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THE STUDY OF INDIAN OCEAN TSUNAMI 26 DECEMBER 2004: ANALYSIS OF NATURE OF SEISMIC SOURCE FOR THE EARTHQUAKE

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ABSTRACT

In this work, it is performed an analysis of physical aspects of underwater earthquake of 26 December 2004 in Indian Ocean on the basis of keyboard model of tsunamigenic earthquakes. For numerical simulation of generation and propagation of surface water waves in the Indian Ocean basin it is used a simplified keyboard model of tsunamigenic earthquakes with vertical displacements of keyboard blocks, from which the seismic source consists, taking into account the real bathymetry. It was performed the numerical simulation for 26 December 2004 Sumatra-Andaman earthquake with taking into account the oblique character of the subduction zone characteristic for this earthquake. There were considered different scenarios of keyboard blocks motion, corresponding to real seismic and hydroacoustic studies of given earthquake process presented in a number of works on given earthquake. Adequateness of the calculations performed was verified by comparison of real altimetric records of satellite "Yason-1" with virtual altimetric record obtained by us for each calculation. The computations performed explain the complex character of tsunami wave propagation for given earthquake.

Introduction

The special interest to study processes in seismic source of underwater earthquake occurred near Sumatra Island (Indonesia) and generated catastrophic tsunami in Indian Ocean on 26 December 2004 is caused with two main factors distinguishing this earthquake from conventional tsunamigenic earthquakes. There are unusually extended length of this source – near 1200 km and rupture duration – of the order of 10 min. Such spatio-temporal features of seismic source complicate essentially, in particular, process of treating of seismograph records using for express-estimations of possible tsunami amplitude in any point of the World Ocean with using of conventional methods of numerical simulation of tsunami, since seismographs have also registered reflected signals what have led to delay with determination of preliminary source parameters with

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conventional method (Ishii et al. 2005). Then, in contrast to Pacific Ocean, in which there are deep-water pressure sensors, permitting to obtain deep-water data on tsunami amplitude, in Indian Ocean there were available only data of near-coastal tide gauges providing direct measurement of tsunami amplitude which data become to be available only with certain delay. So, one of the most effective manners to trace tsunami parameters in the open sea, in real time, it appears to be the using of the altimetric satellite information (see, e.g. Hirata et al. 2006).

The using of altimetric data obtained from satellites "Jason-1" and "Topex-Poseidon" (USA-France) in analysis and numerical simulation of generation and propagation of tsunami (Hirata et al. 2006; Titov et al. 2005) have confirmed that as it was waited, parameters of above Indian Ocean tsunami, 2006 are determined firstly by details of processes in seismic source. As known, formation of tsunami depends on character and dynamics of movements in earthquake seismic-source zone, or more definitely, on initial bottom displacements, and initial stress distribution determines essentially the movement character nearby the earthquake source. So, the earthquake occurs when stress on any part of contact surface exceeds the strength limit and slip on it is accelerated. This process, depending on earthquake preparation time and initial stress level before seismic movement, will proceed in quite different way: at the same vertical displacement, tsunami waves generated by it will be quite different which fact should be necessary taken into account while analyzing tsunami mechanism.

As known, the slopes of oblique in character subduction zone in the region of deep-water Sunda trench, coming along west coast of Sumatra Island as well as Nicobar and Andaman Islands, are strongly indented, with large segments, formed by transverse faults coming down to top of underthrusting plate. Such block structure of slopes permits use, for underwater seismic source, at numerical simulation of generation and propagation of tsunami wave, keyboard model of underwater earthquakes in subduction zone (Lobkovsky et al. 2004). The sources of such earthquakes are usually connected with deformed and shooting at stress releasing keyboard blocks characteristic size of which is near 100 km. This model with alternative motion of keyboard blocks was successfully applied by us to simulate 26 December 2004 Indian Ocean tsunami after event (Lobkovsky and Mazova 2007). In particular, it was performed a numerical simulation of a 'domino' effect when one of keyboard blocks, 'shooting' in earthquake epicenter, excites the next keyboard blocks ('cord') what was correspondent to uniform character of motion of rupture front along source and decrease of movement magnitude with distance (see, (Lobkovsky 1988)). The calculations then appearing also used similar multi-block models of the seismic source (Hirata et al. 2006; Ishii et al. 2005; Lay et al. 2005; Song et al. 2005; Wilson 2005).

