.al. (2022).

For the correct, false, and missed alerts, we see (Fig. 3) that the most common outcome in almost every case is mean lead time (time horizon) of μ(N)=11.62 days. The dispersion is σ(N)=6.7 days.

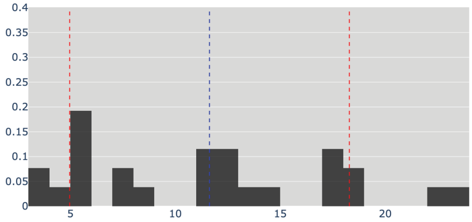

Fig. 3. The plot is lead time distribution in case study: μ(N)=11.62 (blue line), σ(N)=6.7 (red line)

This is true for the correct, false, and missed alerts at the M5.2+ threshold. However, missed alerts increase rapidly at the M4-M5 threshold, and missed alerts are dominant below the threshold M2.5-M3.9 due to the scaling law of seismicity.

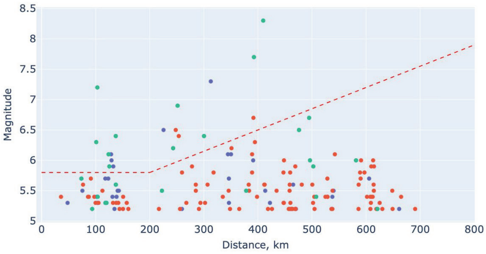

Fig. 4. The dotted line is illustration to the problem. Total number of events are 156 for a 10-year interval from 01-st July 2006 to 30-th January 2016 located in Kamchatka.

Figure 4 represents total number of seismic events at the M5.2 threshold. The hypocenter parameters of events were selected in the National Earthquake Information Center database (https://www.usgs.gov/programs/earthquake-hazards/earthquakes) between 48...60 North and between 150...168 East. The total number of false alerts for the M5.2 threshold is small (Fig. 5). For example, 17% of these numbers represent missed alerts, and 83% represent correct alerts (Fig. 6).

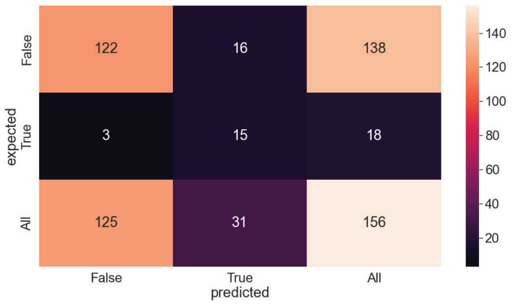

Fig. 5. Confusion matrix (events) – reliability of prediction.

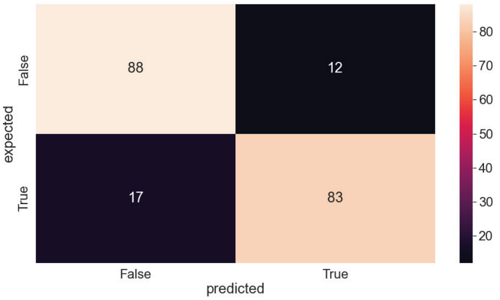

Fig. 6.Confusion matrix (%) – reliability of prediction

The results indicate that the model is most likely able to produce reliable earthquake forecasting in a specific time frame. Stakeholders will have time to take the right action, they will be able to implement specific preparedness actions or activate the company business continuity plan to mitigate earthquake consequences.

4. Discussion

The final decision is ultimately determined by scientists and emergency managers to approve a given earthquake alert before it is disseminated. The existence of a soundly based, easy to explain and understand, methodology may however help to ensure that decisions are set rationally. This has not been the case with operational (days) earthquake forecasting, primarily because of lack of scientific consensus. Risk managers argued that this is a new class of warning that carries significant uncertainties. The situation is gradually changing with new scientific discoveries (Hou, 2021) and enhancement of the capability of the Cosmetecor technology for earthquake forecasting.

.

