KINEMATIC MODELS AND APPLICATIONS FOR THE EARLY WARNING SYSTEMS – EARTHQUAKES AND TSUNAMIS

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Abstract: *The kinematical models about seismic and tsunami early warning systems are developed using the standard methodology of the travel times for seismic S and P waves as well as for the tsunamis travel times. For both types the travel times of the P, S, and S-P seismic waves are calculated. These calculations can be used by the local authorities, decision makers and other responsible institutions (like Civil Defense, Administrations, etc.) for the development of a SEWS providing resilience of the infrastructure and population in case of strong earthquake occurring anywhere. Several models of the travel times of tsunamis propagation trough the Adriatic Sea have been used. The travel tames from some seismogenic sources in the Black Sea also show the time limitations for the warning issue. Both needed complex hardware for the effective operation. The decision matrix is suggested using all available hardware for the marine hazards observations. Some practical considerations are presented about the organization of a SEWS and TEWS, using the existing seismic networks or creation the own infrastructure of these early warning systems.*

КИНЕМАТИЧНИ МОДЕЛИ И ПРИЛОЖЕНИЯ ПРИ СИСТЕМИТЕ ЗА РАННО ПРЕДУПРЕЖДЕНИЕ – ЗЕМЕТРЕСЕНИЯ И ЦУНАМИ

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Резюме: *Системите за ранно предупреждение при земетресения и цунами са практически приложения на най-напредничавите постижения на съвременните науки за Земята. Всички сеизмични системи се основават на едно фундаментално свойство на сеизмичните вълни: P - вълните (с по-малки амплитуди и по-малък разрушителен потинциял) се разпространяват в твърдите среди със скорост приблизително 1.71 пъти по-бързо от S – вълните (с няколко пъти по-големи амплитуди и благодарение на свойството частичките на средата да трептят в перпендикулярна посока на разпространение на вълните имат значително по-голям разрушителен потинциял. Всички системи за предупреждение от цунами се основанват на разликата в скоростите на разпространение между сеизмичните вълни и цунами вълните.*

Няколко специфични кинематични модела се използвани, като е създадена матрица на решенията включваща:

- *Сеизмична система за ранно предупреждение от типични земетръсни огнища*
- *Система за ранно предупреждение от цунами генерирани в Адриатическо и Челно море*

Introduction

The seismic early warning systems (SEWS) and tsunami early warning systems (TEWS) are the world innovative product. Heavy earthquakes and tsunamis occurred in Japan (2011), Sumatra (2004), Chile (2010, 2014), Solomon Islands (2014), etc. These earthquakes and the following tsunamis demonstrated clearly the need of Seismic and Tsunami Early Warning systems. 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 11^{th} March, 2011. All TEWS are based on the time differences between the propagation velocity of the seismic and the tsunami waves which differ in the range of 10^2 to 10^4 of seconds. 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 TEWS about a case of the tsunami sources located near the Bulgarian Black Sea coast.
- A combination of TEWS and SEWS developed for Venice.

Theoretical basics

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

- 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.

The TWES such like the transoceanic tsunamis required (for example PTEWS and ITEWS – located in the Pacific and Indian oceans) time of warning issue between hours and days. All known SEWS are based on the fundamental physical property of the seismic wave's propagation: the P-waves (with lower amplitudes and smaller destructive potential) travel approximately 1.71 times faster then the S waves. The S-waves do not propagate trough liquids.
The range of the Vs and Vp according the theory is $2^{-1/2}$
The equation

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

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. The travel time function is the main relationship, which is used to calculate the kinematic models of the SEWS. 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. The TWES are based on a similar relationship but in the two mediums – water and the solid Earth. The time difference between the tsunami and the seismic waves can reach the range of 10^2 to 10^4 of seconds. The important peculiarity of the tsunami waves is that they are moving with very low amplitudes (not larger then few meters – in the extreme cases) and very low frequencies (long lengths of about tens to hundreds of kilometers) in the open ocean, where they propagate with higher velocity (between 800 and 1 000 km/h).

Kinematic models for Bulgaria. Tsunami Early Waning System (TEWS) in the Black Sea

The projects related to the TEWS have been developed during the last years – like ESNET, MARINEGEOHASARD, etc. All of them are closely related to the seismic generation of the tsunamis they have as main component a complex equipment – for seismic (on land and in the sea) monitoring and the sea complex stations. As the MARINEGEOHASARD Project is the only one related to the hardware establishment and is intended to act as a real time warning system here only this case is under discussion. (Ranguelov et al., 2011). The MARINEGEOHAZARD Project represents the first major initiative to address in an integrated and coordinated manner the establishment of a geohazard early-warning system for the Black Sea**.** General objective of the Project is - Implementation of an integrated early-warning system accompanied by a common decision-support tool, and enhancement of regional technical capability, for the adequate detection, assessment, forecasting and rapid notification of natural marine geohazards of risk to the Ro-Bg Black Sea cross-border area. The modeling (Ranguelov, 2010) of the travel times using most conservative model shows that the time interval that tsunami can reach the coast is between 20 and 40 minutes. This time is very limited to any safety measures. Thus is shown that the intended TEWS in the black sea (Romania-Bulgaria border region) is really time deficit system. – Figure 3.