In present work, it is performed a numerical simulation of tsunami wave generation by underwater keyboard (multi-block) seismic source located in zone of earthquake 26 December 2004 as well as propagation of this wave in the Indian Ocean basin. There were studied a several scenarios of alternative motion of keyboard blocks in this extended underwater seismic source and performed a comparison of tsunami wave heights obtained in given point of the basin with data of satellite altimetry and coastal tide gauges as well as with observations on the beach. There was also performed detailed comparison with calculation data of another works, in particular, using geometry of their model seismic sources.

Governing equations for numerical simulation of tsunami wave

To describe wave generation and propagation process it was used a nonlinear system of shallow water equations (see, e.g. Lobkovsky et al. 2006, Lobkovsky et al. 2007) which for given case can be presented as

$$\begin{cases} \vec{U}_t + \vec{U} \cdot grad\ \vec{U} + g \cdot grad\,\eta = \vec{F} \\ \eta_t + div\left(\left(H + \eta - B\right)\vec{U}\right) = B_t \end{cases}$$

where η is the water surface displacement, H is the basin depth, u and v are the components of horizontal wave velocity, and

$$\vec{F} = \begin{pmatrix} fv - g\dfrac{u\sqrt{u^2+v^2}}{Ch^2\left(H+\eta-B\right)} \\ -fu - g\dfrac{v\sqrt{u^2+v^2}}{Ch^2\left(H+\eta-B\right)} \end{pmatrix}, \qquad \vec{U} = \begin{pmatrix} u \\ v \end{pmatrix},$$

where f is the Coriolis parameter, g is the gravity acceleration, Ch is the Shezi coefficient, $B(x, y, t)$ describes the basin bottom motion. To perform numerical simulation, the computation region was taken in the area 10^0 S – 25^0 N, 70^0 – 110^0 E, with grid, including 1501x 2701 points.

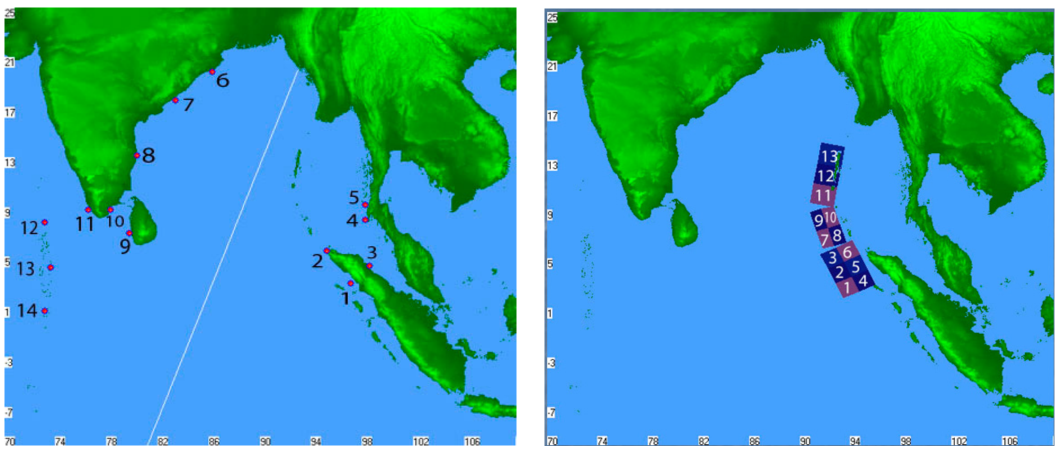

Fig. 1. The map of the region of Indian Ocean tsunami 26 December 2004. a) figures 1-14 at the panel correspond to the number of tide gauge location points; white direct line corresponds to the satellite trajectory; b) figures 1-13 at the panel correspond to the number of underwater keyboard blocks: 1-6 - Sumatra segment, 7-10 - Nicobar segment, and 11-13 - Andaman segment.

Main points of numerical simulation

The analysis of numerical simulation scenarios was performed on the basis of results of works (Ammon et al. 2005; Fine et al. 2005; Hirata et al. 2006; Ishii et al. 2005; Lay et al. 2005; Lobkovsky 1988; Nagarajan et al. 2006; Park et al. 2005; Titov et al. 2005). The evaluation of results obtained was performed with using of real tide gauge records and satellite altimetry of USA-France satellite “Jason-1”. As known, almost two hours after first strike of earthquake low-orbit altimetric satellite “Jason-1” crossed ocean surface at the distance of 1500 km of Sri-Lanka towards Bengal bay. During 10 min satellite cames over tsunami wave front and have measured with accuracy of several centimeters surface profile with 5 km width along its track (Wilson 2005).