As these warnings have a relatively short lead time (days) and are dependent on the accuracy and global multi-point monitoring along tectonic plates, this should not prove such a big barrier if there is a lively and expanding community of stakeholders. Traditionally, the estimated return period of the earthquake is set to be reliable at one in a hundred year horizon. It may be the reason that discourages companies from investing on earthquake catastrophe risk management. We need to understand if stakeholders can deviate to new practices and the warning time horizon provides the framework for this investigation.

The survey was designed into two main parts – the first to assess the current earthquake mitigation practices of the target sample, and the second to assess benefits of the new seismic methodology for different groups of stakeholders. This survey was administered on a non-random sample of the companies in various parts of Italy to ensure that the results can be generalised to the entire state. The total number of companies in the sample was 19 such as service and SME companies – 8; insurance companies – 1; manufacturing companies – 7; critical service operators – 3.

Insight in launching the survey clearly illustrates the extremely cautious approach that is implicit in the adoption of new risk management practices. While (1) 82% of the sample has already adopted BCP plans, (2) 70% of the sample operates its services in areas subject to seismic risk and (3), a significant portion of the sample, (77%) has already explored the market for natural hazard forecasting services, only a minority of the sample (30%) has already adopted a predictive service for natural events within their organisation, of which only 17% has already incorporated a service specifically aimed at predicting seismic events such as EEW system.

But the business experience is likely to change over time. A significant proportion of the sample (77%) believes that their business would benefit from the availability of a seismic prediction service, and this is linked to the fact that 62% of the sample state that their business is negatively impacted by the occurrence of a seismic event. 78% of the sample also state that the availability of such service would positively impact their service level.

To capture each of the phases of impact, two groups of stakeholders need a warning in a specific time frame (have strictly individual preferences for a particular time warning issuing). Critical service operators need alerting only 3-5 days in advance, while insurance companies need alerting more than 21 days in advance. Manufacturing companies and SME/service companies reflect the same interest in the 3-5 days, 14 days or 21 days time interval. These results indicate that current stakeholder preferences are centered on an assumption that next-generation seismic hazard assessment are around the 1st percentile level of their potential 'true' loss distributions. In other words, the current stakeholder expectations appear to almost totally disregard the results of the traditional long-term earthquake catastrophe modelling. The urban lifeline operators and manufacturing companies may also require more time for activating best mitigation strategies rather than automatic shutdown systems, which may explain the low penetration of EEW systems within both stakeholder groups, 0% vs. 38% (average).

This observation still leaves the question of an appropriate choice for the mitigating options by a stakeholder. An airport does not need many days to activate BCP, before the event occurs. While a railway network or electricity network operator has to verify the feasibility of planning alternative routes for the trains or power transmission in the area affected by the event in the forecast period. In the interview with the motorway network manager, this question was further explored. The manager envisaged the use of Cosmetecor warning information may not reach its full potential without a regulatory framework. Either a legislative act is passed to regulate the matter or, alternatively, a public body purchases the service and then makes it available to its users, as in the case of the ISNet seismic network in Campania (AMRA). Each of these matters warrants further investigation.

5. Concluding Remarks

Present risk management practices describe measures for preparedness prior to a major seismic event and at several intervals following it. If activated at the right time, these measures may have an impact on the duration of the impact and remedy. While companies must deal with the seismic risk and rare catastrophic events, they must also maintain financial capital in order to activate business recovery in the case of an event.

The probability of occurrence of a major seismic event is 1% (1 in 100 years). While the safety of personnel and material is priority for businesses, risk managers are limited with actions by the significant uncertainty of an impending earthquake occurrence. Earthquake alerting, in the form of early warning (seconds) or operational warning (days and months) is the most viable information to achieving this goal.

For this purpose, we assessed the reliability of the novel short-term earthquake forecasting methodology developing a 2-layer neural network model. The trained model demonstrated that 17% of all warnings represent missed alerts, and 83% represent correct alerts where events occurred in Kamchatka in a 10-year interval. The detailed survey confirmed that stakeholders need to have time to activate business continuity plan. We found lead times $\mu(N)=11.62$, $\sigma(N)=6.7$ using the novel short-term and operational prediction methodology. Critical service operators and manufacturing companies confirmed that they will be able to implement specific preparedness actions to mitigate earthquake consequences in this specific time frames. Authors envisage the appearance of new risk management practices that rely on the next-generation scientific methodology for earthquake forecasting.

