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IV. REMOTE SENSING OF THE ENVIRONMENT

METHODOLOGY FOR A KINEMATIC MODEL OF SEISMIC EARLY WARNING SYSTEM ABOUT CRITICAL INFRASTRUCTURE

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Abstract: The destructive earthquakes generated huge losses and human victims. As for the moment the time of impending strong seismic event is unpredictable, during the last years – new global innovation is under development – the seismic early warning systems (SEWS). All of them signalize the population and/or governmental bodies and after the earthquake starts just providing information that the seismic event is fact, to expect stronger shakings and some very fast measures to be performed – for example NPP’s reactors stop, as well as superfast trains, chemical production, gas and oil pipeline disconnection, etc. In lucky cases some people can react (especially in the areas of low buildings) and to evacuate effective in the time domain of few seconds, thus saving their lives. Such system is in operation in Japan since 2007 and some other countries also develop their own SEWS. The present investigation is targeted to the methodology development of so called kinematic SEWS. They are using a fundamental property of the body seismic waves P and S. As it is well known from the theory, the P-waves are faster and less destructive than S-waves. This property gives the possibility to use the detection of the P waves as important signal that after a while (the time domain depends on the distance between the seismic source and the investigated site) the slower (1.41 times) more destructive S waves will arrive and struck the infrastructure. Our previous experience of the developed SEWS (for example for Baku and Venice) gives the possibility to upgrade the modeling methodology extending to the formalized algorithm and accuracy estimations, especially for the critical infrastructure (for example NPP).

Keywords: kinematic model, early warning system, critical infrastructure

INTRODUCTION

The seismic early warning systems (SEWS) are the world innovative product. Heavy earthquakes and tsunamis occurred in Japan (2011), Sumatra (2004), Chile (2010, 2014), Solomon Islands (2014), Turkey (2023), etc. These earthquakes and the following tsunamis demonstrated clearly the need of Seismic and Tsunami Early Warning systems. All known SEWS are based on the fundamental physical property of the seismic waves propagation: the P-waves (with lower amplitudes and smaller destructive potential) travel approximately 1.41 times faster than the S waves (with larger amplitudes and much more destructive potential, due to the medium particles movement, perpendicular to the wave ray propagation). Up to now – only Japan has fully operative and effective SEWS introduced in operation in 2007. Its efficiency was demonstrated during the M9 earthquake on 11th March, 2011. During the recent years Indonesia is another country developing SEWS. Some failures after the tsunami generated by heavy mud flows and volcanic eruption, focus the specialists’ attention to new developing SEWS considering the non-tectonic sources of tsunami and other hazards generating destruction and loss of human lives. Working SEWS are these in Pacific, Indian ocean, Atlantic ocean and some regional in Mediterranean – Italy, Greece, Portugal, France, etc. Several cases (for example Baku and Venice) have been investigated and kinematic models about earthquakes and tsunamis developed in Bulgaria and tested.

During the last years SEWS and TEWS have been on focus in Bulgaria. Many projects related to this issue have been executed. Several very peculiar cases and kinematic models have been developed in two directions:

- The SEWS about two typical cases – Vrancea and Pernik seismic sources;
- The tsunami EWS for the Bulgarian Black Sea coast.

PHYSYCAL CONDIDERATIONS AND SIMPLE THEORETICAL BASICS

The typology of the Early Warning Systems (EWS) working in the real time mode could be systemized in two big groups (Ranguelov B., 2014):

- Seismic EWS (SEWS) – working in the time domain of seconds to tens of seconds (very rare to minutes) and
- Tsunami EWS (TEWS) - effective in the time domain of minutes to hours.

For now we’ll focus to the SEWS.

All known SEWS are based on the fundamental physical property of the seismic wave’s propagation: the P-waves (with lower amplitudes and smaller

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destructive potential and frequently called “signaling”) travel approximately 1.41 times faster than the S waves. The P-waves have compression/ extension movements of the particles of the solid strata and move to the ray propagation path. These waves are fastest and have highest velocity – between 6 and 8 km/s. The amplitudes of the P-waves are frequently the lowest in the whole phase package of any seismic wave emitted by the seismic source. The S-waves have several times larger amplitudes and a much greater destructive potential, and due to the medium particles movement perpendicular to the propagation of the wave beam, they have a lower velocity. The S-waves also do not propagate trough liquids and have a dominant rotational component. The range of the Vs and Vp according the theory is $2^{-1/2}$.