For adequateness of comparison of calculated data with observations, under numerical simulation, for each scenario, there was fixed a virtual altimetric record. In addition, at calculations there were 'installed' a model tide gauges mainly in those points of basin where there were real tide gauges in good repair which performed records (see, Fig.1a). In Fig.1b a location of model seismic source comprising 13 keyboard blocks is presented; flight trajectory of satellite "Jason-1" is marked by white direct line.

Effect of seismic source extension to characteristics of propagating tsunami wave

Since for the event of 26 December 2004 there exists an uncertainty in literature with source structure and movements in its whole extension, then it is of interest to study in details the dependence of characteristics of seismic-source generated surface water wave on extension of this source (cf. with (Lobkovsky 1988)). First, consider the effect of extension of underwater seismic source to wave field in basin of Bengal Bay and central part of Indian Ocean. To analyse the effect of each large segment of seismic source of Indian Ocean tsunami 26 December 2004 to formation of wave field in basin, it is considered a generation of tsunami wave by three independent sources (cf. with (Song et al. 2005)): Sumatra segment, Sumatra and Nicobar segments and Sumatra, Nicobar and Andaman segments (see, Fig.1b). The magnitudes of maximum keyboard-blocks displacements in seismic source for each of three scenarios considered, are presented in Fig.2.

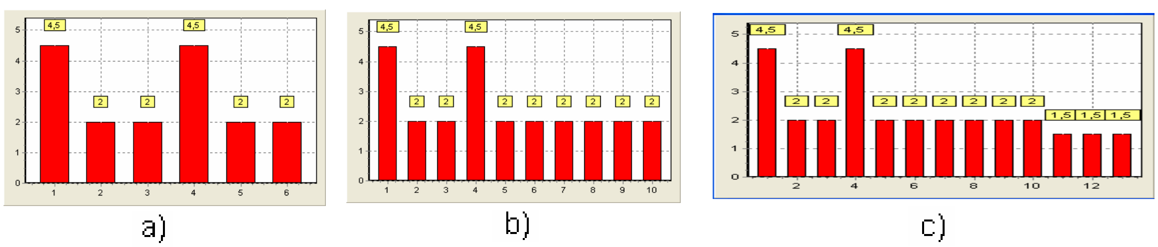

Fig.2. Scheme of uplift of keyboard blocks for numerical simulation: a) Sumatra segment; b) Sumatra and Nicobar segments; c) Sumatra, Nicobar and Andaman segments. The horizontal scale corresponds to the number of keyboard block (see, Fig.1b) while vertical scale corresponds to the magnitude of keyboard-block vertical shift (m); figures at the panels correspond to the maximum shift magnitude (m).

In Fig.3 there are presented results of calculation of tsunami wave generation and propagation for each of scenarios. In this figure it is also fixed the satellite position (point at white direct line) in given time moment. As it's seen from Fig.3a, tsunami source, formed at the ocean surface, (for first scenario) generates almost circular wave which, due to the bathymetry of given basin, persists its form and propagates most quickly in west and south-west direction. Towards north-west to Indian coast, the wave is coming with significant delay as compared with real tide gauge records. As it's seen from wave field picture for second scenario (Fig.3b) wave front, as it was waited, becomes more elongated and the time of front reaching of east coast of India, as compared with the case of wave generation only by Sumatra segment, is decreased. When third segment is included (scenario 3) wave field is characterized by still more elongated to north wave front (Fig.3c) and time of front reaching of south-east coast of India is decreased still more. It can be seen that from source side, faced to Bengal Bay, there are well pronounced three wave fronts in correspondence with marked segments (Fig.3c). These fronts then form plane enough united front with bend in the region of Nicobar Islands.

