

# Modelling of Strass-stain State in Epicentral Zone of Strong Earthquake

Vladislav Morozov  
Geophysical Center of RAS  
Moscow, Russia  
v.morozov@gcras.ru

Viktor Tatarinov  
Geophysical Center of RAS  
Institute of Physics of the Earth  
of the RAS  
Moscow, Russia  
v.tatarinov@gcras.ru

Alexander Manevich  
Geophysical Center of RAS  
Moscow, Russia  
a.manevich@gcras.ru

**Abstract**—This article describes the results of modeling the stress-strain state of the epicentral earthquake zone, which occurred on December 26, 2003 in the southeast of Iran in the province of Kerman (Bam), before and after the formation of the fault. It is shown that the main earthquake shock is located in the zone of high intensity of stresses, and the formed fault traces this zone on the surface and corresponds to its extent. Aftershocks are localized in the area of the maximum released stress intensity after the formation of the fault. Stress release stimulates the discharge of accumulated tectonic stresses in the subsequent aftershock process. The results obtained can be useful for deterministic approach to assessment and prediction of seismic hazard, as well as for geophysical observations clearly suited for the goal of predicting strong crustal earthquakes in continental regions.

**Keywords**—epicentral earthquake zone, tectonic stresses, modelling, stress-strain.

## I. INTRODUCTION

A strong earthquake with  $M_w$  and seismic moment  $6\div 9\cdot 10^{18}$  occurred in the southeast of Iran on December 26, 2003. The epicenter of the earthquake was located near the town of Bam in the province of Kerman. The ancient town of Bam, whose population was more than 100 thousand people, was practically demolished at the moment of main shock, and the number of victims exceeded 30 thousand people. The epicenter of the earthquake was located at a depth of 10 km [1]. On the surface, cracks were found tracing the direction of the formed gap 18-20 km long. After the earthquake in the vicinity of Bam, a network of seismic stations was set up (Figure 1), which registered more than 1,000 aftershocks  $M > 2.7$ . This allowed us to outline the main area of aftershock activity (about 25 km in length and 7 km in width) stretched in the meridional direction [10]. Hypocenters of aftershocks were localized at depths from 6 to 20 km. At the same time, most aftershocks were concentrated within the seismogenerating layer of the earth's crust with a thickness of 5 to 15 km. [9].

The nearest to the town of Bam tectonic fault (Bam fault) is located 4 km east of the town, its length is about 50 km (Figure 1). In the northwest there is a system of meridional faults (Gowk fault). Based on the analysis

of the mechanism of strong shock and GPS data, the regional field of tectonic stresses is characterized by the dominant pressure stresses of submeridional orientation [10]. The confinement of strong earthquakes to faults in crystalline foundation suggests that tectonic faults, as an area of destruction of the geological medium [6, 7, 8], lead to the formation of a local non homogeneous stress-strain state (SSS) in the Earth's crust.

A contemporary view on tectonic faults is related to the dispersed geological material therefore they can be represented by a model (giant blocked tectonic melanzh [11]). The presence in such a homogeneous massif of similar dispersion zones, the elastic modulus of which is substantially lower than that of the surrounding massif, leads both to the formation of anomalous local zones of high stress intensity, which initiate the development of a fault in a focus of tectonic earthquake [2, 3]. Formation of a fault leads to a change in SSS in the epicentral zone. In this case, regions of dropped stresses immediately adjacent to the new fault arise together with regions of increased stresses (at the termination points of a fault) exceeding the stresses that existed before the seismic event.

Modeling the stress-strain state in the epicentral zone of the December 26, 2003 Bam earthquake made it possible to distinguish an abnormally high area of stress intensity, which correlates with the stretch zone and the length of the predicted fault formed as a result of the earthquake. In this case, strong aftershocks with  $M > 5$  are in the region of high stress intensity preceding the formation of the main shock (rupture). The localization of aftershocks epicenters and the mechanisms of shocks with  $M \geq 2.7$  suggest that they are associated with the zone of ejected stresses, after the main shock.

The obtained results confirm the hypotheses of "nonlinear elasticity" of geological medium, where the model of SSS of the epicentral zone assumes an "instantaneous" release of stresses in the initially elastic medium, but the real process goes on with a certain delay in the aftershock activity time interval. In this connection, the possibility of forecasting the area of a strong tectonic earthquake in seismically dangerous regions according to the results of SSS modeling of rock massifs destroyed by systems of tectonic faults, acquires practical significance.