The equation

$$Vp/Vs = 2^{-1/2} \qquad (1)$$

is the fundamental relationship on which the kinematic SEWS are functioning. This relationship always exists in the solid ideal body and is an immanent property of any ideal elastic medium. Frequently in the earth crust this relationship shows smaller value due the not ideal elasticity of the Earth’s strata.

The travel time function F (d, $t_{p,s}$) presents the relationship between the travel times of the different waves phases (S, P, Sg, Pg, Sb, Pb, etc.) and the distance to the seismic source. The function in the coordinate system (d, t) is usually a straight line, depending of the velocity of the seismic waves in the respective layer. The travel time function is the main relationship, which is used to calculate the kinematic models of the time deficit EWS. The main principle of the SEWS requires longer time propagation from the seismic source to the threaten territory, which means longer distance. This time (t_p-t_s) is called “warning time” and presents the difference between the P and S waves arrivals to the threaten object (Parushev I, B. Ranguelov, 2014). In our case it is the critical infrastructure. Then the kinematic model used the travel times of S and P waves and their differences (Fig. 1). To model the coverage of each wave phase isochrones diagrams are constructed dependent to the distances (Fig. 2).

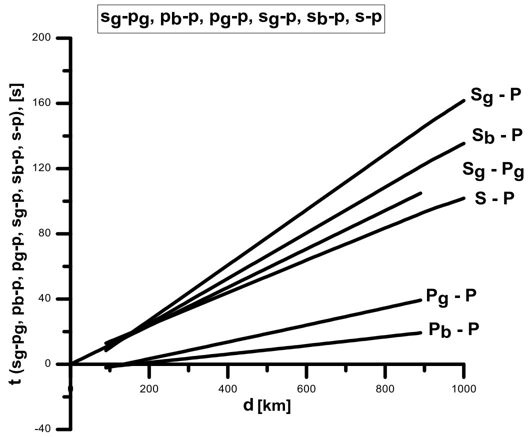

Fig**.** 1. The example of the different S, P travel times differences and their phases according the distance

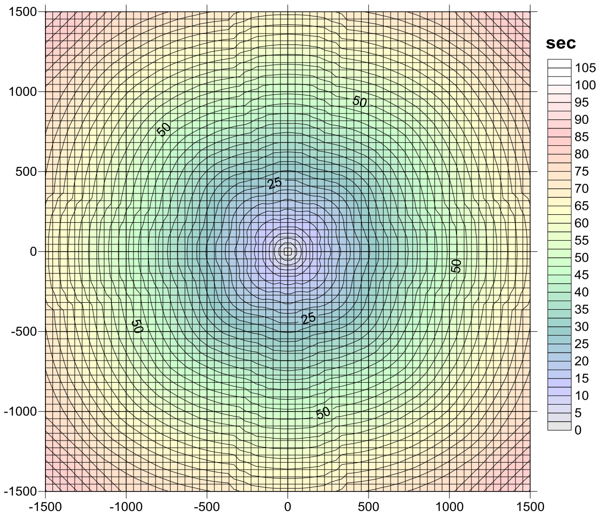

Fig 2. Modeled isochrones versus distances - coverage of the knots. In the model they represent the seismic sensors for the best coverage.

EARLY WARNING SYSTEMS AND THE INFORMATION TRANSFER

An important issue related to the EWS is the data and information transfer – both from the sensors to the operation center and from the center to the public (Ranguelov et al., 2011; Ranguelov et al., 2014; Ranguelov, 2013; Mardirosian and Ranguelov, 2013, etc.).

The data and information transfer may use some recent high effective facilities and technologies: space satellites, radio links, cell networks, telephone lines, etc. The data used by the early warning systems usually are signals generated by the sensors in the frequency diapason 0.001–100 Hz. The high dynamic range is around 120 dB. These signals could be transferred by analog or digital channel. Usually the analog signal (former EWS) has low amplitude and needs some measures and devices to provide its reliable transfer like magnifiers, filters and compensators, etc. There are cable networks in use to transfer the data into the information centers for data processing. The disadvantages of such networks are the high price of the transfer and the larger losses of the useful part of the signals. There are as well the transfer networks using the telephone cables. They need a modular requency (500 to 2500Hz) to modulate the signal. These networks have also some disadvantages – high noise ratio, vulnerability to the different construction works, high price cables, etc. All analogue channels have one biggest advantage − they allow the real time analog signals transfer. The digital networks (even the most sophisticated) work in the near real time mode. The digital technology goes fast in all recent systems. The advantages of this technology are much more – the digital signals are reliable to the noise protection, the data transfer and processing are much easier using the recent computer technologies, the data storage is much more effective. The low prices and the wide use of the digital technologies make them leaders in the recent early warning systems. In many cases the analogue channels are eliminated by the high density information channels compressed even in a single cable doublet. The telephone companies introduce the digital technology and increase the security and reliability levels of their transferred signals. The recent cellular networks are also suitable for the signal and information transfer. Such type transfer networks are related to the radio links. The price is lower, but the special regime of use needs more administration and formalities, like retranslations, heavy problems connected with the sharp topography, etc.