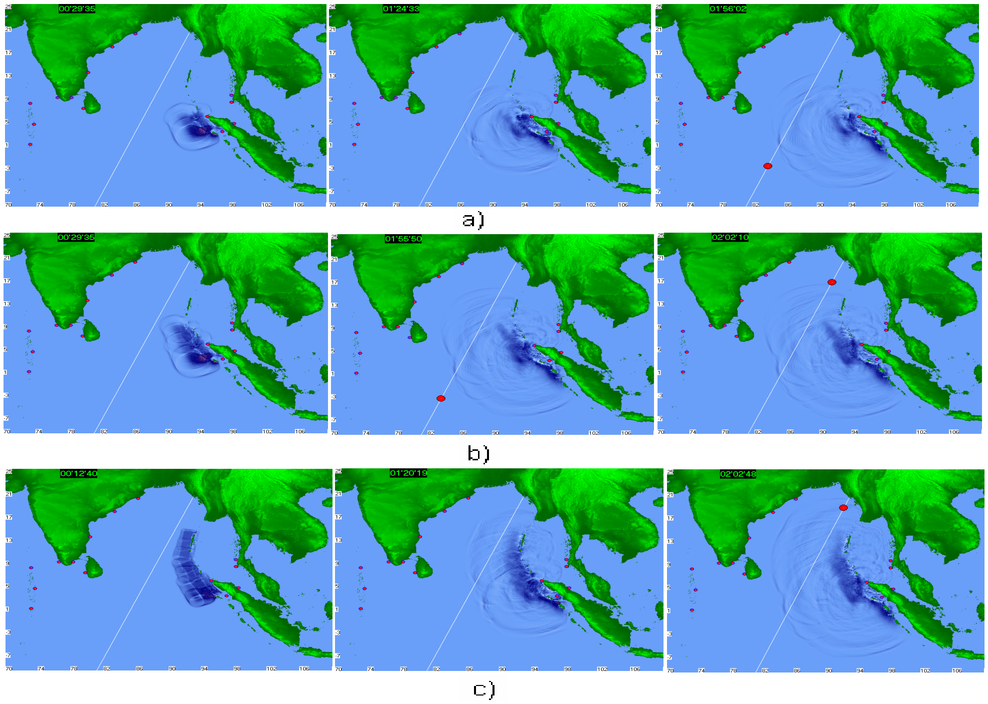

Fig.3. The generation and propagation of tsunami wave in the Indian Ocean basin: scenario a) - 1; b) - 2; c) - 3.

The change in character of wave field for these three scenarios is well seen from calculated satellite altimetry presented in Fig.4. In calculated picture of wave field, corresponding to satellite trajectory (Fig.1a), there are observed some features connected with wave generation only by one segment (Fig.4, upper panel). The characteristic feature is first positive peak and essentially larger, negative one. When including second segment, it's seen that there are changes in satellite altimetry: it is formed second positive wave and altimetric record is prolongated (Fig.4, middle panel). The including of third segment (Fig.4, lower panel) brings still more changes in altimetric record, however, a number of characteristic features of wave fields is persisted. So, leading wave, its height and propagation character in all three scenarios remain to be unchanged, however, it is well seen that rise in wave level behind two negative peaks is formed and has larger magnitude as compared with that at scenarios 1 and 2 (upper and middle panels). The characteristic negative peak appearing already for scenario 1 with only Sumatra segment is observed for all three scenarios, however, in scenario 3 its magnitude somewhat increases (lower panel).

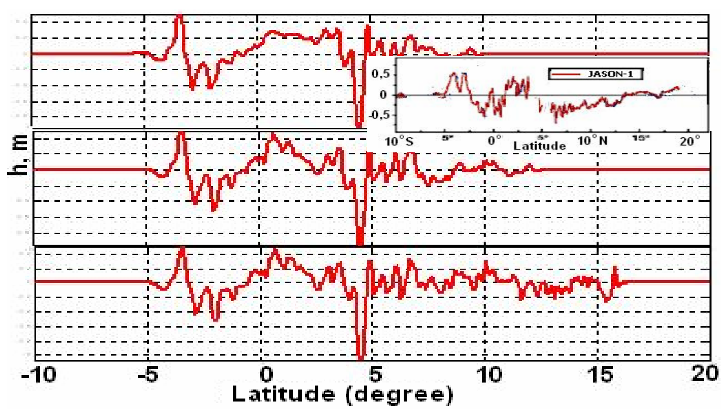

Fig.4. The virtual satellite altimetry at numerical simulation with scenario 1, 2 and 3 (from up to down). Inset: the real altimetry from satellite "Jason-1".

