ГОДИШНИК НА МИННО-ГЕОЛОЖКИЯ УНИВЕРСИТЕТ "СВ. ИВАН РИЛСКИ", Том 52, Св. I, Геология и геофизика, 2009
ANNUAL OF THE UNIVERSITY OF MINING AND GEOLOGY "ST. IVAN RILSKI", Vol. 52, Part I, Geology and Geophysics, 2009

TSUNAMI INVESTIGATIONS – VULNERABILITY AND RISK ASSESSMENT TO THE BULGARIAN BLACK SEA COAST

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ABSTRACT. Tsunami investigations – cataloguing, modeling and satellite imaginary have been performed during the last years. Lowlands, steep bays, lagoons, beaches, river deltas and estuaries – the whole spectrum of the natural tsunami vulnerable elements could be observed on the North Bulgarian Black sea coast. Depending of their spatial position and size these elements are local traps for increasing the tsunami negative effects due to their magnification of the tsunami inundation. Some of these objects could be concentrators of the more dense populated areas (such as beaches, and lagoons with the SPA possibilities). Some others are not so much populated due to their spatial position and worse conditions of everyday human practice (such as river beds, deltas and estuaries). Statistical assessment of the vulnerability of these structures is performed according to their distribution and sizes. Similar approach of classification of the man-made tsunami vulnerable structures is performed. Modern practices such as DEM, satellite images, GPS measurements are performed to assess more accurately the vulnerability functions of the different structures. Preliminary classification and typology of all such structures is done to be able to separate different vulnerable elements of the tsunami influence parameters – inundation heights and velocity currents. The area under investigation is located from Varna city to the Bulgaria-Romania border.

ИЗСЛЕДВАНИЯ НА ЦУНАМИ – УЯЗВИМОСТ И ОЦЕНКА НА РИСКА ЗА БЪЛГАРСКОТО ЧЕРНОМОРИЕ

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РЕЗЮМЕ. Изследвания на цунами включващи каталогизация, моделиране и дистанционни методи са прилагани през последните години. Низини, остри заливи, лагуни, лимани, речни делти и естуари – целият спектър от природни уязвими за цунами уязвими елементи са представени по Северното Българско Черноморие. В зависимост от пространственото си разположение и размера си, тези елементи са локални дадености увеличаващи негативните ефекти в резултатн на усилващото си влияние върху цунами нахлуванията. Някои от тези елементи могат да бъдат и концентратори на по плътно населени ареали (напр. плажове, тузли и др.) Други са по-малко посещавани (напр. речните легла – делти и естуари). Статистическа оценка на уязвимостта на тези природни структури е предложена на основата на техните размери и пространствено разположение. Подобен подход е използуван и при оценка на уязвимостта на антропогенни конструкции. Модерни подходи (като цифров модел на релефа, измервания с ГПС, сателитни изображения и др.) са използувани за оценка на функциите на уязвимост за различните елементи. Предварителни класификации и типология е направена с цел разделяне на различните уязвими елементи от въздействията на цунами – по височина на вълната и скоростите й. Изследваната област е разположена между град Варна и румънската граница.

Introduction

Recent investigations and research about tsunami waves in the Black Sea increased the knowledge about these rare, but hazardous events. This really dangerous phenomenon exists for the Black Sea and formulates the tsunami hazard and risk. Tsunamis in the Black Sea could be triggered by the same phenomena triggering tsunamis in the world ocean – seismic sources: earthquakes (inside and/or outside the aquatory of the sea), and nonseismic sources: underwater and/or surface landslides, mud volcanoes (active real volcanoes have not been reported for the Black Sea) and any kind of underwater blasts. The available data shows that the Black Sea coast could be attacked heavily by the tsunamis.

The available data are collected and a relative completed catalogue created. Tsunami zoning to the Black Sea coasts is applied. The extreme events are considered, based on the available data. The vulnerability analysis to natural and man-made elements is considered and the structures classified in this direction. The multi hazard approach is performed for the first time and results obtained show existing, but neglected up to now, danger.