A variant of the radio links is the satellite connection. After the big numbers of geostationary satellites have been launched to orbit they build up a network which is largely used about the telemetry of the geophysical and meteorological data. The satellites on Low Earth Orbit (700−1400 km) are called LEO, on the medium (10000−15000 km) – MEO and on the Geostationary (36000 km) – GEO. All these satellite systems created the global communication ring, which is under operation for different purposes. To use it as an element of the early warning systems is the main challenge of the recent times (Ranguelov et al., 2006).

The differences between the recent and the time deficit early warning systems are the two heavy and slower components: the processed information - transfer and the end users and decision maker’s solutions. They could be eliminated by the simplest, but most powerful software and hardware able to decrease the false alarms using the triggering mechanism and intelligent sensors, which may provide more reliable information and take decisions about the early warning dissemination automatically. The philosophy about the recent and the near future systems shows that it could be possible to eliminate the slower and less effective blocks concerning the transfer of the processed information and the end users and decision maker’s solutions – to be or not to be issued the early warning. This task could be reach by the more sophisticated software, supperfast computing abilities and the “smart” location of the sensors (Frantzova et al., 2006).

The use of the “smart” sensors, which are able to “take and perform” the decision, the sophisticated software, which is able to prove the reliability of the warning issue and the fastest recent digital technologies are the main elements which could provide the highest reliability of the effective and rather autonomic early warning systems. The main problem in this competition is to save time. The fastest communications can win against the velocity of the natural hazards. This could be reach by recent technologies and better software. The effectiveness of the early warnings in time deficit domain is the most important parameter taken into consideration. The main parameters defining the effectiveness are the velocity of the hazardous process, the velocity of the data and information transfer, the organization of the early warning issue and the transfer of the reliable information to the public. Two ways are under consideration. The established EWS existing up to now and the recent new established and near future SEWS (Mardirosian G., B. Ranguelov, 2012). The use of the recent technologies in all aspects of the information collection, processing transfer and dissemination appears essential. The main issue is considered the possibilities to save time due to the fast recent technologies for the information collection, data transfer and warning issues. The combination between EWS projects and smart EWS devices – smart sensors and "smart" communications is the essential way to increase the effectiveness of the recent time deficit EWS. The role of the remote sensing and satellite communications is very important although they are able to provide the smart recent technologies for the fast and safe information transfer. The use of the cell phones, smart-phones and i-phones provides the new and efficient opportunity to disseminate the early warnings not only to the decision makers but also to the wide public. Some failures of modern TEWS are due to the communication problems (Ranguelov, 2018).

MODEL CONSTRUCTION – ALGORITHM

The algorithms of the early warning system action is developed on the kinematics of the seismic (respect. tsunami) waves, considering the different velocities of the P and S waves (for the SEWS) and seismic and tsunami waves (in case of the TEWS) (Ranguelov and Frantsova, 2017). The installation of the hardware needs to follow some general considerations (Ivanov et al., 2016; Parushev and Ranguelov, 2014):

1. Selection of the locations according the seismic sources geography
2. Travel times curves for the transformation of the distances to the time domain.
3. Use of the P-waves arrival times for the signalization of the event and triggering the whole system.
4. Seismic station optimization according the seismic sources locations and the sensors of common use (in some cases) of the same equipment (if possible). This means use of existing national or regional seismological networks.
5. The trigger stations location to the nearest point of any epicenter.
6. Use of some stations locations of the equidistant travel times to the seismic sources for the direction assessment of the seismic source.
7. Peripheral stations for detection of the strong seismic motions with sources outside the network geometry.