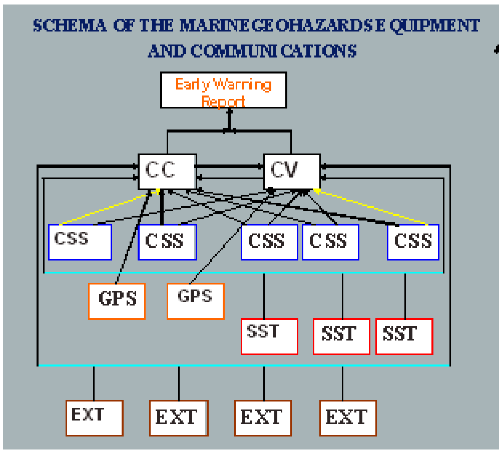

Fig. 1. Main components of the TEWS according the MARINEGEOHASARD project
CC – Centre Constanta, CV – Centre Varna (Both Centers are equivalent in their operational activities)
LEGEND: CSS – Complex Sea Station, SST – Strong motion Station, GPS – GPS Station, EXT – Extensometer Station, SAT – Satellite communication (yellow), INT – Internet Communication (blue)

To create the correct precalculated kinematics models, the virtual (closer to the reality) seismic sources, with their respective parameters have been selected (Ranguelov, 2010). The travel time of a tsunami front is between 20 and 30 minutes to the nearest sea coast.
During the efforts to make such a system operational in a real time mode special investigations were performed to establish a Decision Matrix (DM) before warning issue. – Figure 2. The main focus of this research was to incorporate all the available equipment deployed on land and in the sea. The main hardware components included in the system are as follows (Ranguelov, 2014):

- SMD – strong motion devices (detect strong motions generated by)
- SMD and local/regional seismic networks (BG,ROM) (provide earthquake parameters determination
- Complex Bottom Stations (CBS=OBS+DART) (detecting the tsunami generation)
- GPS networks: Bulgaria (5 stations), Romania (13 stations);
- EXT – Extensometers networks (Bulgaria local network)
- The two data centers – Varna and Constanta

SMD	CBS	GPS		EXT		Tsun warning
green	green	green	red	green	red	green
orange	green	green	red	green	red	green
red	green	green	red	green	red	orange
green	orange	green	red	green	red	orange
orange	orange	green	red	green	red	red
red	orange	green	red	green	red	red
green	red	green	red	green	red	red
orange	red	red		green	red	red
red	red	red		red		red

Fig. 2. Decision Matrix for the tsunami warning – three levels of alert

Local seismogenic and tsunamigenic conditions are considered about the combination of the seismic and tsunami warnings (Ranguelov, 2011):

Seismic early warning system – Bulgaria applications

Kinematic model for the Bulgaria seismic sources

During the last years several projects related to the SEWS have been executed (DACEA, SIMORA – still active, etc.). The Bulgarian kinematic model for SEWS is developed in (Ranguelov, 2013). 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. Parameters of the main seismic sources in Bulgaria

№	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 time's curves of S and P waves and their differences (Figure.3.) to calculate the respective times. To model the coverage of each wave phase isochrones diagrams are constructed dependent to the distances. – Figure.3. 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 – Figure. 3.

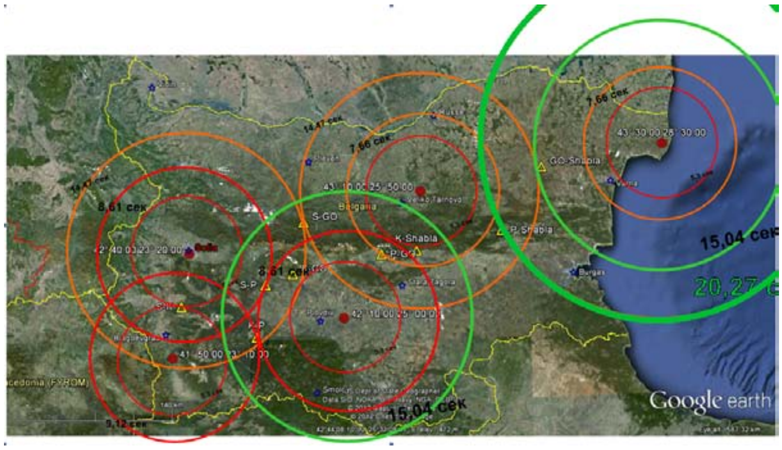

Fig. 3. The t_s-t_p isochrones of each seismic source at the levels of 5.3 (dark red), 7.6 (light orange), 8.6 (red), 14,5 (orange) 15 (light green) and 20,2 (green) seconds, covered almost the entire territory of Bulgaria

