GEENERAL PRINCIPLES OF THE KINEMATIC MODELS USED IN EARLY WARNING SYSTEMS – EARTHQUAKES AND TSUNAMIS (VENICE CASE)

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ABSTRACT. The seismic early warning systems (SEWS) and tsunami early warning systems (TEWS) are the product of the last and most modern achievements of the recent practical Earth's science. Heavy earthquakes occurred in Japan (2011), Sumatra (2004), Chile (2010), Solomon Islands, etc. These earthquakes demonstrated the need of such 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 1.71 times faster than the S waves (with several times 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 and TEWS some years earlier. Their efficiency was demonstrated during the M9 earthquake on 11th March, 2011. All TEWS are based on the time differences between the propagation velocity of the seismic and the tsunami waves. Several very peculiar cases and models have been developed for Venice in two directions: 1) The SEWS about some typical cases – seismic sources defined according the seismic zoning maps of Italy; 2)The TEWS about a case of the tsunami sources located around the Venice in the Adriatic Sea. The results of these models are under investigations and discussion.

ОБЩИ ПРИНЦИПИ НА КИНЕМАТИЧНИТЕ МОДЕЛИ ИЗПОЛЗВАНИ ПРИ СИСТЕМИТЕ ЗА РАННО ПРЕДУПРЕЖДЕНИЕ – ЗЕМЕТРЕСЕНИЯ И ЦУНАМИ (НА ПРИМЕРА НА ВЕНЕЦИЯ)

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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. Тежки земетресения станаха в Япония (2011), Суматра (2004), Чили (2010), Соломоновите острови и др. Тези земетресения показаха нуждите от подобни системи. 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. Понастоящем, само Япония притежава функционираща сеизмична система за ранно предупреждение, пусната в експлоатация през 2007г. както и такава за предупреждение от цунами. 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 отнасят за Венеция и са развити в тази разработка: 1) Сеизмична система за ранно предупреждение от типични земетръсни огнища заплашващи града; 2) Система за ранно предупреждение от цунами генерирани в Адриатическо море. Получените резултати са изследвани и обсъдени в тази разработка.

Introduction

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. Our investigations are related to the possible hypothetical kinematic models of both hazards and possible building of the early warning systems related to these both dangers. Even though there is no strong evidence about the influence of these hazards during the historical times, the increased urbanization and the complex combined effects create our interest to model such EWS, in the context of the vulnerability assessment and resilience of Venice. 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. The tsunami danger was assessed as a few centimeters (Paulato et al., 2007), but during the flooding time these few centimeters could significantly increase the influencing negative effects to the flooded areas. The methodology of the hypothetic kinematic models and their application to the early warning systems (seismic and tsunami) is developed and applied to other regions in Europe, specifically Bulgaria and Romania.

Theoretical fundamentals and methodology

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

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

The TEWS such as the transoceanic tsunamis required (for example PTEWS and ITEWS – located in the Pacific and Indian oceans) time of warning issue between hours. 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 than the S waves. The P-waves have compression movements of the particles of the solid strata and move to the ray propagation path. These waves are the fastest and have the 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 - with several times larger amplitudes and much larger destructive potential due to the medium particles movement perpendicular to the wave ray propagation have lower velocity. The S-waves also do not propagate trough liquids.
The equation:

$$V_p/V_s=2^{1/2} \quad (1)$$

is the fundamental relationship on which the kinematic SEWS are functioning (Ranguelov and Iliev,2013). 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 endangered 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 arrival to the threaten object.

The TWES are based on a similar relationship, but in the two strata – water and the solid Earth.

As was pointed out that the seismic waves are propagating with very high velocities – in the range of km/s. The tsunami waves are propagating with much lower velocity – between tens and hundreds of km/h. The time difference between the tsunami and the seismic waves can reach the range of 10^2 to 10^4 of seconds. The case of time deficit in such systems can be conditionally limited to 2-3 hours between the time of occurrence of the earthquake that generated the tsunami and the arrival time of tsunami to any vulnerable object located on the coast. 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 1000 km/h). Near to the coast the amplitude of the tsunami wave increased dramatically and can reach tens of meters. The velocity is decreasing, but in any case is over 40 km/h (the highest speed anybody can reach in sprint short distances is always lower).

