KINEMATIC MODELS AND EARLY WARNING SYSTEMS (EARTHQUAKES AND TSUNAMIS) FOR AZERBAIDJAN (BAKU CASE)

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ABSTRACT. The fundamental relationship of the velocities of P- and S-seismic waves is used to calculate the travel times between the well known seismic sources of Azerbaijan to Baku (capital and the most populated city). The time differences between the P and S waves' arrivals are used for signalization and some preventive measures (gas and fuel pipelines switch off, electrical lines disconnection, dangerous production factories stop, etc). It is well known that the seismic waves are tens to thousands faster then the tsunami waves. On the same principle the seismic waves travel times from the tsunmiagenic zones as well as the travel times of tsunamis to Bakuare calculated for practical purposes.

КИНЕМАТИЧЕН МОДЕЛ НА СИСТЕМИ ЗА РАННО ПРЕДУПРЕЖДЕНИЕ (ЗЕМЕТРЕСЕНИЯ И ЦУНАМИ) В АЗЕРБАЙДЖАН (НА ПРИМЕРА НА БАКУ)

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РЕЗЮМЕ. Като е използвано фундаменталното свойство, че Р вълните се разпространяват 1,71 пъти по бързо от S вълните (които са разрушителни) е изработен кинематичен модел за времената на пристигане на сеизмичните вълни от всички известни земетръсни огнища в Азърбайджан до Баку (столица и най-голям град в страната). Разликите във времената на пристигане на S и Р вълните е време достатъчно за сигнализация и предприемане на превантивни мерки – изключване на газопроводи и електропроводи, опасни производства и др. Сеизмичните вълни се движат десетки пъти по бързо от вълните-цунами. Тази разлика в скоростите и тук позволява сеизмичните вълни да служат като сигнализиращи за евентуални (при достатъчни силни земетресения) вълни – цунами. За всички известни цунамигенни огнища са построени времеви диаграми за практическо приложение.

Introduction

Baku is the capital of Azerbaijan and as a large city is threatened by many natural hazards – floods, earthquakes, tsunamis sedimentation fulfillment, water and air pollution, etc. Our research in this paper is focused to the possible negative influence of two natural hazards - earthquakes and tsunamis. Both hazards are wide spread in Azerbaijan 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.There are strong evidences about the influence of these hazards during the historical times. The increased urbanization and the complex combined negative effects of these hazards create our interest to model such EWS. The research is performed in the context of the vulnerability assessment and resilience of Baku (as a most prominent and fast growing city) in Azerbaijan. According to the new seismic zoning maps of Italy, 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 expected seismic shaking, which could be dangerous for the historical buildings in Venice. The tsunami danger was assessed as a few centimeters, but during the flooding time these few centimeters could significantly increase the negative effects influencing 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 about tens of 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 and frequently in the SEWS are called "signaling" waves. The amplitudes of the P-waves are 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 and are called "destructive" waves. The S-waves also do not propagate trough liquids.The equation:

$$\frac{V_p}{V_s} = \sqrt{2}$$

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 some variations to the lower values due to 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 for the direct waives, 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_s-t_p) is called "warning time" and presents the time 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 it was pointed out 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 in the open sea (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 (in the case of Caspian sea - between 80 and 200 km/h). Near to the coast the amplitude of the tsunami wave increased dramatically and can reach tens of meters. In the case of Caspian Sea there are evidences of few meters run-ups. (Dotsenko et al, 2002).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:

Realseismic kinematic modelfor Azerbaijan (Baku case)

It is based on the assumption that P waves are traveling from each seismic source to the city of Baku for different times. The seismic sources are outlined by the researchers during the construction of the seismic zoning map of Azerbaijan. (Akhundov et al., 2011). The seismotectonic model considered all known seismic events occurred on the territory of Azerbaijan simplified as geometrical polygons.

As it is well known the seismicity of Azerbaijan is wide spread in space and time (Akhundov et al., 2011 and Hasanov et al., 1987) (fig.1).