The tsunami research in Bulgaria has been developed to several directions: new data and homogeneous catalogue (as part of the standardized GITEC catalogue) has been compiled

(Tinti, Ranguelov, 1995); tsunamigenic sources and natural vulnerable areas have been outlined; ray refraction analysis and tsunami energy dissipation/concentration have been performed for the whole Black Sea area; special vulnerability analysis has been performed for some areas and test site areas; fractal properties of the tsunami in the Black Sea according the bottom and coastal geometry; first attempts of the tsunami zoning for the whole Black sea at large scales and in case of not completed information have been executed and rough schemes created, assessing the expected average run-ups and attack velocities of the tsunami to the shore, based on the average repeated recurrence time established by the real data (Ranguelov, 2002); original equipment about the tsunami laboratory generation and physical modeling investigations has been patented; paleotsunami deposits have been discovered for the first time on the Black Sea coasts (Ranguelov, 2002).

Data and earlier studies

There are many case studies reported by different authors about the tsunami observations on the Black Sea coasts (Murty, 1977; Никонов, 1997). Our research allows us to compile a new Black Sea catalogue of tsunamis. It consists of about 30 cases since ancient times up to the present days (Tinti et al., 1995) cross-checked and updated during the last years. The acting and potential sources of the tsunamis could be studied and mapped with their tsunamigenic potential, frequency of tsunami generation, expected run-ups, etc.

The calculations of the travel times from the different tsunami sources show, that the closed sea like Black Sea, has sometimes very short response time – 10-15 minutes (Kaliakra source for example), up to 2-3 hours for the distant located sources. In any case the short reaction time could be a big problem for any kind of the early warning system. It must be organized on a wide frame of international cooperation between the Black Sea countries.

Paleotsunami deposits have been discovered and studied on the Bulgarian Black Sea coast for the first time (Ranguelov, 2002). Several sample points have been observed, measured and investigated by the microfossil and macrofossil analysis, showing the heights of 7-8 meters above sea level.

Vulnerability and tsunami zoning methodology

There are two vulnerable structures from tsunami at the Black Sea cost. Natural vulnerable areas from the tsunamis (like – steep bays, estuaries, flat lowlands, etc.) and vulnerable man-made elements: cities, dangerous installations, ports, military bases, etc. The mapping of the first groups of elements is already done (Ranguelov, 1994). A map about the most vulnerable natural elements has been prepared for the Black Sea. Some calculations about the tsunami energy dissipation/concentration and the accuracy estimations have been done (Ranguelov, 2001). According these results some selected big cities or different port facilities and other vulnerable objects have been investigated about their vulnerability (Ranguelov, 1996).

The tsunami zoning is the action when all tsunamigenic sources, which can affect the selected coastal sites (or the coast lines), are considered. They are taken into account and all possible regional expected tsunami influences are presented as maps, graphs, tables, etc. (Ranguelov et al., 2005).

This procedure, which can present and use for practical purposes the most vulnerable to the tsunami effects elements – natural and/or artificial (man-made) is very useful. The vulnerability assessment is done on the basis of the observations during the 26.12.2004 tsunami in Indian Ocean. The vulnerability is calculated by statistical approach to the different man-made structures as well as to the space distributions of the natural vulnerable elements (Table 1).

Table 1
Tsunami natural vulnerable elements for the North Bulgarian Black Sea coast

Elements/ Parameter	Length/ area	% vulnerability by 3 m tsunami height	% vulnerability by 5 m tsunami height
Coast line	118 km	76.5	80.2
Lowlands	73.8 km^2	94.1	97.2
Bays	20 km	42.3	48.7
Lagoons	9.1 km^2	~98.1	100
River beds	54.8 km^2	~92.6	99.7

The environmental consequences also are considered using the approach extraction the results of observations in many cases of the occurred tsunamis all over the world. Table 2 presents an extraction of several environmental vulnerable elements by tsunami and the destructive processes which affect them. The rough qualitative assessments to three levels and ways of protection are added.

Table 2
Tsunami vulnerable environmental elements (example table)

Name/ Parameters	Destruct. process	Vulnerab. elements	Level of vulnerability	Protection (Y/N)
Beach	Erosion, pollution	sand, dunes	High	Not possible
Soil	Erosion, pollution	salinity, silt	High	Not possible
Sand, gravel	Erosion, pollution	grains	High	Not possible
Water	Pollution	purity, salinity	High	Not possible
Low veget.	Pollution	grass, bush	Middle	Possible
Forest	Pollution	trees	Low	Possible
Rocks	Erosion	cracks	Low	Possible
Biodiversity	Live environ.	creatures	High	Not possible

The long-term expectations about the active tsunami sources, travel-time charts, and the expected tsunami amplitudes are essential elements of the tsunami zoning. All of these elements could be calculated in dependence of the different initial conditions and limitations. This procedure, which takes into account all case studies and extrapolate probabilistic the expected tsunami influence in terms of tsunami heights for different time intervals shows: maximum expected run-ups; extreme events; expected velocity of inland inundation, etc.