Print ISSN 1691-5402

Online ISSN 2256-070X

<http://dx.doi.org/10.17770/etr2019vol1.4119>

© 2019 Vladislav Morozov, Viktor Tatarinov, Alexander Manevich.

Published by Rezekne Academy of Technologies.

This is an open access article under the Creative Commons Attribution 4.0 International License.

## II. SEISMOTECTONIC POSITION OF THE EPICENTRAL ZONE OF THE DECEMBER 26, 2003 Mw 6.6 BAM EARTHQUAKE

To the north and south of the city of Bam within a radius of 70 - 80 km over the past twenty years, several strong earthquakes  $M > 6.0$  were recorded, associated with active fault zones of meridional orientation (Nayband - Gowk - Sabzavaran system) [10]. The 2003 earthquake turned out to be unexpected, since historical data only testify to several earthquakes located north of the city, and instrumental observations are limited to sufficiently remote seismic stations [1]. The parameters of strong earthquakes were instrumentally determined on June 11, 1981 ( $M_w$  6.6) and July 28, 1981 ( $M_w$  6.6). These earthquakes and the March 14, 1998 strong earthquake ( $M_w$  6.6) are associated with tectonic activity of the extended fault of submeridional orientation (Gowk fault) [1, 10] (Figure 1). According to GPS-observations, the right lateral displacement along the fault is  $\sim 6$  mm / year.

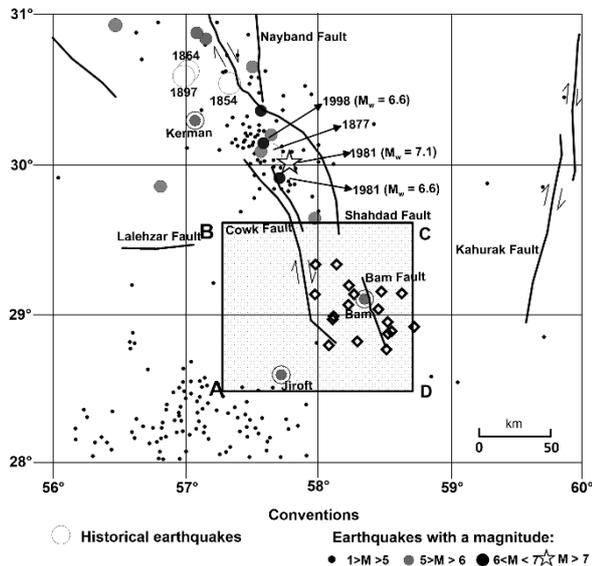


Fig.1. Structural-tectonic scheme and epicenters of strong earthquakes in the area of the city of Bam (Iran). ABCD - the area of the simulation of the SSS of the epicentral zone of the earthquake on 26.12.2003

9 seconds after the main shock, a strong aftershock ( $M_w = 6.5$ ) with an epicenter located south of the main shock was recorded [10]. Three days after the main shock, a network of mobile seismic stations was set up to record subsequent aftershocks. Figure 2 shows the area of aftershocks development 25 km long and 7 km wide (Figure 2). Aftershocks were registered at depths of 5 to 15 km, with maximum density in the “layer” from 9 to 12 km. The spatial distribution of aftershocks and crack systems on the surface suggest a submeridional orientation of the plane of the newly formed cracks, shown in Figure 3 taking the data into account. Figure 3 also shows the horizontal projection of P-axes in the epicenters of registered aftershocks and the position of a newly formed crack [9, 10]. These data are used to model the epicentral zone of the December 26, 2003 earthquake.

The GPS/GLONASS observations in Iran, mechanisms of strong earthquake epicenters north of the

city of Bam and aftershocks after the December 26, 2003 earthquake give grounds to assert the prevailing pressure stresses in the Bam area with an axis oriented in the range  $0-10^\circ$  relative to the meridian.