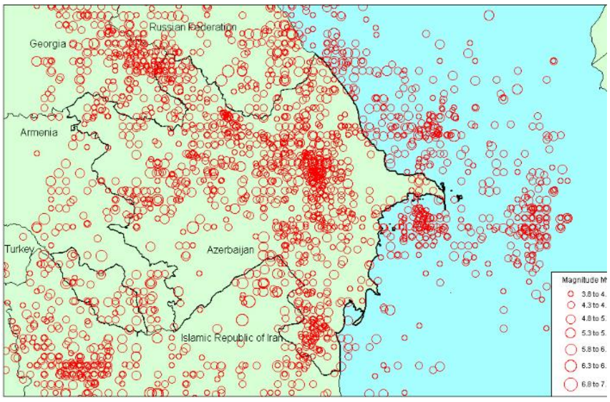

Fig.1. Seismicity of Azerbaijan and surroundings (Akhundovet al., 2011)

We followed the recent seismic zoning mapping by Akhundov et al.(2011), considering all known active faults and established 10 seismic zones. To increase the accuracy of our model (Ranguelov, 2014 andRanguelov, Iliev, 2013) we subdivided the established zones to subzones. After that a standard procedure for calculation of the distances between Baku and each seismic subzone have been modeled (Parushev and Ranguelov, 2014)(fig. 2).

To investigate the expected travel times of the first P wave arrivals (called "signaling" - seismic phase) we use the calculated model on the base ofthe Jeffrey's-Bullen travel times-tables. (Ranguelov, 2014). The graph is presented on figure3. On the same graph the S-P travel times ("warning time") are 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 (virtual center) seismic zone and the city of Baku.

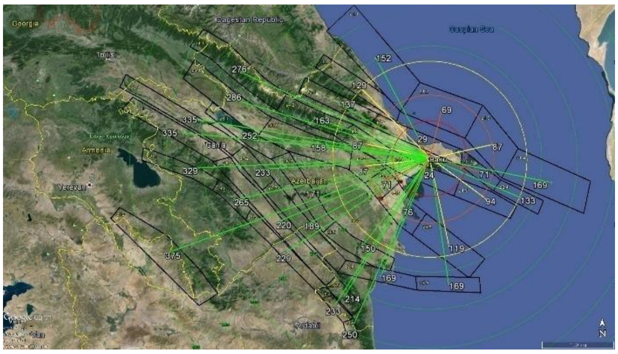

Fig.2. Distances between Baku and the each seismic zone/subzone.Four zones of distances have been outlined: up to 50 km (red), 85 km (orange), 130km (yellow) and over 130 km (green)

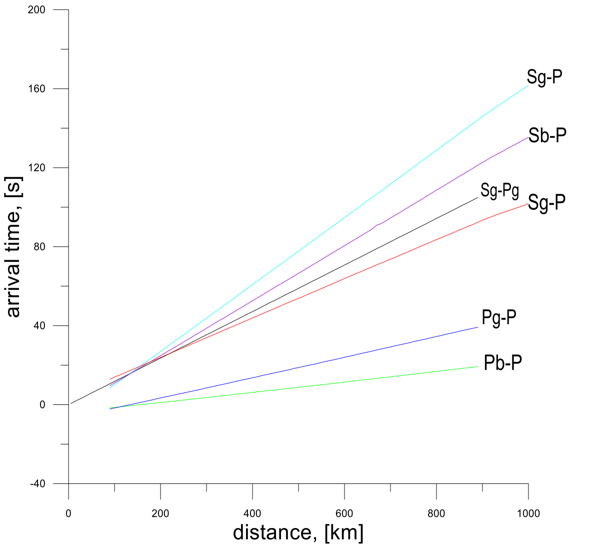

Fig.3. The travel times for the different seismic phases according to Jeffries - Bullen tables

Fig.4. Travel times of the P waves. Four zones according the distances between Baku and each seismic source are outlined – red,orange, yellow and green

Following the explored model (Ranguelov, 2014; Ranguelov et al., 2012) the travel times for the P, S and S-P waves have been modeled (figs.4, 5 and 6).