A) The tsunami zoning maps usually present:

a) The probability (in selected time domain) of occurrence of different wave heights on any particular site on the coast.
b) The maximum expected wave height (run-up) on the coast line and/or different elements of the coast – lowlands, steep bays, deltas, estuaries, etc.
c) Usually the combinations with other phenomena (meteoevents, underwater landslides, rockfalls, etc.) which can bring additional effects are under consideration.
d) The expected velocity (acceleration) of the tsunami wave at the coast is the very useful element for the engineering purposes.

If the vulnerability is added to the tsunami zoning maps, the tsunami risk maps could be created showing the expected influence in terms of different scenarios – expected flooded areas and/or destructed facilities; expected victims; expected economic losses, etc.

B) General input data necessary for the tsunami zoning:

The tsunami catalogue – is compiled for the Black sea. Tsunami records are very few available. Paleotsunami diggings are hard, expensive and slow processes, but they help a lot the long term clarifications. Earthquake catalogues are useful about the potential tsunami generation sources establishment. The information about the surface and underwater landslides is also useful. These data can help also the source identification. Possible useful information could be extract from the DEM and other geophysical and distant prospecting. Maps about the tsunami vulnerability elements (natural – steep bays, deltas, estuaries, etc.) – could be found on the world atlas. Tsunami vulnerability elements (artificial – ports, facilities, structures, etc.) – could be extracted from satellite and field maps).

C) The output of the tsunami zoning could be useful for: tsunami warning systems optimization; land use planning; tourism; structures' safety, people's protection; Civil Defence plans, Military bases safety, etc. For the first time the repeatability of tsunamis are studied, based on the probabilistic approach. The results obtained show that in average in 300 years a tsunami with height of about 3-4 meters can be expected. The extreme cases show much bigger heights, but are much rarer.

Several cases of parametric maps have been created and used for the zoning purposes. The main parameters considered are: the bathymetry and the geometric coastal configurations; the landslides – surface and submarine; the extreme meteoevents – like storm surges and sashes and finally – the concentration and dissipation of the tsunami energy calculated using the ray refraction. Several output maps are calculated: Average run up for the certain time period; Maximum expected velocity, Maximum expected run ups – with their probabilities, concerning all possible events which can produce additional effects, like storm surges, changes in the atmosphere pressure, etc..

The tsunami zoning – Black Sea exceptional case

The general scheme about the tsunami zoning is presented. Using the general methodology explained earlier and the established earlier relationships about the time repeatability, the tsunami zoning is applied about the Black Sea. The specific relationships have been established and the maximum run-ups calculated using the formulae (Ranguelov, 2001).

$$H_{max} = H_{av} + H_{av}(Kg+Ks+Kf) \qquad (1)$$

where H_{av} – is the average height extracted from the recurrence graph and the three empirical correction coefficients introduced:

Kg – geometry coefficient – it reflects bottom and coastal geometry influence and tsunami energy dissipation/concentration according to the refraction.

Ks – source coefficient – reflects the source location influence (in and out the aquatory of the Black Sea)

Kf – landslides and rockfalls coefficient – reflects the effects of the surface or underwater landslides and rockfalls as possible tsunami generators.

These coefficients have been preliminary mapped and used for the Hmax calculations (Ranguelov 2001). Then the velocity map – V=f(Hmax) – has been created according Pelinovski's approach (Pelinovsky, 1999) and Hmax map was drown.

The new maximum run up's map – MaxHmax – has been created and presented as well as. It reflects the most conservative approach and shows also the reliability (rel.) of the obtained values. The map incorporates all possible effects due to other different sources of the additional effects, which could be added to the influence of a tsunami accompanied by other similar events (for example storm surges, high water levels due to sashes, etc.). Many new and unavailable data have been incorporated concerning the observations about storm and wind influences to the wage generation and power. They are summarized and based on the real observations done during the last century. The important element is the reliability of such calculations taking into account the probability of occurrence and coincidence of such events with the occurrence of tsunamis.

Case studies about Bulgarian coastal tsunamis

III-rd (*Demetrious Kalatious)* (I-st?) century BC case – IX-X tsunami intensity (Papadopoulos-Imamura (P-I) scale)

"Ancient town Bisone (Greek colony) sank in the sea waters" (Strabo). Major earthquake (M~8), accompanied by huge slides and large inundation (probably tsunamis). "The whole" ancient city (most probable – the port and the facilities) went under water. The rest part of the town was moved on the top hills. Paleotsunami findings.