## III. SIMULATION RESULTS OF THE DECEMBER 26, 2003 EARTHQUAKE EPICENTER

The external field of tectonic stresses (border conditions) for ABCD square (see Figure 1) was given by the following values:  $\sigma_{yy} = -30$  MPa,  $\sigma_{xx} = -10$  MPa. The modulus of crystalline basement rocks elasticity  $E = 8 \times 10^3$  MPa, the modulus of elasticity of fault zones of the dispersed medium is two orders lower than  $E = 8 \times 10$  MPa, the Poisson’s ratio  $\mu = 0.25$ .

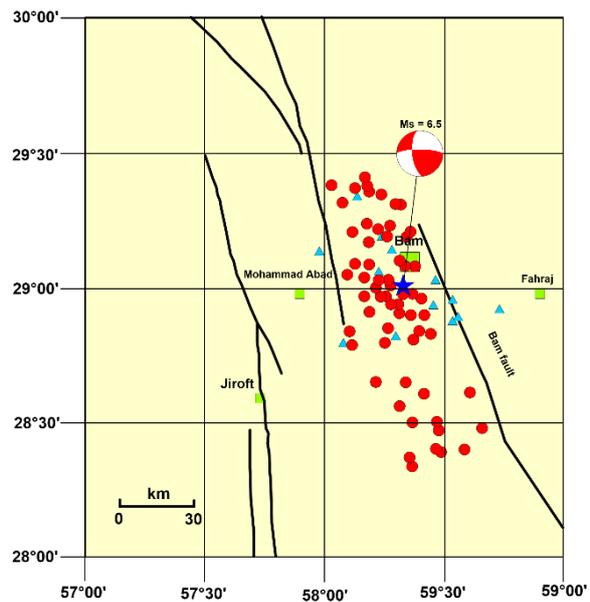


Fig. 2. Map of epicenters of aftershocks of the Bamsky earthquake on December 26, 2003.

Figure 3 shows the map of stress intensity distribution prior to the December 26, 2003 earthquake. High stress intensity zones are allocated on it, which could be associated a priori with possible zones of initiation and development of the fault. Moreover, the zone of high intensity of stresses between the Bam fault and Gowk fault about 75 km long, oriented in the meridional direction has three extremes and is more preferable in forecast evaluation of the possible development of seismotectonic process.

The distribution map of stress components  $\sigma_{yy}$  (Figure 4) has roughly the same morphology-an extended zone of high  $\sigma_{yy}$  values between the Bam and Gowk faults that extends north and the high  $\sigma_{yy}$  region at the southern end of Bam fault. Within the framework of the model, it has to be expected that abnormally high pressure stresses stimulate the start of destruction in the earthquake epicenter and the subsequent spreading of the fault.

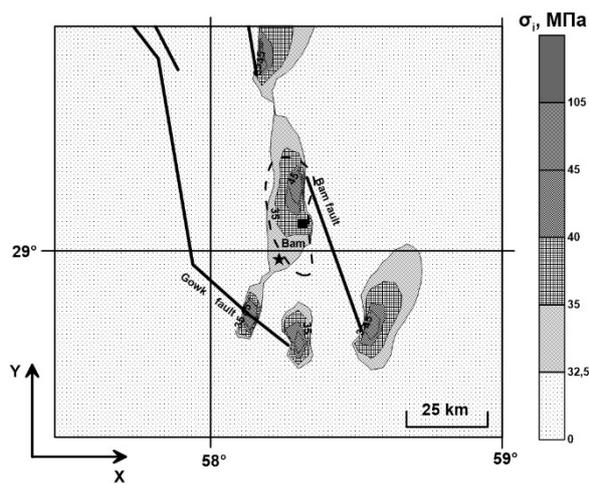


Fig. 3. Stress intensity map  $\sigma_1$  before the earthquake.

From considerations of distraction mechanism (the Mohr-Coulomb model), it would be logical to expect that the fault began from the area of maximum pressure stresses  $\sigma_{yy}$  and the minimum values  $\sigma_{xx}$ , under these conditions the probability of a fault in the form of a shear is extremely high.