It is well seen also that with increasing of source extension satellite altimetric record is prolongated and in third scenario satellite fixes wave up to the moment of disappearance of the basin from the screen of locator. So, the wave field picture becomes to be in more agreement with results of satellite altimetric observations in both the region of leading wave and, essentially, in region of latitudes, corresponding to Nicobar Islands (cf., e.g. with (Lay et al. 2005)). Thus, the including in calculations of second and third segments of underwater seismic source, has no noticeable effect to leading wave, however, there appear significant changes in wave characteristics in the region of Nicobar and Andaman Islands as well as along coasts incoming to activity zone of these segments. As it's seen from Fig.4 (lower panel), calculated wave field picture corresponding to satellite trajectory is approached to observed altimetry of satellite "Jason-1" (see inset at Fig.4).

Numerical simulation of tsunami wave generation by seismic source comprising various number of keyboard blocks and its propagation in the basin

On the basis of analysis of seismic and hydroacoustic data of works (Ammon et al. 2005; Borges et al. 2005; Guilbert et al. 2005; Hirata et al. 2006; Ishii et al. 2005; Lay et al. 2005; Nagarajan et al. 2006; Park et al. 2005; Song et al. 2005; Titov et al. 2005; Park et al. 2005) there were considered scenarios at which motion of keyboard blocks in seismic source was not only successively from south to north with various orientation of movements and with different speed but was alternative and there were performed evaluation of results obtained on virtual satellite altimetry. In Fig.5 there can be seen two cases of simulation: upper panel corresponds to scenario 4 and lower one to scenario 5. In Fig.5a there are presented the results of altimetric record at simulation of motion of virtual satellite along trajectory of real satellite "Jason-1"; in Fig.5b schematic view of the moment of maximum shift of keyboard blocks is presented; in Fig.5c the calculated picture of wave field and satellite position for time moment 2 hours 40 min after earthquake strike is presented.

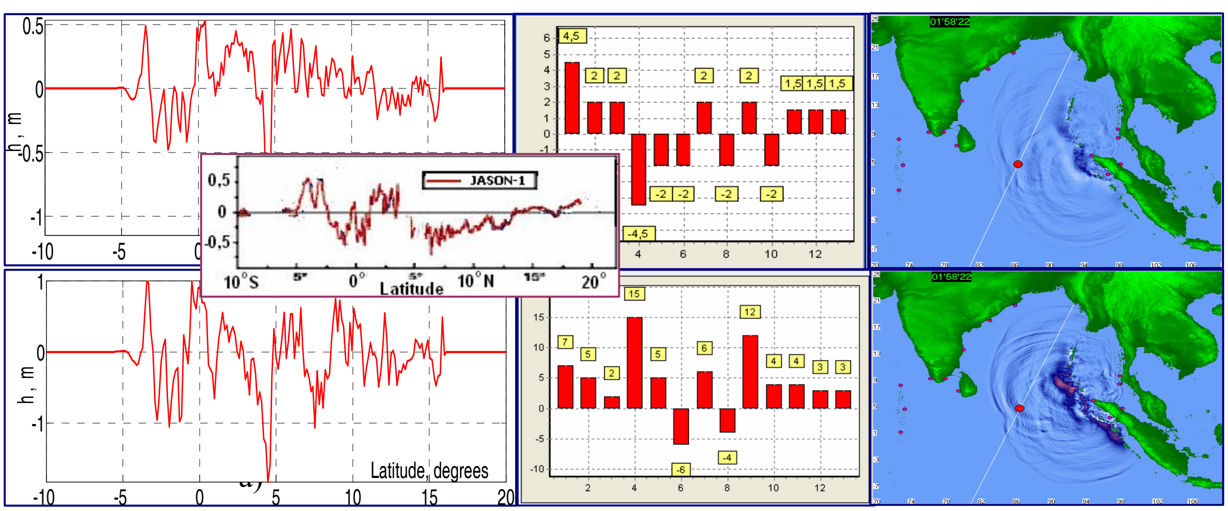

Fig.5. The results of numerical simulation with scenarios 4 и 5: a) virtual satellite altimetry with scenarios 4 и 5; b) sketch of location of keyboard blocks in seismic source; c) wave field character for each scenario; white direct line corresponds to the flight trajectory of satellite "Jason-1", point at this line corresponds to the position of satellite at given time moment.