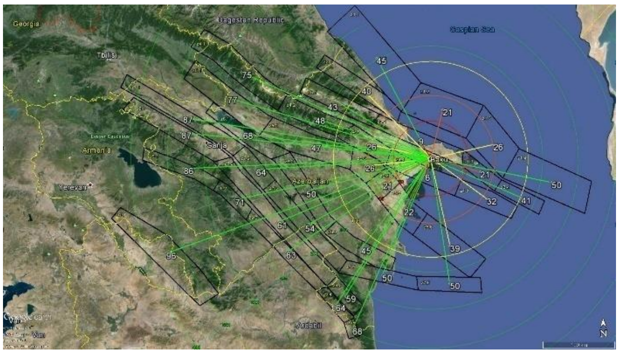

Fig.5. Travel times of the S (destructive) waves. Four zones according the distances between Baku and each seismic source are outlined – red, orange, yellow and green

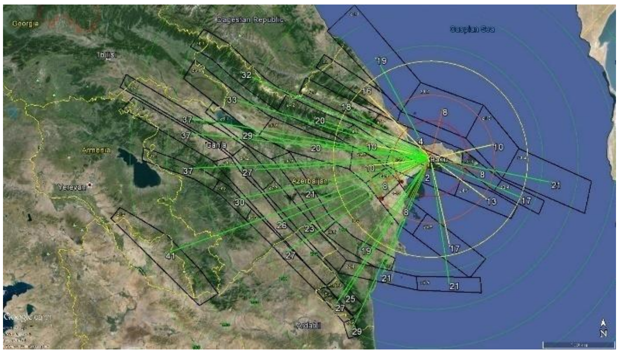

Fig.6. Travel times of the S-P - "warning time". Four zones according the distances between Baku and each seismic source are outlined – red, orange, yellow and green

For easier use of the results in everyday practice the travel times between each zone/subzone and Baku, have been tabulated(Table 1). For each zone/subzone the minimum and the maximum travel time is calculated. Thus the reliability of the modeled travel time can be assessed.

Analysis

The complicated seismogenesis of the Azerbaijan territory suggested complex solutions about a seismic early warning system for Baky city as the biggest and largely populated area. For this study some near filed seismic sources threatening Baku are located at distances less then 50 km. In this case,the earliest signal of the P propagating waves (in the idealized model) can reach the city within 4-5 to 15 seconds. This means thatfor these seismic sources the SEWS appeared as low effective for any evacuation measures. The respective S and S-P travel times are in the range of 10-12 and 4-6 seconds respectively. Based on these results the zone can be considered as "red" - leading to relatively low efficiencyand limited possibilities of fast evacuation, etc.

The P-waves travel times for distances of about 130 km and greater vary starting from 25 seconds (S about 40 and S-P - about 15-20 seconds. These time intervals are relatively longer and give possibilities for effective protective measures (stop the dangerous productions, gas and oil pipelines, electrical and other life-save communications, etc.). That's why this zone, which is larger then 130 km is consideredas "green" . All other cases are in between these values of the travel times of P, S, and S-P and are outlined as orange and yellow zones -only some particular measures are possible.

Table 1.

Travel times from each seismogenic zone/subzone (their virtual centers) to the city of Baku are tabulated for the different waves' phases. Minimum and maximum times for each zone/subzone are also presented