543AD case – VII tsunami intensity (P-I scale)

Earthquake (magnitude ~7.5), probable local tsunami, activated landslides, destroyed and buried the Cibele temple. Possible paleotsunami findings.

31st March 1901 earthquake and tsunami – V tsunami intensity (P-I scale)

Earthquake of magnitude M=7.1 occurred in the sea. Large destruction in the epicentral area (more than 5 villages and small towns have been affected; more than 830 houses damaged.). Aftershock sequence lasted more than 7 years. Land subsidence and landslides (probably submarine as well) occurred. Rockfalls were reported. A witness reported a sea level rise of about 3 meters at the port of Balchik, recognized as tsunami.

The case of 7th May, 2007 – V tsunami intensity (P-I scale)

Northeast Bulgarian coast – nonseismic origin (possible underwater turbidities). Data about withdrawal and inundation – frequency of the phenomena (3-5 – 6-8 minutes) are collected. Data about the water peculiarities consequences – observed turbulences, currents and water boiling supports the used models. Data about the consequences – moved boats, tetrapodes and other items also have been assessed (the detailed description – see later on). The systematic data of the parameters of these events are presented at Table 3 and 4.

Table 3

The tsunami cases to the North Bulgarian Black Sea coast

Time/parameters	Events observed	Tsunami intensity
I-st (III?) century BC multihazards event	Earthquake, slides, regional inundation	IX-X tsunami intensity (P-I) scale
543AD multihazards event	Earthquake, slides, local inundation	VII tsunami intensity (P-I scale)
31st March, 1901	Earthquake, slides, rockfalls, local inundation	V tsunami intensity (P-I scale)
7th May, 2007	Nonseismic origin, only frequent water level oscillations	V tsunami intensity (P-I scale)

The suggested scenario for the North Bulgarian Black Sea coast is based on the 1901 case (referent event – as a better studied and the most informative and reliable case), intend a multihazard assessment, possible inundation areas outlines, risk mapping and possible evacuation roads indication.

Table 4

The known tsunami generating events to the North Bulgarian Black Sea coast

Year	Latitude E	Longitude N	Depth, km	M	Macros. Int. (EMS)
IIIrd (Ist?) c. BC	43.4	28.4	20	8.0	IX-XI
543	43.5	28.3	20	7.6	IX-X
1901	43.4	28.6	14	7.2	IX-X
2007	43.1	28.6	0	-	slide(?)

Results

For the modeling purposes the basic scenario earthquake has the following parameters: epicenter location: 43,2E; 28,6N; depth – 15; epicenter intensity – X EMS; magnitude: 7.2; vertical displacement: 2-3 m; strike: E-W (1st variant) and NE-SW (2nd variant). This scenario is based on the event of 1901 as best studied earthquake and its consequences. Due to the not reliable information about earthquake mechanisms several experiments have been modeled using different parameters about fault dimensions and movements (displacements, rake, dip, slip, etc.). Two variants are explored and their parameters are presented on Table 5.

Table 5

Earthquake parameters about the modeled cases 1 and 2

Earthquakes parameters	Case 1	Case 2
L (m)	57000	57000
W (m)	22000	22000
Strike	90°	40°
Dip	40°	40°
Rake	270°	270°
Slip (m)	2	2
Position (°)	28.7°, 43.4°	28.7°, 43.4°
M	7	7
Fault	1	2

The initial conditions about the case studies models are presented on Fig. 1.

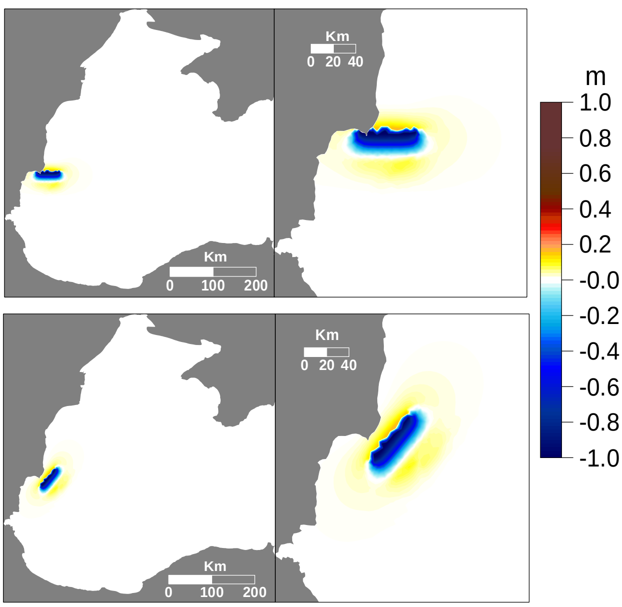

Fig. 1. Initial conditions about case 1 and case 2

For the calculations Digital Elevation Model extracted by the satellite images is created based on scale 1: 50000 (Fig. 2).