Acknowledgement

Thanks to MBA holders Marco Bersano and Marco Ravalli.

References

Bobrovskiy, V. et.al. (2017) Nonstationary electrical activity in the tectonosphere-atmosphere interface retrieving by multielectrode sensors: case study of three major earthquakes in central Italy with M6. Earth Science Informatics 10, 2 , 269–285.

Bobrovskiy, V. and P.Trucco (2020) Developing a new framework for earthquake resilience: stakeholders' needs assessment. Proceedings of 30th European Safety and Reliability Conference.

Bobrovskiy, V. and et.al. (2022) Mathematical modelling of proton migration in Earth mantle. Math. Model. Nat. Phenom.Vol. 17, 2022 https://doi.org/10.1051/mmnp/2022018

Calvi, G.M. et.al. (2006). Development of seismic vulnerability assessment methodologies over the past 30 years. J Earthq Technol 43(3): 75–104

Cauzzi, C. et.al. (2016). Earthquake Early Warning and Operational Earthquake Forecasting as Real-Time hazard Information to Mitigate Seismic Risk at Nuclear Facilities. Bull. Earthquake Eng. 14, 2495–2512.

Galasso, C. et.al. (2022) Investigating the potential effectiveness of earthquake early warning across Europe. Nat Commun 13, 639.

Cremen G. et.al. (2022) Developing a risk-informed decision-support system for earthquake early warning at a critical seaport, Reliability Engineering & System Safety, Volume 218, Part A, 2022, 108035.

Guenan, et.al. (2016). Accounting for end-user preferences in earthquake early warning systems. Bulletin of Earthquake Engineering, 14(1), 297–319.

Hou, M. and et.al. (2021) Superionic iron oxide–hydroxide in earth's deep mantle. Nat. Geosci. 14 (2021), 174–178.

Kammouh, O. et.al. (2018). Downtime estimation and analysis of lifelines after an earthquake. Engineering Structures, 173:393-403.

Lackner, S. (2018) Earthquakes and economic growth, FIW Working Paper, No. 190, FIW - Research Centre International Economics, Vienna.

McDonald G. et.al. (2015) Economic Impact of Seismic Events: Modeling. In: Beer M., Kougioumtzoglou I.A., Patelli E., Au SK. (eds) Encyclopedia of Earthquake Engineering. Springer, Berlin, Heidelberg.

Minson S.E. et.al. (2021) A Framework for Evaluating Earthquake Early Warning for an Infrastructure Network: An Idealized Case Study of a Northern California Rail System. Frontiers in Earth Science. 9.

Pant, R. et.al. (2014). Static and dynamic metrics of economic resilience for interdependent infrastructure and industry sectors. Reliability Engineering & System Safety, 125:92-102.

Sathurshan, M. et.al. (2022) Resilience of Critical Infrastructure Systems: A Systematic Literature Review of Measurement Frameworks. Infrastructures. 7, 67. https://doi.org/10.3390/infrastructures7050067

Tierney, K. J. (1997) Business impacts of the Northridge earthquake. Journal of Contingencies & Crisis Management. 5(2). pp. 87-97.

Vatenmacher M. and et.al. (2022) Performance-driven vulnerability analysis of infrastructure systems. Inter. Jour. Dis. Risk Red.. Volume 76, 103031.

Weng, Y. Z. (2021) A Bayesian Network Model for Seismic Risk Analysis. Risk Analysis. Oct;41(10):1809-1822.

Xiao Y., et.al. (2022) Seismic resilience assessment of urban interdependent lifeline networks Reliab Eng Syst Saf, 218 (2022), Article 108164

Zhang, Y. et.al. (2009) Vulnerability of community businesses to environmental disasters. Disasters. 33(1). pp. 38-57.