The general steps follow the philosophy that it is essential to have a signal for the hazardous event (earthquake or generated tsunami) as soon as possible after its generation (Ranguelov, 2014). As the seismic P, S − waves velocities are in the range of km/s it is essential to have a seismic sensor as possible as to the nearest point of the epicenter. The same is valid when tsunami wave is generated by the seismic (or other type tsunamigenic event – landslide, turbidities, volcanic ash slump, etc.). When the threshold is considered for the dangerous event, if the registered level is higher, then the whole algorithm is triggered. After that the following steps are necessary:

1. P-wave signal that the event is generated and the waves then propagated. (Usually such signal triggers the entire network).
2. Modeling of the wave's propagation direction, following the consecutive triggered seismic devices.
3. Selection of the precomputed scenario (this is valid for the tsunamigenic sources, because of their variety in magnitude, location, bottom and costal geometry and other influencing the tsunami propagation parameters). For the earthquakes the scenario is generated by the network automatically. This step is closely related to the so called – decision matrix – a protocol determining the early warning issue.
4. Modeling of the time of incoming S-waves (for the SEWS) and the time delay of the S-waves, following the P waves. Zonation to near distance, middle distance and long distance and introduction of the "red", "orange" and "green" signaled zones.
5. Same for the tsunami waves (if considered). The confirmation of the tsunami waves generated by the disturbing event (earthquake, slump, fast subsidence, etc.) usually is performed by the bottom located devices (microbarographs, sea-level measuring devices, OBS, DART, etc.) like effective hardware.
6. Automatic decision for the warning issue – the preliminary decision matrix development.
7. Warning issue to the clients – population, civil defense authorities, decision makers, administrations, etc.
8. The combined warning issue in case of simultaneous action of earthquakes, landslides, turbidities (or other generating events) and tsunamis.
9. The transmit on possibility of the warning is in various ways – SMS, i-phone adds, e-mail message, pager signal, TV, radio emissions, sound or light signals, etc.

10. Cancelation of the warning after the event passed.

To use effectively these algorithms a lot of specific actions must be performed (Ranguelov and Frantsova, 2017). The most important one is the hardware (devices) installation as possible closer to the seismic (tsunami) source. This could be a specialized seismic strong motion device, or the nearest seismic station of the national seismological network.

PRACTICAL APPLICATION

Kinematic model for the Bulgaria seismic sources

During the last years several projects related to the SEWS have been executed. The Bulgarian kinematic model for SEWS is developed in (Ranguelov 2014). To build up such kinematic model several seismic sources are outlined (these are coinciding with the approximate locations of the real earthquake sources on Bulgarian territory) and presented to the Table 1.

Table 1

№	Seismic source	coordinates		Depth
		ϕ [E]	λ [N]	[km]
1	Sofia	23°20'00"	42°40'00"	10
2	Kresna	23°10'00"	41°50'00"	10
3	Plovdiv	25°00'00"	42°10'00"	10
4	G. Oriahovica	25°50'00"	43°10'00"	10
5	Shabla	28°30'00"	43°30'00"	10

Then the kinematic model used the travel times of S and P waves and their differences (Fig. 4). To model the coverage of each wave phase isochrones diagrams are constructed dependent to the distances. The implementation of the methodology related to the main Bulgarian seismic sources shows the time intervals between 5 and 20 seconds according to the selected seismic source (Fig. 3). The time deficit SEWS are very sensitive to the accuracy and reliability (Ranguelov, 2014).