There is another peculiarity of the tsunami wave propagation and interaction with the bottom bathymetry – this is so called refraction. The refraction means that frequently the tsunami energy can be focused to the selected parts of the coast due to the ray refraction of the wave (Ranguelov, 2014).

There are also some specifics in the wave-coast interaction:

a. smooth bottom and long waves – the increase of the water level is going smoothly like fast tide
b. deep bottom and short waves – the increase of the wave water front is like wall – so called "bore"
c. intermediate cases, sometimes accompanied by dispersion – higher frequency, but lower amplitude of the incoming waves.

All described peculiarities suggested that in case of tsunami (especially in the time deficit domain is possible to observe high waves and low sea level very close in space, sometimes just few kilometers). Such an effect increased the probability of the false alarms. So such cases need compromising approach – economy of time versus more frequent false alarms (Ranguelov, 2011). In our case of research two hypothetical approaches are performed:

Hypothetical Seismic kinematic model (Ranguelov and Iliev, 2013)

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 (Slejko et 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. (Ranguelov, 2014). The graph is presented on fig. 1. On the same graph the S-P travel times ("warning time") are also plotted. All these data are 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. 2.). 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 by special software (Golden Software's Surfer).

Hypothetical tsunami kinematic model (Ranguelov, 2013)

The hypothetical tsunami kinematic models have been investigated by many scientists - for example (Ranguelov, 2011). The travel times of the tsunami wave's propagation from the respective tsunamigenic source to Venice have been calculated using acceptable models – for example (Ranguelov, 2013). The results of (Paulato et all, 2007), 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.

Results and discussion

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 presented only the "high" seismic active zones (fig. 3). 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.

On fig. 3A 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. 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.3B. 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. 4). The distances and the travel times are modeled following the methodology described in (Paulatto et al, 2007) and presented at fig. 4. and the Table 1. The distances varied between 130 to about 700 km and the travel times respectively between 130 to about 380 minutes.

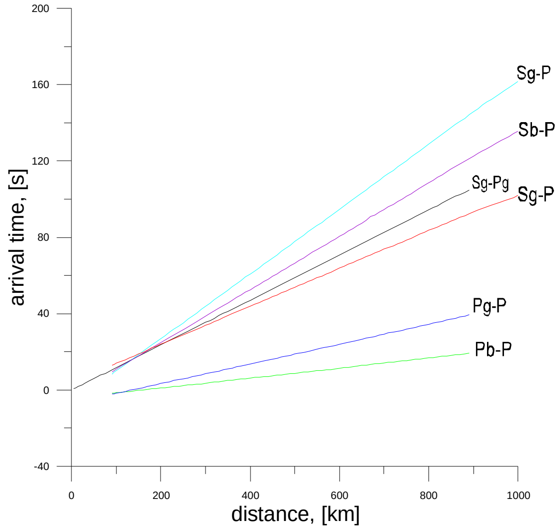

Fig. 1. The travel times for the different seismic phases – according to Jeffries - Bullen tables