According to scenarios 4 and 5, seismic source comprising 3 segments (see Fig.1b) is subdivided to the following blocks: Sumatra one (1-6 blocks), Nicobar one (7-10 blocks), and Andaman one (11-13 blocks). For scenario 4 keyboard blocks with negative displacement (4,5,6,8,10) are faced to Sumatra Island. It was considered a successive motion of keyboard blocks in source from south to north. For scenario 5 keyboard block displacement reaches to 15 m; keyboard blocks with negative displacements (6 and 8) are faced to Sumatra Island but the motion of keyboard blocks begins from keyboard block 4 (see Table 1).

Table 1

Block number	1	2	3	4	5	6	7	8	9	10	11	12	13
Shift value (m)	7	5	2	15	5	-6	6	-4	12	4	4	3	3
Start time (sec)	30	30	60	0	30	60	120	120	240	240	360	440	520
Stop time (sec)	120	60	180	30	240	300	300	360	360	360	480	480	600

For scenarios 4 and 5, the change in displacement magnitude of first keyboard blocks affects the behavior of central part of mareogram what in both cases can be explained by resonance effects at interaction of wave fronts coming from different segments. The picture of wave field, computed for scenario 4, can be viewed in Fig.6 where 6 moments of generation and propagation of tsunami wave from the seismic source are presented. It is well seen the forming tsunami source (upper panels), dipolar in character: closer to Sumatra Island it is observed a depression while from ocean side of the source it is formed an elevation of water surface.

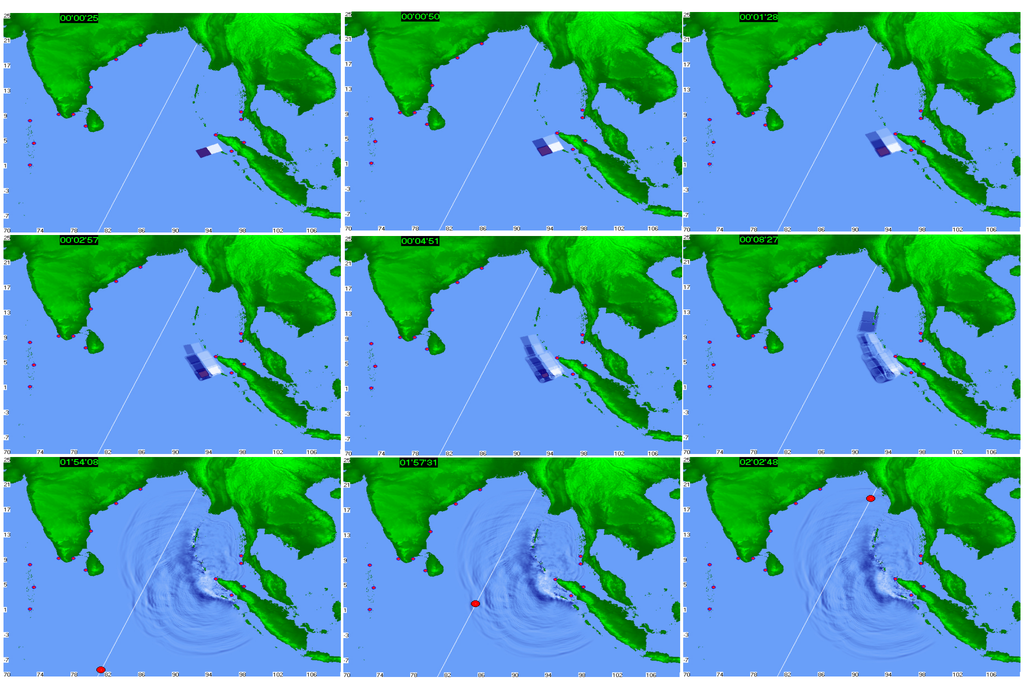

Fig.6. Formation of tsunami source and propagation of tsunami wave in Indian Ocean basin for scenario 5. At lower three panels there are fixed time moments of the flight of virtual satellite.

