# Aftershock Analysis for the 1997 Ghaen-Birjand (Ardekul) Earthquake

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**ABSTRACT:** In this study at the first step, the database of two temporary networks of International Institute of Earthquake Engineering and Seismology (IIEES) and Institute of Geophysics of Tehran University (IGTU), which deployed independently after the Ghaen-Birjand earthquake, were merged. Based on the new database, focal mechanisms of some larger aftershocks were obtained and crustal model of eastern Iran [3] modified for the epicentral area of Ghaen-Birjand earthquake and its aftershocks. The Vp/Vs ratio is inferred as 1.85 for the region covered by the temporary seismic networks. After relocation of more than two hundred events, it was cleared that at least three of the largest aftershocks were estimated to be located with a precision corresponding to error ellipsoid axes within 5 to 10 km (Ground Truth level of 5 to 10).

Keywords: Aftershock; Ghaen-Birjand; Velocity model; Focal mechanism

## 1. Introduction

On May 10, 1997 at 12:27 (local time), an earthquake with magnitude Mw 7.3 (USGS), 7.2 (Harvard), Me 7.7 (USGS), Ms 7.2 (Berkeley) occurred in the Ghaen-Birjand region in northeastern Iran. The radiated energy and seismic moment of this event estimated to be  $Es = 8.9 \times 10^{15} Nm$  (USGS),  $Mo = 9.5 \times 10^{19} Nm$  (USGS),  $Mo = 7.3 \times 10^{19} Nm$  (Harvard) respectively. The earthquake was felt over a large area including the cities of Mashad, Kerman and Yazd. The epicenter of the earthquake was located close to the town village of Ardekul at 33.88°N latitude and 59.82°E longitude according to *ISC* report. Most of the damage and human casualty occurred in a 100km strip between Birjand and Ghaen.

The epicenter of Ghaen-Birjand earthquake is situated in the north of Sistan collision zone which separates the central Iranian block on the west from the Afghan block on the east [17, 6]. This region is well known for destructive earthquakes. The last large earthquakes in this region were occurred in 1979. One was the Korizan earthquake with magnitude Ms 6.6 on November 14, 1979 and another was the Koli-Boniabad earthquake with magnitude Ms 7.1 on November 27, 1979 [1]. The Korizan earthquake occurred in the same area and along the northern part of the same fault (Korizan fault) associated with this most recent event, see Figure (1).

As a result of the recent earthquake, 1,567 people were killed, and more than 2,300 were injured. In addition, 147 villages experienced damage. Some of these villages were completely destroyed while many others suffered heavy damage, especially to housing units. From the observed damage, an intensity of *X* on



Figure 1. Isoseismic map of the Ghaen-Birjand earthquake area, Korizan fault and the largest events near the fault during the past two decades. This map was originally taken from Michael West, Columbia University (1999), with some modifications.

the *MSK* scale was assigned to affected areas in the close vicinity of the epicenter. The peak ground acceleration (*PGA*) at places close to the epicenter is estimated to have been about 0.7g [13].

This event followed by a large number of aftershocks as large as Ms 5.9.

In the present paper some of the recorded aftershocks and the results derived from in ir analysis will be discussed.

#### 2. The Database

Shortly after this event, bot  $IC^{-}U \leftarrow IIEES$ installed temporary networks 1 t. epicentral area [15, 14]. The temporar ne vork of IIEES consisted of five stations win an operating period of approximately 7 wee's, staling May 13, 1997. IGTU deployed a "emporal network of 15 stations 5 days after the main. bock which operated for a period of two months, an a in November 1997 IGTU installed a small loci1 network of five stations near the southern end of the fault, aimed for monitoring the aftershock activity and their possible migration. This network was in operation for one month. Recorders, which were deployed by *IIEES*, were Kinemetrics SSR1 with SS-1 seismometers while IGTU used three MEQ-800 analogue recorders and twelve PDAS-100. All the recorders used radio signals via WWVT receivers for time setting.

The first step in the present analysis was merging the two datasets and establishing a joint database for the time period in which a maximum coverage existed. This resulted in a database of 215 aftershocks recorded over a period of 48 days from May 15 until July 1. As the main goal of this paper is improving the location of the aftershocks, the new database was consisted of the events, which were recorded by the both networks.

Time distribution of recorded aftershocks in the new database is shown in Figure (2). The distribution in Figure (2) is regarded as quite normal for an aftershock sequence following such a large earthquake.

The modified Omori relation could characterize the rate of aftershock decay for this event as Eq. (1) [7]:

$$N(t) = 246.4t^{-0.63} \tag{1}$$

In which N(t) motes e number of aftershocks, t days after the h in slock. It must be noted that Figure (2, only nows the number of events recorded by the both networks and it does not indicate the sciencic activity. On day 26 due to some instrumental p oblems, no common event was re orded by the networks.



Figure 2. Number of events per day in the aftershock sequence of the 1997 Ghaen-Birjand earthquake which was recorded by the both networks, from five days after the main shock, covering about two months of recording.

### 3. Vp/Vs Ratio

Estimation of Vp/Vs ratios is useful to examine the accuracy of the readings of S arrival times in the regions where this ratio was previously obtained. S waves are in some cases very difficult to interpret on seismograms.