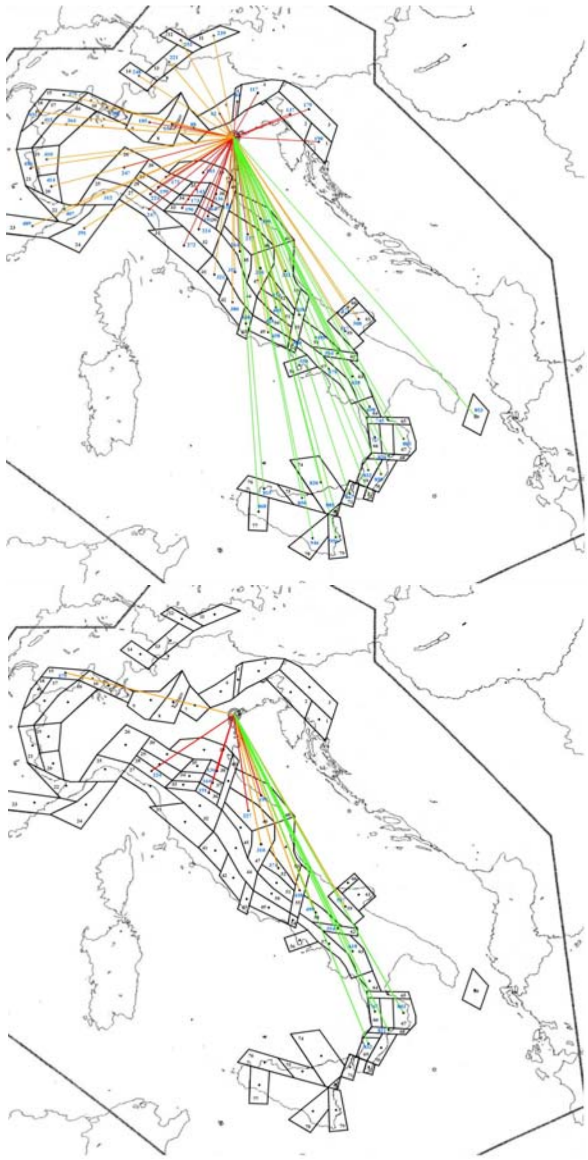

Fig. 2. A) Seismotectonic sources of Italy according (Slejko[1998]) and distances between them and Venice. B) Distances between the high seismically active zones Venice

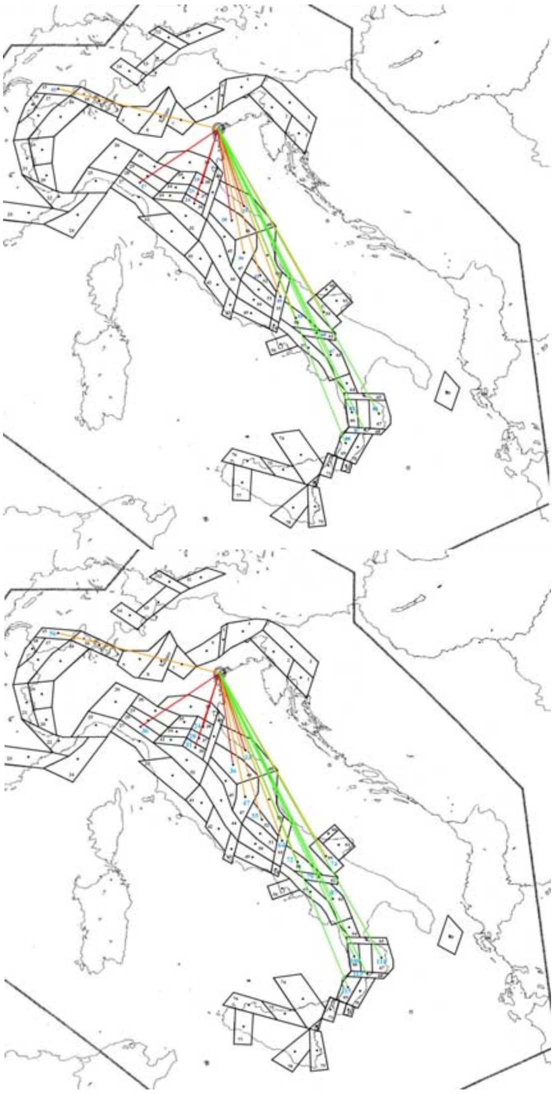

Fig. 3. A) Average travel times of the P-waves between the highly active seismic sources in Italy and Venice. B) Travel times differences ts-tp between the high active seismic sources and Venice

Algorithms of the kinematic early warning systems (models for earthquakes and tsunamis). The algorithms of the early warning system action is developed on the kinematics of the seismic (respect. tsunami) waves. The algorithms are developed on the basics described in the fundamentals section and consider the different velocities of the P and S waves (for the SEWS) and seismic and tsunami waves (in case of the TEWS) (Ranguelov et al., 2006).