The Vrancea (Romania) 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. Due to the model and the results obtained, the Vrancea seismic source model shows the pretty reliable and high effective SEWS. The minimum tp of the seismic waves reaching Bulgarian territory is about 50 seconds and the t_s-t_p – about 40 seconds. This time is rather effective about the EW issue for such a limited territory – Figure 4. 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.

The Pernik seismic source kinematic model

The results due to the kinematic model application to Pernik seismic source are investigate by a specific methodology (Ranguelov et al, 2013)

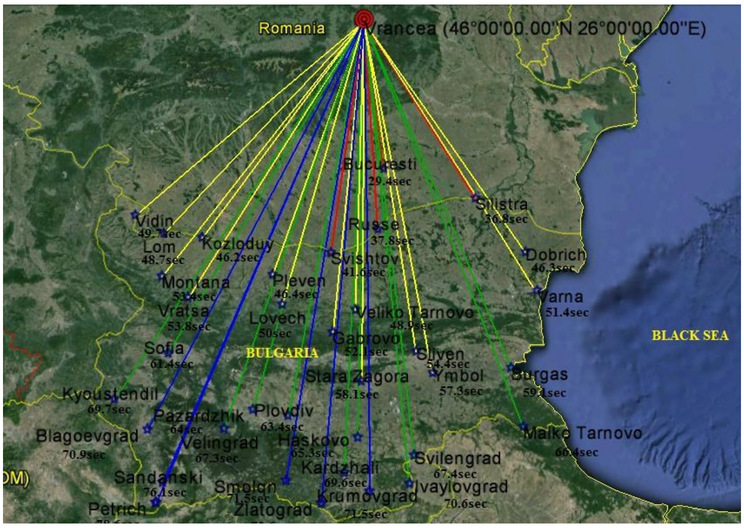

Fig. 4. The travel times t_s-t_p (Vrancea source) show the time for reaction after the early warning is issued

Venice case – SEWS and TEWS kinematic models

Venice as a world cultural heritage city is threatened by many natural hazards – floods, lagoon fulfillment, pollution, etc. This part of our research is focused to the possible negative influence of two natural hazards - earthquakes and tsunamis. Both hazards are wide spread in Italy since historical times until the present days.

Hypothetical Seismic kinematic model

It is based on the assumption that P waves are traveling from each seismic source to the city of Venice. The seismic sources are outlined by the researchers during the construction of the seismic zoning map of Italy (Slejkoet al, 1998). The seismotectonic model considered all known seismic events occurred on the territory of Italy simplified as geometrical polygons.

According to the new seismic zoning maps of Italy (Slejko et al, 1998), Venice is attributed to the zone of expected PGA between 0.08 and 0.12 g for 475 return period (which is a standard for EU) and macroseismic intensity of VII MSC, with a probability of exceeding 0.1g in 20 years. This suggests the expected seismic shaking, which could be dangerous for the historical buildings in Venice.

To investigate the expected travel times of the first P wave arrivals (“signaling” - seismic phase) we use the calculated model of Jeffrey’s-Bullen table. The data is used to model the kinematic peculiarities of the P, S and S-P waves travel times for each distance between the respective seismic zone and the city of Venice. (Fig.5). The zones are extracted from the seismic zoning map of Italy (Slejko et al, 1998), applying the same approach of the “Low” and “High” seismic active zones. The geometric centers of each zone are obtained using Golden Software’s Surfer.

Hypothetical tsunami kinematic model

The travel times of the tsunami wave’s propagation from the respective tsunamigenic source to Venice have been calculated using acceptable models – for example. The results of (Paulato et all, 2011) show the travel times from the established tsunami sources, together with the expected wave heights at the lagoon of Venice. According these results the travel times are enough for the evacuation measures, thus decreasing the tsunami risk for the city of Venice from the influence of the possible tsunamis generated in the Adriatic Sea. On one side this is acceptable low risk for the population. On the other – the possible additional tsunami influence to the effects of the floods – seasonal or generated by storm surges can increase dramatically the destructive potential in case of such coincidence. That’s why an effective tsunami warning system could be very useful for the Venice resilience to the combination of the tsunami and seismic risks. To avoid such risks a combination of the seismic and tsunami early warning systems could benefit by the city administration of Venice. Such experience have been developed and used by the Bulgaria-Romania border region including marine hazards in the sea and on the land (Ranguelov, 2013).