Zone	Distance [km]		Travel Time [s]					
			P waves		S waves		S-P	
	Min	Max		Min	Max		Min	Max
1.1	75	226	14	36	22	63	8	27
1.2	42	100	7	20	12	34	5	14
1.3	55	118	10	22	16	38	6	16
1.4	100	220	20	35	34	61	14	26
2	68	196	12	32	20	55	8	23
3.1	92	195	16	32	27	55	11	23
3.2	8	88	1	16	2	26	1	10
3.3	45	98	8	20	13	34	5	14
3.4	97	162	20	27	34	47	14	20
4.1	208	351	34	52	59	91	25	39
4.2	114	212	21	34	36	59	15	25
4.3	54	129	10	24	16	40	6	16
4.4	13	58	2	11	4	18	2	7
4.5	50	133	9	24	15	40	6	16
5.1	218	345	35	51	61	89	26	38
5.2	105	230	20	36	35	63	15	27
5.3	64	110	11	21	18	36	7	15
5.4	54	91	10	16	16	27	6	11
5.5	54	103	10	20	16	34	6	14
5.6	75	165	14	28	22	48	8	20
6.1	189	305	31	46	54	80	23	34
6.2	151	211	26	34	45	59	19	25
6.3	141	171	25	29	43	50	18	21
7.1	250	424	39	61	68	107	29	46
7.2	211	262	34	40	59	70	25	30
7.3	175	226	29	36	51	63	22	27
7.4	157	193	27	32	47	55	20	23
7.5	157	190	27	31	47	54	20	23
8.1	270	415	42	60	73	105	31	45
8.2	198	288	33	44	56	77	23	33
8.3	200	232	33	37	56	64	23	27
9.1	284	384	43	56	76	99	33	43
9.2	248	292	39	44	68	77	29	33
9.3	217	259	35	40	61	70	26	30
9.4	220	246	35	39	61	68	26	29
9.5	235	262	37	40	64	70	27	30
10	333	433	50	63	87	110	37	47

Real tsunami kinematic model for Caspian Sea (Baku case)

The tsunami kinematic models have been investigated before (Ranguelov, 2014; Parushev and Ranguelov, 2014, etc.). The travel times of the tsunami wave's propagation from the respective tsunamigenic source to Baku have been calculated using accepted models (Ranguelov, 2013).

According to the results the travel times are enough for the evacuation measures, thus decreasing the tsunami risk for the city of Baku from the influence of the possible tsunamis generated in the Caspian Sea (excluding some very peculiar cases of the near-field located tsunamigenic zones. 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, underwater landslides (Soltanpour and Rastgoftar, 2011) can dramatically increase their destructive potential. This is way an effective tsunami warning system could be very useful for the Baku resilience to the combination of the tsunami and seismic risks. Similar warning system has been developed and used in the Bulgaria-Romania border region including marine hazards in the sea and on the land (Ranguelov et al., 2011) and developed and assessed for the city of Venice (Parushev and Ranguelov, 2014).

Results and discussion

The tsunamigenic zones at the Caspian Sea, which are the most dangerous for the Baku coast are extracted from Kulikov et al.(2014).The distances and the travel times are modeled following the methodology described in Parushev and Ranguelov (2014) and used for the case of Venice. The results for Baku are presented at figures 7 and 8 and the Table2. The distances varied between 45 km to about 335 km and the travel times respectively between 30 to about 200 min.

Table 2.

Distances and travel times from tsunamigenic zones in the Caspian Sea to Baku.

Zone	Distance [km]	Travel Time [min]
1	282	154
2.1	236	128
2.2	301	191
3	82	62
4.1	45	33
4.2	75	46
5	202	132
6	334	183