The installation of the hardware needs to follow some general considerations:

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 times for the signalization of the event and triggering the whole system.
4. Seismic station optimization according the seismic sources locations and common use (in some cases) of the same equipment (if possible)

Table 1.
Distances and travel times from tsunamigenic zones to Venice

Zone №	Epicentral distance, (km)	Travel time (min)
1	331	188
2	219	135
3a	451	215
3b	474	259
4	693	379
5	567	310
6	130	132

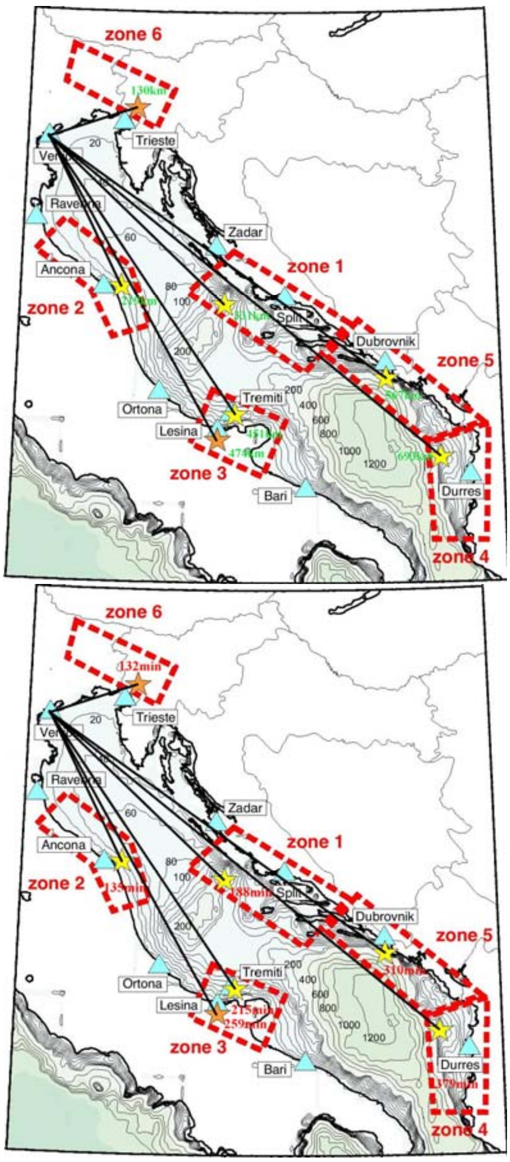

Fig. 4. A) Tsunamigenic zones in the Adriatic Sea and surroundings. B) Travel times for the tsunami waves from the tsunamigenic sources to Venice

5. The trigger stations located to the nearest point of any epicenter.
6. Use of some stations locations of the equidistant travel times to the seismic sources.

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, 2010). As the seismic P,S - waves velocities are in the range of km/sec 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. Then the following steps are necessary:

1. P-wave signal that the event is generated and the waves are 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). The selection is closely related to the so called – decision matrix.
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 "green", "orange" and "green" signaled zones.
5. Same for the tsunami waves. 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. Decision for the warning issue – the decision matrix.
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 transmitting 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 perform these algorithms a lot of specific actions must be performed (Ranguelov et al., 2011). 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 (fig. 5 and fig. 6).