With increasing time, depressive wave reaches the coast of Sumatra Island, leading to recession of water from the beach, what was indeed observed there. However, in whole, wave field character in ocean is not changed what is consistent with calculations of another authors. The profile of sea surface height, during passing of tsunami wave computed along line, corresponding to both flight trajectory of Earth satellite and time interval of satellite measurements in this scenario, is essentially closer to satellite data: it relates to both leading wave and characteristic sharp depression of the ocean surface fixed by satellite during flight of the region of Nicobar Islands. This permits to suggest that such a scenario is closer to realization of given structure of movements in seismic source. However, it is necessary to note that altimetry obtained in its tail part is somewhat different of real record: in real altimetry the curve of profile of sea surface height along with satellite trajectory is located below the zero level what in fact denotes that at large part of its flight the satellite has fixed the depression of the water level in ocean. To approach character of computed curve to observed one it was performed a numerical simulation on scenario 6 which differs from scenario 5 by order of motion of some keyboard blocks. In scenarios 5 and 6, setting of keyboard motion in earthquake source was approached to results of work (Ishii et al. 2005) (see, Tables 1 and 2) and is in the following order: $4 \rightarrow 2$, $1 \rightarrow 3 \rightarrow 5 \rightarrow 6$, $7 \rightarrow 8$, $9 \rightarrow 10 \rightarrow 11 \rightarrow 12 \rightarrow 13$.

Table 2

Block number	1	2	3	4	5	6	7	8	9	10	11	12	13
Shift value (m)	4,5	2	2	-4,5	-2	-2	2	-2	2	-2	1,5	1,5	1,5
Start time (sec)	30	30	60	0	120	180	180	240	240	300	360	420	480
Stop time (sec)	120	60	180	30	240	300	300	360	360	360	480	480	600

The values of shifts are somewhat less than at scenario 5 since altimetric record of virtual satellite at simulation on scenario 5 results in essentially excessive magnitudes of sea surface height (see Fig.5, lower panel). For scenario 6 magnitudes of height in altimetric record (Fig.7) is closer to real data, moreover, the magnitude of negative peak is decreased and curve of sea surface height profile is located below the zero level what is better corresponds to real altimetric record from satellite “Jason-1” as compared with simulation on scenarios 4 and 5.

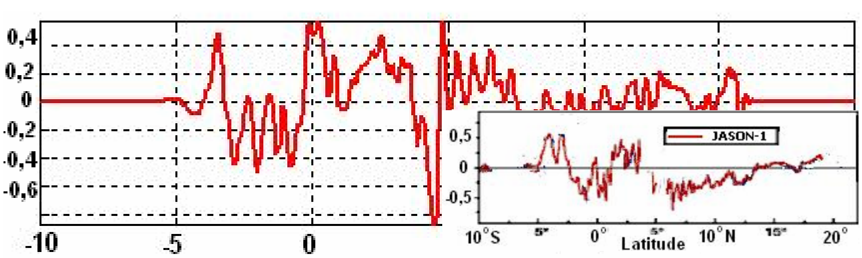

Fig.7. The virtual satellite altimetry for scenario 6.

Thus, a tendency of formation of source of earthquake 26 December 2004 becomes to be more definite: multi-block source in which fault is oriented to Sumatra Island while strong upthrust is oriented to ocean in Sumatra part of source, in Nicobar part of source fault is oriented towards Thailand, and upthrust, somewhat weaker as compared with Sumatra part, is also oriented towards ocean, and keyboard motion is not strictly successive from south to north.

Discussion and conclusion

The using of simplified keyboard model taking into account vertical component of keyboard block displacement in seismic source permit us to select most possible kinematic process describing adequately the wave field behavior in Indian Ocean basin at given tsunami. It is necessary to note also that motion of keyboard blocks in seismic source is not successive from south to north what is consistent with analysis of given earthquake performed in a number of works. The results of analysis of considered scenarios of kinematic motion of keyboard blocks in seismic source and generated tsunami waves permit us to conclude that most adequate is the formation of such source of underwater earthquake where fault is oriented towards Sumatra Island, and strong upthrust towards ocean in Sumatra part of the source, in Nicobar part of the source fault is oriented towards Thailand, but upthrust, somewhat weaker, than in Sumatra part, is oriented towards ocean. It is necessary also note that using of wavelet analysis of altimetric records of virtual satellite flights for each scenario permits us to confirm our suggestion on probability of realization of such scenario.

The obtained results of numerical simulation demonstrate that using the keyboard structure of underwater earthquake source and by changing the source dynamics, it is possible to obtain essentially different wave field character at surface water wave generation. During this process it is determined a process of tsunami source formation, magnitudes of maximum wave runup height and their distribution at the beach. The estimations of wave height at 10 m isobate, even in simplified model, give the possibility to select seismic source configuration.