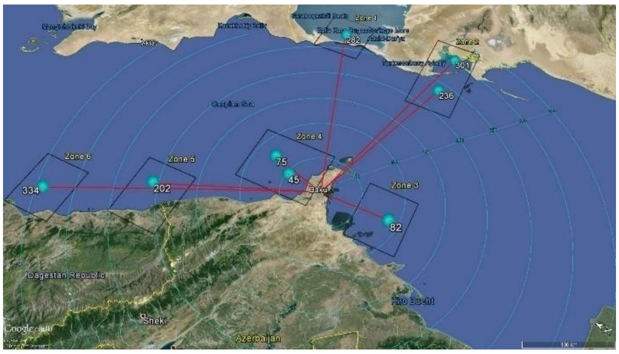

Fig. 7. Distances from the tsunamigenic zones in the Caspian Sea and Baku

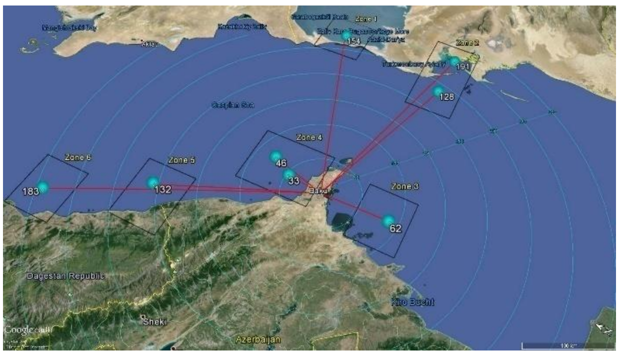

Fig. 8.Travel times for the tsunami waves from the center of each tsunamigenic source to Baku

The travel times of tsunami are calculated by simplified method used in Parushev et al.(2015). The analysis show that the travel times are enough for emergency primitive measures (signalization to population and administrations in case of nearfiled tsunamigenic source - travel times about 20-30 min) to effective measures (evacuation and stopping the activities of the dangerous production facilities in case of far field tsunamigenic zones -travel times about 2-3 hours).

Algorithms of the kinematic early warning systems (simultaneous models for earthquakes and tsunamis)

The algorithms of the simultaneously acting early warning system (both seismic and tsunami) are developed on the kinematics of the seismic (respectivelytsunami) waves. They are using 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);
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 and Swaves velocities are in the range of km/s, it is essential to have a seismic sensor as close as possible 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'ssignal detection 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) (Ranguelov, 2010). 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 "red", "orange", "yellow", and "green" signaled zones (Ranguelov et al., 2011);
5. The 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 (micro-barographs, sea-level measuring devices, OBS, DART, etc.) as effective hardware (Ranguelov et al., 2011);
6. Decision for the warning issue - the decision matrix development(Ranguelov, 2014);
7. Warning issue to the clients - population, civil defense authorities, decision makers, administrations, etc. (Ranguelov., 2014);
8. The combined warning issue in case of simultaneous action of earthquakes, landslides, turbidities (or other generating events) and tsunamis;
9. Different ways to communicatethe warning - sound or light signals, messages, TV and radio emissions, social networks etc. (Parusehv et al, 2015);
10. Cancelation of the warning after the event passed.

To perform these algorithms a lot of specific actions must be done (Ranguelov et al., 2011). The most important one is the hardware (devices) installation as close as possible to the seismic (tsunami) source. This could be a specialized seismic strong motion device, or the nearest seismic station of the national seismological network.

Suggestions for the early warring systems - tsunamis and earthquakes (Baku case)

Considering the results obtained by the investigations of the kinematic models - both for the earthquakes and tsunamis the following possible directions of EWS development could be suggested (Ranguelov, 2014):

- To create the new established seismic early warning system with sensors located in each seismic source.The specific devices have to be connected in a specialized SEWS. This 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 flooding 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), and considering the local conditions. In any case, the complex bottom stations are an obligatory element of such systems (Ranguelov, 2014 and Ranguelov, 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 Azerbaijan. They have been divided into several main groups -red, orange, yellow and green seismic zones. For allof them, the travel times of the P, S, and S-P seismic waves to the city of Baku 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 Baku infrastructure and population in case of strong earthquake occurring anywhere in Azerbaijan.

The models of the travel times of tsunamis propagating trough the Caspian Sea and the calculations of them show relatively high effectiveness of the TEWS regarding Baku city and the oil and gas productive systems and low coasts.

Some practical considerations are presented about the organization of a SEWS and TEWS in the region of Baku, using the existing seismic network of Azerbaijan or creation the own infrastructure of these early warning systems.

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