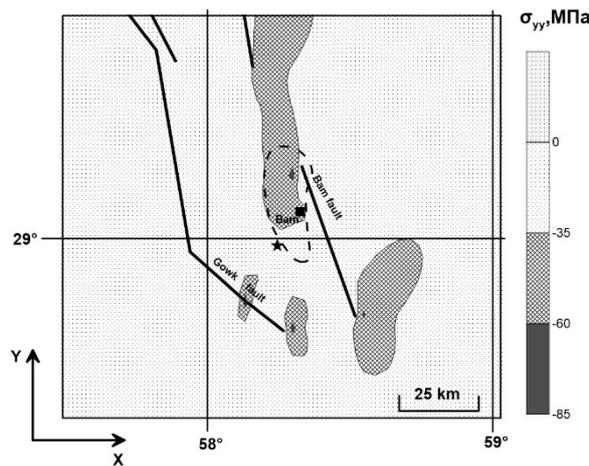


Fig. 4. Stress map  $\sigma_{yy}$  before the earthquake.

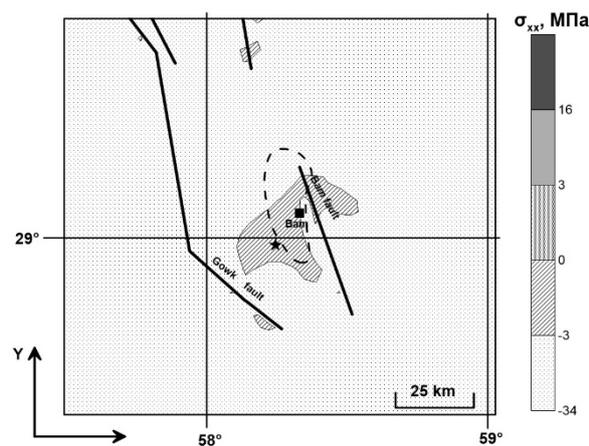


Fig. 5. Stress map  $\sigma_{xx}$  before the earthquake.

Figure 5 shows the stress tensor  $\sigma_{xx}$  component map before the earthquake. In the central part of the ABCD quadrant, a zone of anomalously low stresses (lower than 2 MPa, at background values of 10 MPa) is identified in the center of the region between Bam fault and Gowk fault. The  $\sigma_{xx}$  stresses are transformed into strain stresses.

Figure 6 shows the map of stress components ratio  $\sigma_{yy}/\sigma_{xx}$ . It can be seen that at the initial background value  $\sigma_{yy}/\sigma_{xx} = 3$ , in the central zone between the faults this value exceeds background values by 6 or more times.

On the maps (Figures 3-7), the epicenter of the main shock is indicated by a star. The epicenter of the main shock is associated with an extended zone of high stress intensity (Figure 3). Similar results were obtained earlier when simulating SSS of epicentral zones of strong earthquakes in India and Turkey [2, 5]. At the same time, the epicenter of the main shock falls in the area of high  $\sigma_{yy}$  values at the minimum  $\sigma_{xx}$  values, evolving into strain stresses (Figure 6).

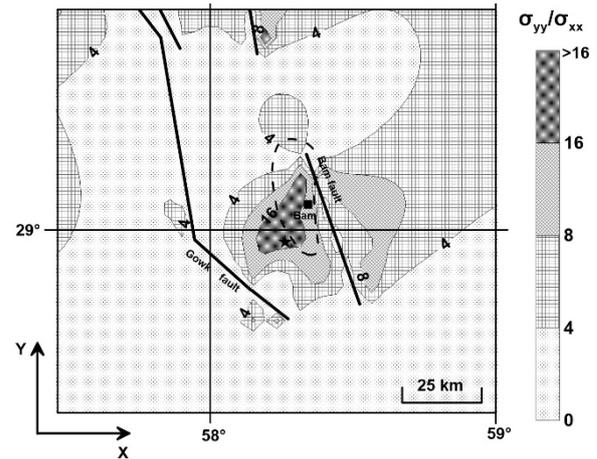


Fig. 6. Map of relations  $\sigma_{yy}/\sigma_{xx}$  before the earthquake.

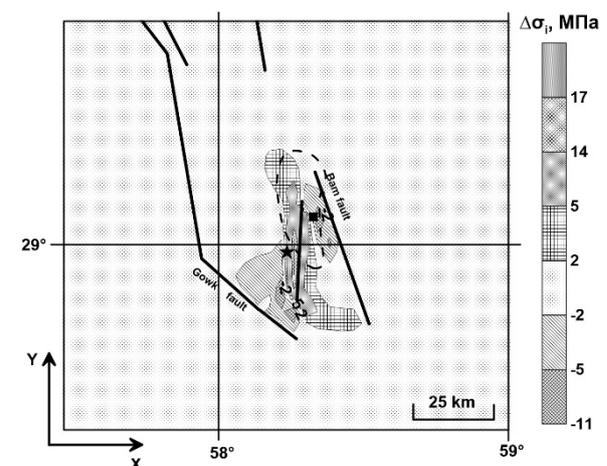


Fig. 7. Map of stress intensity difference ( $\Delta\sigma_1$ ) Before and after earthquake.