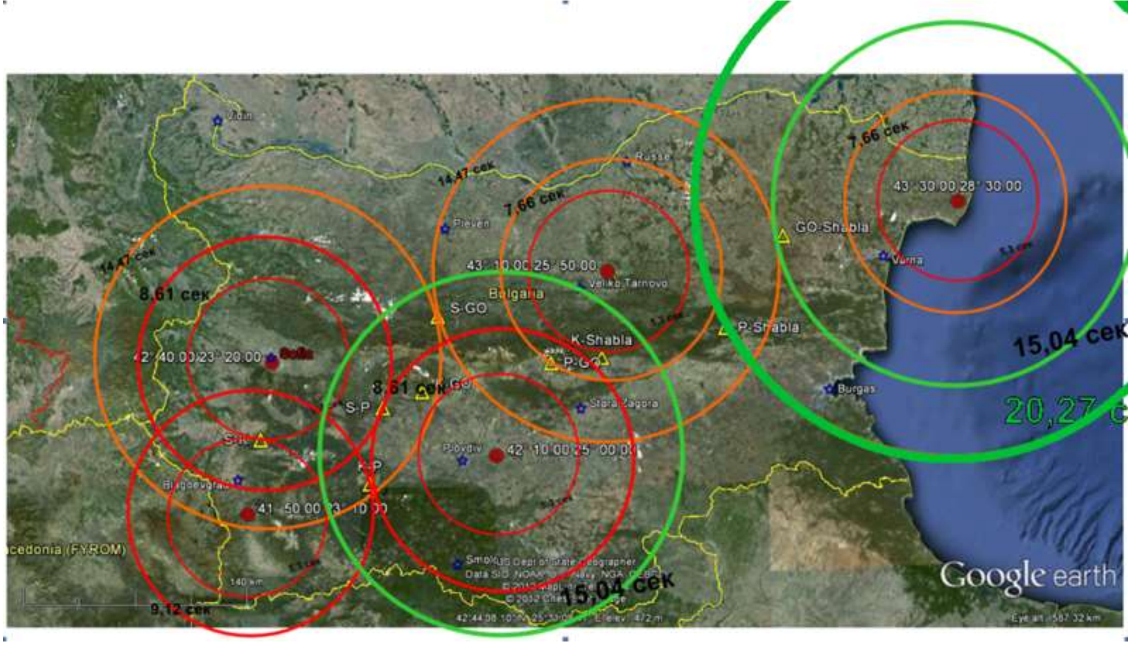

Fig. 3. The t_s-t_p isochrones of each seismic source at the levels of 5.3 (dark red), 7.6 (light orange), 8.6 (red), 14.5 (orange) 15 (light green) and 20.2 (green) seconds, covered almost the entire territory of Bulgaria

The Vrancea seismic source

The same methodology described for the whole country, including all local seismic sources is applied as well as for the Vrancea source. The Vrancea seismic source is rather specific and has several peculiarities: very clear fixed position in space (location and depth), well defined P and S phases of the direct body seismic waves and due to these specifics could be easily accepted as a point source – Table 2.

Table 2

Vrancea seismic source			
Cities	Distance (km)	Travel time - ts-tp	Travel time - tp
Vidin	334	37,3	49,7
Lom	326	36,5	48,7
Russe	241	28	37,8
Dobrich	307	34,6	46,3
Pleven	308	34,7	46,4
Vratsa	365	40,4	53,8
Tarnovo	327	36,6	48,9
Varna	347	38,6	51,4
Gabrovo	352	39,1	52,1
Sofia	425	46,4	61,4
Burgas	407	44,6	59,1
Blagoevgrad	499	53,7	70,9
Plovdiv	441	48	63,4
Stara Zagora	399	43,8	58,1
Haskovo	455	49,4	65,3
Kardzhali	489	52,8	69,6
Madan	509	54,7	72,2
Smolian	504	54,2	71,5
Gotse Delchev	525	56,3	74,2

Fig. 4. The travel times t_s-t_p (Vrancea source) show the time for reaction after the early warning is issued

Due to the model and the results obtained, the Vrancea seismic source model shows the pretty reliable and high effective SEWS. The minimum t_p of the seismic waves reaching Bulgarian territory is about 50 seconds and the t_s-t_p – about 40 seconds (Ranguelov, 2013). This time is rather effective about the EW issue for such a limited territory. The time response is easy to be transferred into measures – for example – shut down the reactors of the NPP, to close gas and oil pipes, to stop the electricity, to shut down the dangerous production activities, etc. Of course, the evacuation time for the population is rather short, but in case of a good preparation and effective education about the correct behavior in case of strong seismic event, the individual reactions can safe many lives.

ACCURACY AND RELIABILITY (ESPECIALLY FOR THR CRITICAL INFRASTRUCTURE)

Due to the sensitivity of the model to the time, it is important to assess the accuracy and the reliability of the kinematic SEWS to the parameters of the propagation time of the seismic waves.

There are several factors influencing the results and accuracy of the seismic kinematic model:

- The travel times used for the calculations. It is well known that the different phases of the seismic waves travel with different velocities trough the Earth's layers and have different travel time in dependence of their propagation trough these layers. Usually to increase the accuracy the local travel times tables are in use depending of the velocity model between the seismic source and the threaten object. To establish correct velocity model specialized investigations must be performed using blasts (or other sources of vibrations) and movable seismic stations. Thus the influence of the local velocity non homogeneities could be avoided.
- The delay time of the triggering device. Recent devices have the starting time delay less than 0.1 s and thus it couldn't be a hardware problem.
- The reliability of the triggering device. It depends on the stable electric power supply. The usual way to eliminate this factor is the duplication of the devices and the electricity charging devices using batteries, solar panels, other reliable power sources.

CONCLUSION

The methodology for construction of the seismic kinematic model related to threaten objects (in focus are the critical infrastructures) is developed based on a previous experience and investigations.

The methodology presented the physical basics and the theoretical considerations regarding the kinematics of the different types of seismic waves and their destructive potential. The functional algorithm and accuracy and reliability of the model of seismic early warnings are also considered.

Some illustrative examples support the results and promise further development up to the practical application and realization of a real seismic early warning system for any type of critical infrastructure.

The described development is subject to patent protection at the Bulgarian Patent Office. (Mardirosian et al., 2023)

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