Suggestions for the early warring systems – tsunamis and earthquakes (Venice)

Considering the results obtained by the investigations of the kinematic models – both for the earthquakes and tsunamis two

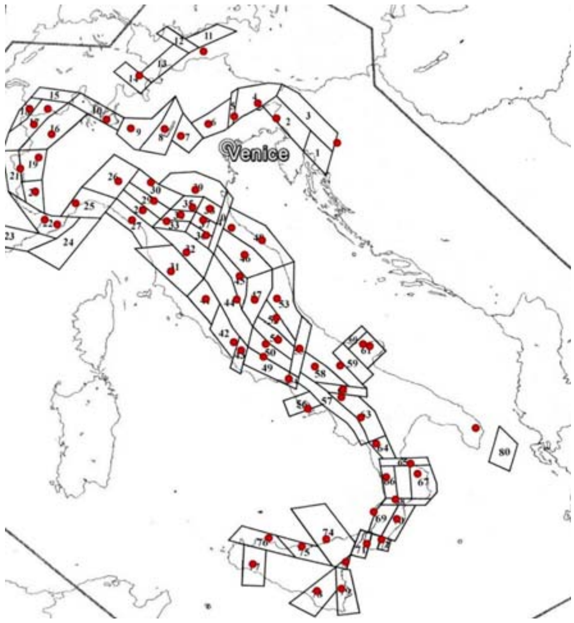

Fig. 5. Seismic sources (according Slejko, 1998) and the nearest seismic stations of the Italian national network to each source

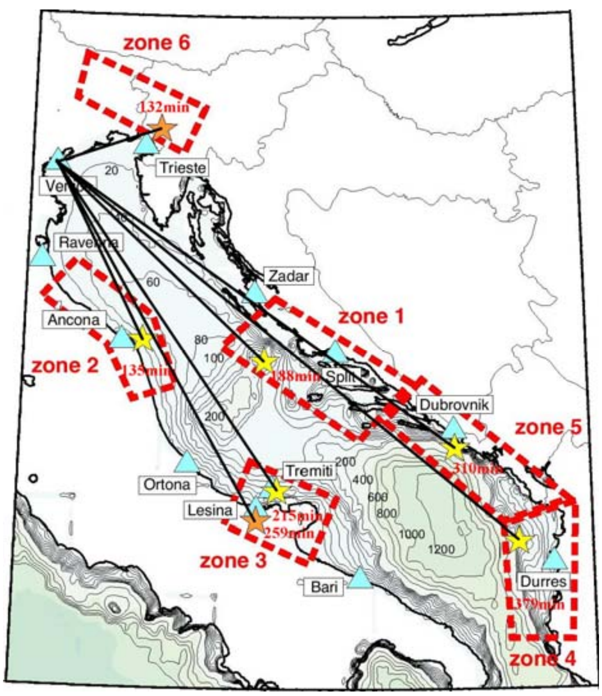

Fig. 6. Travel times from the center of each tsunamigenic source to the city of Venice

possible directions could be suggested (Ranguelov et al., 2012):

- To use the existing infrastructure of the national seismic network in Italy. This means to use the closest seismic sensors to the respective seismic zone, to trigger the signaling device in Venice. The advantage of such approach do not need special network creation covered the whole Italy.
- Another approach is to create the new established system locating in each seismic source specialized devices and connect all of them in a specialized SEWS. This approach

creates independent approach to the SEWS use, but a unification of all devices in the SEWS and TEWS is essential.

- The creation of a TEWS is necessary due to the possibility of a coincidence in time of the high water level (for example seasonal flood or storm surge, etc.) and the tsunami generation in a far field source. In such a moment the small additional water level increase can generate much more destruction due to the nonlinear effects observed in similar situations.
- The TEWS needs a specialized approach for the assessment of the locations and the equipment of it. The previous investigation show that each site needs rather specific equipment, based on the specialized investigations (Ranguelov, 2011), based on the local conditions. In any case the complex bottom stations are an obligatory element of such systems. (Ranguelov, 2014; Ranguelov et al, 2013).
- The construction of a specific decision matrix, specialized protocols of announcements and other elements providing the warning issue to the authorities and population is another direction which must be developed for any EWS.

Conclusions

The kinematic modes 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.

The models covered all seismic active zones in Italy. They have been divided into two main groups – "high" and "low" 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 creation the own infrastructure of these early warning systems.

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