Using the results given in [10], the contour of the aftershocks area is indicated on the  $\sigma_{yy}/\sigma_{xx}$  ratio map, the position of which is determined with an error not exceeding 2 km.

From this area of maximum stresses, the fault propagates in a submeridional direction and, from the analysis of cracks formed on the surface, probably occupies the position between the Bam and Gowk faults, as shown in Figure 3 by a dotted line. In Figures 3 - 7 the area of aftershocks localization of is indicated by a dotted line. In Figure 4, this area corresponds to the zone of maximum stress intensity, which includes the epicenter of the main shock. In Figure 5, the aftershocks area coincides with the area of maximum pressure stresses  $\sigma_{yy}$ , which apparently determines the mechanism

of aftershocks in this zone. The correspondence between the aftershocks area and the area of minimum pressure stress  $\sigma_{xx}$  is shown in Figure 6.

Formation of a new tectonic rupture (dotted line in Figures 6 - 7) leads to a change in SSS of the epicentral zone. Relaxation of "secular" accumulated stresses occurred as a result of aftershock process. A drop of stresses in the area of a new fault stimulated this process. The cluster of aftershocks, as shown above, is localized in the area of high intensity of stresses preceding the earthquake, and the mechanisms of shocks corresponds to the condition of submeridional pressure, as shown in Figures 3 and 4.

Figure 7 shows the stress intensity difference map  $\Delta\sigma_i$  before and after the earthquake. In the area adjacent to the proposed fault, the level of stress intensity becomes significantly lower than the previous level before the formation of the fault. At the same time, new zones of increased stress intensity arise. It can be seen that the zone of epicenters of aftershocks is localized mainly in the zone of the dropped stress intensity.

The method used to calculate SSS of the epicentral zone (elastic formulation of the problem) assumes that "secular" static stresses drop completely in the area of a new fault (adequate tectonic fault) in the process of its "conditionally instantaneous" propagation. The energy of the dropped secular stresses is within  $10 \times 10^{16} - 10 \times 10^{17}$  J. Under real conditions, only a part of static secular stresses can "conditionally instantaneously" drop - the dropped energy of deformation, during the earthquake, does not exceed first percent of the dropped energy calculated by [2]. The real "non-linear elasticity" of the geological medium holds it in the process of aftershock activity, because time is required for a drop of static stresses. Aftershocks epicenters as elements of elastic properties weakness of the geological medium lead to a new stress state of the epicentral zone due to a change in its physico-mechanical characteristics in a much larger volume, compared with the volume of dispersed geomaterial of an emerging new tectonic fault.

#### IV. CONCLUSION

It follows from the foregoing that:

1. The epicenter of the Bam earthquake in Iran, which occurred on December 26, 2003, is located in the area of anomalously high stress intensity, obtained from the data of SSS modeling of the epicenter area.
2. It can be assumed that the "starting point" (the hypocenter of the December 26, 2003 earthquake) is associated with the stress state of the geological medium when high meridional pressure stresses  $\sigma_{yy}$  cause destruction of the geological medium at minimum pressure stresses passing into stretch stresses  $\sigma_{xx}$ .
3. The results of SSS modeling in the area of the source of December 26, 2003 earthquake correspond to the mechanism of the main shock source obtained from seismic data.
4. Orientation of the "plane" of the fault and its length are adequate to the zone of high stress intensity

obtained as a result of SSS modeling of the Ms 6.9 earthquake of December 26, 2003 epicentral zone.

5. The strong aftershocks that followed after the main shock are localized in an abnormally high stress intensity zone preceding the main shock.
6. After the formation of tectonic fault, SSS of the epicentral zone changed. There are areas of intensity drop adjacent to the newly formed fault in the area of increased stress intensity.
7. The zone of epicenters of aftershocks (including more than 1000 events) with a length of 26 km and a width of 7 km is localized in the zone of high intensity of stresses preceding the main shock. In this zone, after the earthquake (i.e., after the newly formed fault), the stress intensity decreased substantially as a result of the development of the subsequent aftershock process.