Acknowledgments

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References

Ammon C.J., C.Ji, H.-K. Thio, D.Robinson, S.Ni, V.Hjorleifsdottir et al., 2005. Rupture Process of the Great Sumatra-Andaman Earthquake // *Science* 308, 1133-1139.

Borges J.F., Caldeira B., and M.Bezzeghoud, 2005. Source rupture process of the great Sumatra, Indonesia earthquake (M_w=8.9) of 26 December 2004 (Preliminary Results), *unpublished*) 1-6.

De Groot-Hedlin C.D., 2005. Estimation of the rupture length and velocity of the great Sumatra earthquake of Dec 26, 2004 using hydroacoustic signals, *Geophysical Research Letters* 32, L11303 (1-4).

Fine I.V., Rabinovich A.B., and R.E.Thomson, 2005. The Dual Source Region for the 2004 Sumatra Tsunami, *Geophysical Research Letters* 32, L16602(1-4).

Guilbert J., Verzog J., Schissele E., Roueff A., and Y.Cansi, 2005 Use of hydroacoustic and seismic arrays to observe rupture propagation and source extent of the M = 9.0 Sumatra earthquake, *Geophysical Research Letters* 32, L15310 (1-5).

Hirata K., Satake K., Tanioka Y., Kuragano T., Hasegawa Y., Hayashi Y., and N. Hamada, 2006. The 2004 Indian Ocean tsunami: tsunami source model from satellite altimetry, *Earth Planets Space* 58(3), 195-201.

Ishii M., Shearer P.M., Houston H., and J.E.Vidale, 2005. Extent, duration and speed of the 2004 Sumatra-Andaman earthquake imaged by the Hi-Net Array, *Nature* 435, 933-936.

Lay T., Kanamori H., Ammon C.J., Nettless M., Ward S.N., Aster R.C., et al., 2005. The Great Sumatra-Andaman Earthquake of 26 December 2004, *Science* 308, 1127-1133.

Lobkovsky L.I., 1988 *Geodynamics of spreading and subduction zones, and two-level plate tectonics* (Moscow, Nauka Press).

Lobkovsky L.I., Nikishin A.M., and V.T.Khain, 2004. *Current problems of geotectonics and geodynamics* (Moscow, Scientific World).

Lobkovsky L.I., Mazova R.Kh., Garagash I.A., Kataeva L.Yu., and I.Nardin, 2006. To analysis of source mechanism of the 26 December 2004 Indian Ocean tsunami, *Russ.J.Earth Sci. V.8, ES5001, doi:10.2205/ 2006ES000208* http://dx.doi.org/ 10.2205/2006ES000208 .

Lobkovsky L.I., and R.Kh.Mazova, 2007. Source mechanism of the tsunami of 2004 in the Indian Ocean: analysis and numerical simulation, *Izvestiya. Physics of the Solid Earth* 43, 573- 582.

Nagarajan B., Suresh I., Sundar D., Sharma R., Lal A.K., Neetu S., et al., 2006. The Great Tsunami of 26 December 2004: A description based on tide-gauge data from the Indian subcontinent and surrounding areas, *Earth Planets Space*, 58, 211–215.

Park J., Song T.-R.A., Tromp J., Okal E., Stein S., Roult G., et al., 2005. Earth's free oscillations excited by the 26 December 2004 Sumatra-Andaman earthquake, *Science* 308, 1139-1146.

Song Y.T., Li C., Fu L.-L., Zlotnicki V., Shum C.K., Yu Y, and V.Hjorleifsdottir, 2005. The 26 December 2004 tsunami source estimated from satellite radar altimetry and seismic waves, *Geophysical Research Letters* 32, L20601-5.

Tanioka Y., Yudhicara Y., Kususose T., Kathiroli S., Nishimura Y., Iwasaki S.-I., and K.Satake, 2006. Rupture process of the 2004 great Sumatra-Andaman earthquake estimated from tsunami waveforms, *Earth Planets Space*, 58, P.1–7.

Titov V., Rabinovich A.B., Mofield H.O., Thomson R.E., and F.I.Gonzalez, 2005. The global reach of the 26 December 2004 Sumatra tsunami, *Science* 309, 2045-2048.

Wilson M., 2005. Modeling the Sumatra-Andaman Earthquake reveals a complex, nonuniform rupture, *Physics Today*, June, 19-21.