As a result of the modeling done by UNiBo, several variants of inundation by tsunami of the North Bulgarian Black Sea coast have been obtained. All of them are in coincidence with the reported observations. The most appropriate appeared the results due to the Case 2 with the respective parameters of the seismic source. Due to the active depositions along the coast there are some considerations about the existence of movable sliding masses – so called turbidities. That's why the possibilities of additional effects to the tsunami generation due to the underwater slides is not excluded coexisting with the seismic source dislocation movements.

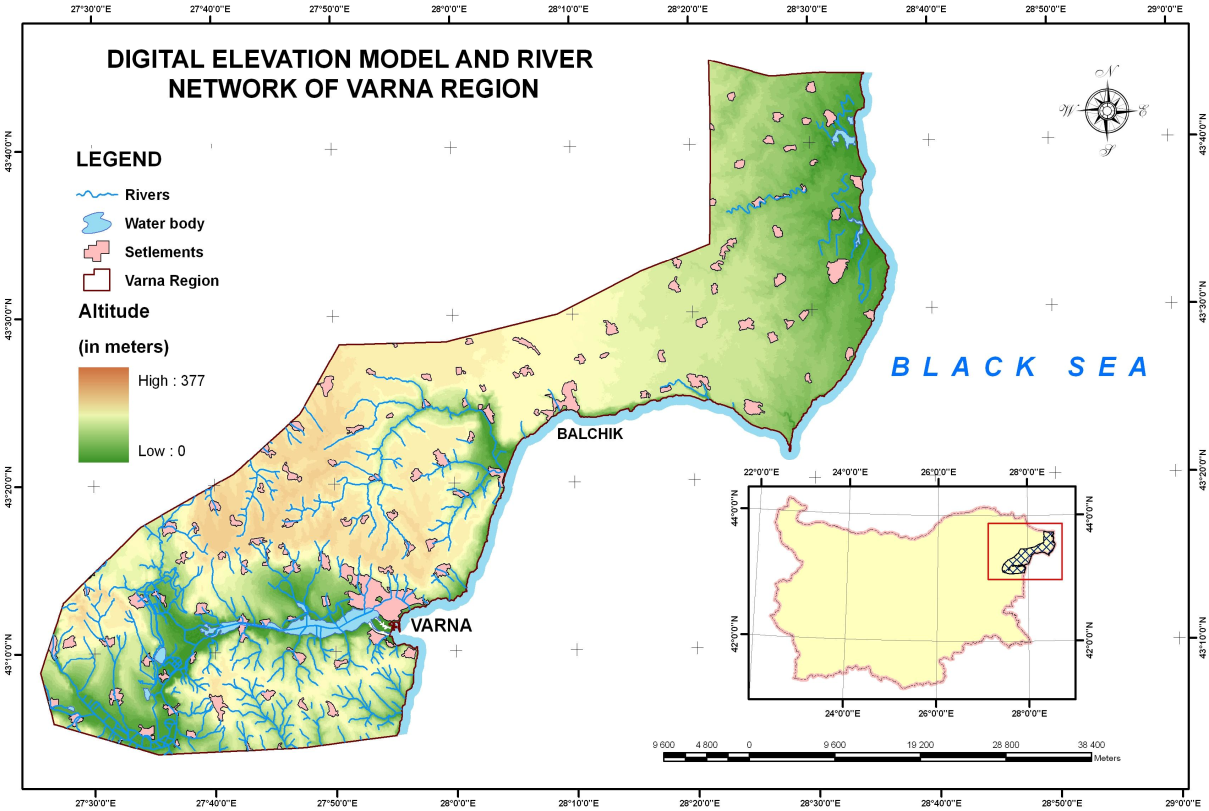

Fig. 2. DEM and water bodies near the coast

Acknowledgments: This study has been supported by TRANSFER and SCHEMA EU Projects. E. Roumenina, G. Jelev, A. Gikov and I. Geleva created the DEM model.

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