The results of SSS modeling of the epicentral zone of the Mw 6.6 strong earthquake in Iran of December 26, 2003, are adequate to the SSS modeling results of the epicentral zones of two strong earthquakes in India [3]. Summing up the results of the presented article and the specified works, it is possible to assert:

1. SSS modeling of epicentral zones of strong crustal earthquakes in continental regions allows us to retrospectively identify regions of localization of epicenters of possible strong earthquakes.
2. The length of local stress intensity zones is adequate to the extension of the formed fault and can serve as a predictive criterion for the magnitude of a possible tectonic earthquake.
3. Formation of a new tectonic fault leads to a change in SSS of the epicentral zone, - regions of resetting the "static" stresses and local areas of their increase arise, which are associated with epicenters of subsequent strong aftershocks.

Thus, the analysis of the results of modeling the Mw 6.6 earthquake epicentral zone of December 26, 2003 in comparison with seismological data gives hope for the possibility of predicting the location and energy of a possible maximum earthquake in seismotectonic environment, similar to the Bam area in southeastern Iran.

The work was performed as part of research works on the state task of the Ministry of Science of the Russian Federation

#### REFERENCES

- [1] Manafpour A.R., The Bam, Iran earthquake of 26 December 2003 // Field Investigation Report., Halcrow-EEFIT. 2004. Report: 59. P. 60.
- [2] Morozov V.N, Manevich A.I, Modeling the stress-strain state of the epicentral region of the earthquake of January 26, 2001, M = 6.9 (India) // Geophysical surveys. 2016. Vol 17, No. 4. P. 23-36., DOI: 10.21455 / gr2016.4-2.
- [3] Morozov V.N., Kolesnikov I.Yu., Belov S.V., Tatarinov V.N., Stress-strain state of the Nizhnekansky massif - the area of possible disposal of radioactive waste // Geocology. 2008. №3. Pp. 232-243.
- [4] Morozov V.N, Kolesnikov I.Yu., Tatarinov V.N, Modeling the danger levels of the stress-strain state in the structural blocks of the Nizhnekansky granitoid massif (to the selection of radioactive waste disposal sites) // Geocology. №6. 2011. p. 524-542.
- [5] Morozov V. N., Kolesnikov I. Yu., and Tatarinov V. N., Modeling the Hazard Levels of Stress-Strain State in Structural Blocks

- in Nizhnekanskii Granitoid Massif for Selecting Nuclear Waste Disposal Sites // *Water Resources*, 2012, Vol. 39, Issue 7, pp. 756–769. DOI:10.1134/S009780781207007X.
- [6] Rogozhin E.A., Tectonics of the foci of strong earthquakes of Northern Eurasia of the XX century // *Russian Journal of Earth Sciences*. 2000. T. 2, No. 1. Pp.37–62.
- [7] Shebalin N.V., Strong earthquakes. Selected Works. M.: Publishing House of the Academy of Mining Sciences, 1997. 542 p.
- [8] Sherman S.I., Seminsky S.A., Bornyakov S.A., Buddha V.Yu., Lobatskaya R.M., Adamovich A.N., Truskov V.A., Babichev A.A., Faulting in the lithosphere: shear zones. Novosibirsk: Science, 1992. 258 p.
- [9] Talebian, M., et al. (2004), The 2003 Bam (Iran) earthquake: Rupture of a blind strike-slip fault // *Geophys. Res. Lett.*, 31, L11611, doi:10.1029/2004GL020058.
- [10] Tatar M., D. Hatzfeld, A.S. Moradi, A. Paul, A.M. Farahbod, M. Mokhtari, Aftershocks Study of the 26 December 2003 Bam Earthquake // *Journal of Seismology and Earthquake Engineering* . 2004. Vol. 5, №4. P. 23 – 31.
- [11] Zabrodin V.Yu. et al., Fracturing tectonics of the continental part of the Far East of Russia / V.Yu. Zabrodin, OV Rybas, GZ Gilmanova. Vladivostok: Dal'nauka, 2015. 129 p.