Results for Venice

As it was mentioned before the seismic sources have been divided in two classes – “high” and “low” seismically active. The modelled calculations covered both types. For illustration we used only the “high” seismic active zones – fig.5. It is clearly visible that the nearest distances are due to the Central Apennines seismic zones located at the distances between 130 and 200 km. On the same figure all other distances are plotted with different colours. This gives the possibility to estimate the farer seismic areas, which can generate seismic signals at the distance more than 800 km.

The average travel times of the P waves are presented. They show that the minimum travel times from the “high seismic” zones range between 30 and 36 seconds. These travel time are very short, but gives a possibility of the automatic systems to switch off the lifelines in the city.

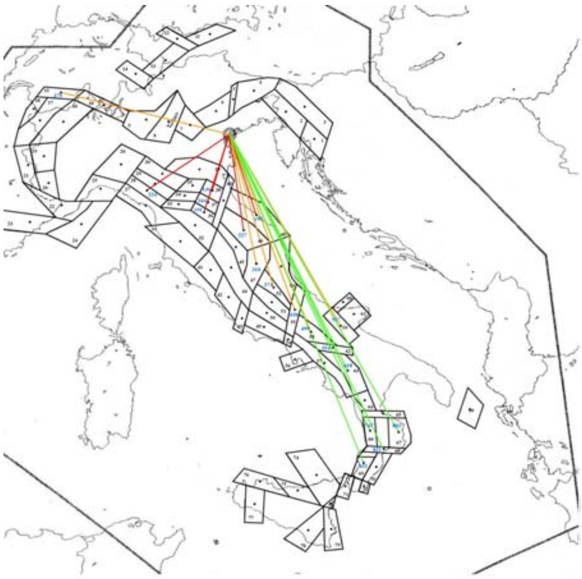

Fig. 5. Seismotectonic sources of Italy according (Slejko et al, 1998) and distances between them and Venice

Some chances for the population to evacuate at the more secure places are also available. The larger “signaling” times are expected from the most far zones and range between 110 and 120 seconds (about 2 minutes). The “warning” times (t_s-t_p) varied between 19 and 88 seconds – fig.5. These time intervals between the first arrivals of the “signaling” P waves and the most destructive “damaging” S waves also provide some time for reaction.

The tsunamigenic zones at the Adriatic Sea – most dangerous for the Venice lagoon are extracted from (M. Paulatto et al, 2007). – Fig.6. The distances and the travel times are modeled following the methodology described in (Paulatto et al, 2007) and presented at fig.8.

The models covered all seismic active zones in Italy creating danger for Venice. They have been divided into two main groups – “high” and “low” active seismic zones. For both types the travel times of the P, S, and S-P seismic waves to the city of Venice are calculated. These calculations can be used by the local authorities, decision makers and other responsible institutions (like Civil Defense of Venice) for the development of a SEWS providing resilience of Venice infrastructure and population in case of strong earthquake occurring anywhere in Italy.

The models of the travel times of tsunamis propagating trough the Adriatic Sea and the calculations of them show relatively high effectiveness of the TEWS regarding Venice lagoon and low coasts.

Some practical considerations are presented about the organization of a SEWS and TEWS in the region of Venice, using the existing seismic network of Italy or creating the new own infrastructure of the early warning systems

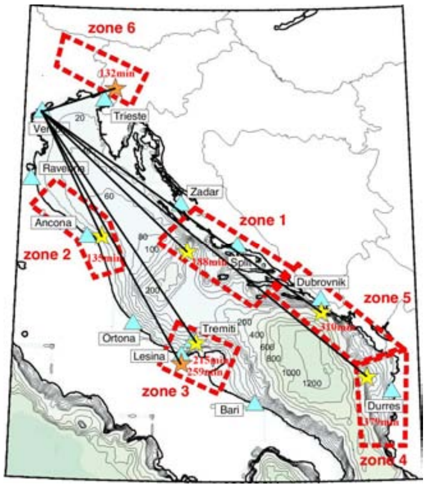

Fig. 6. Travel times for the tsunami waves from the tsunamigenic sources (Paulatto et al, 2007) to Venice

Conclusions

Several kinematical models have been constructed and explored. All of them are targeted to the seismic and tsunami early warning systems. Many examples related to different tsunami cases (Black and Adriatic Sea) and seismic sources (Vrancea (Romania), Pernik (Bulgaria) and Italy sources to Venice) have been modeled. The calculations show that in some cases the seismic early warnings could be more effective (Vrancea, Venice) or less effective (Pernik). The legislation issues could be of a great importance due to the rules of the warning issues emitting actions.

Acknowledgments

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