The Vp/Vs ratio was estimated for the aftershocks of Ghaen-Birjand earthquake, recorded by local temporary networks. Figure (3a) shows the fitting of regression line in the relation between P and *S-P* times. The Vp/Vs ratio and its standard deviation for 262 couples of P and S-P times among 215 events are 1.853 and 0.033 respectively. In this way all the low quality data that the standard deviation of the residual of P times are beyond 0.5 second, were excluded. Also Wadati diagram for the aftershock events is shown in Figure (3b). The maximum number of occurrence can be observed between 1.82 to 1.87 for Vp/Vs. Berberian [4] studied the aftershocks of the 1978 Tabas-e-Golshan earthquake in eastern Iran (approximately 200km west of the city of Ghaen) and obtained the same value of 1.85 for the Vp/Vs ratio.



Figure 3a. P time versus S-P time for the aftershocks c 'ie1 )97 Ghaen-Birjand earthquake based on u ? oc that recorded by both two tempo ary inc 'pi ks.



Figure 3b. Wadati diagram for the aftershocks.

## 4. Crustal Model and Focal Mechanisms

The epicenter location of the main shock, reported by ISC and the relocated aftershocks of Ghaen-Birjand earthquake are shown in Figure (4). These locations were obtained based on a 1-D inversion



Figure 4. The epontre distribution of the aftershocks (o, ring to Ghaen-Birjand 1997 earthquake after relo, ion will improved model, and plotted together with fault surface trace and focal mechanisms (Harvai JMT) from the main event and the largest and thock. The temporary stations (both IGTU and IIEE )) are shown with black triangles.

using the *VELEST* algorithm of Kissling [9, 10, 11]. efor running the *VELEST* program, 33 well-located aftershocks were selected in which the *RMS*< 0.2, number of phases > 8 and the absolute location error is less than 5km. In this case, the event locations are relatively stable and it is possible to estimate reasonable velocity models by using the method of minimizing average *RMS*.

The program *VELEST* is used to solve the coupled hypocenter velocity model problem for local earthquakes. It performs a simultaneous inversion for hypocenters and velocity model. The inversion is limited to first arriving phases. Based on an initial crustal model, this algorithm uses the arrival times of the aftershock sequence to develop a refined model with simultaneous relocation of the events.

As an initial value, the modified Tabas velocity model [2, 3] for eastern Iran was used. The *P* velocity in the first layer of starting model is 5.7km/sand its thickness is 15km which overlies a lower crust with Vp = 6.10km/s. The last layer has a Vp = 7.70km/s, see Table (1). For this model the average *RMS* is 0.179s for 33 aftershocks. The results of minimizing average *RMS* are Vp =5.73km/s in the first layer with 13km thickness and Vp = 6.03km/s in the second layer with 9kmthickness. Trying to minimize the *RMS*, a new layer was introduced beneath the second layer in which the best parameters were estimated as

Table '	<b>1.</b> Initial model for eastern Iran [3] and improved model
	based on inversion process of Ghaen-Birjand after
	shocks. RMS indicates average root-mean-square
	values of the travel time residuals for both initial and
	improved models for all the aftershocks.

Parameters	Layer	$V_p (km/s)$	V <sub>s</sub> (km/s)	D (km)			
Pahavar Madal [2] for	1	5.70	3.08	0.0			
eastern Iran	2	6.10	3.29	15.0			
	3	7.70	4.16	43.0			
Average RMS (s) for 33 well-located events0.179							
1 1 1 1 1 0	1	5.71	3.08	0.0			
Improved Model for	2	5.96	3.22	12.0			
inversion)	3	6.53	3.52	23.0			
,	4	7.70	4.16	43.0			
Average RMS (s) for 33 well-located events	0.127						

Vp = 6.55 km/s and 10 km thickness. Due to short site-source distances within the local network, the velocity of the last layer and Moho depth were assigned as a fixed value. For this model, the average *RMS* for 33 well-located aftershocks is 0.133s. To verify these results, by using the *VELEST* program, a 1-*D* inversion of arrival times for the same events has been carried out. Using the results of minimizing average method, 1-*D* inversion converged to the final model, which is in good agreement with the results of the last step, see Table (1). The proposed cruttal model for the Ghaen-Birjand area reduces the verage *RMS* for locating the whole events in the dat base (215 aftershocks) from 0.381 for the model of eastern Iran [3] to 0.329.

Based on the improved 1 odel, the aftershocks were relocated and plotted in 1. Fe (4). In addition to epicentre distributions, be stations of temporary networks, fault trace with a length about 110km) and the Harvard mortlen tensor (focal mechanism) solutions for the main shock and the largest aftershock are also shown in Figure (4). Focal depth distribution of the aftershocks in a Northeast-Southwest cross-section is given in Figure (5). The aftershock database as displaced in Figures (4) and (5), show some characteristic features:

The epicentres closely follow the main trace, however, with significant activity to the west within the network. This distribution clearly reflects the location of the temporal networks, but also shows that a very large volume around the causative fault experienced aftershock activity.



Figure 5. Depth distribution (in kilometers) of the aftershocks in Ghaen-Birjand area in a NE-SW cross-section. The line in the bottom of aftershocks shows the Moho discontinuity at the depth of 43 kilometers.

The aftershocks that occurred close to the fault trace shows concentration in two pockets of enhanced seismicity but the largest aftershocks occurred near the northern end of causative fault.
 The depth profile ... Figure (5) shows that the aftershock c ivity vas concentrated in the upper 2. n of e c ust with a median value about 11kn. Als this figure clarifies a nearly vertical trend, nich is in agreement with the mann snoe faulting.

Most of the westward scatter in Figure (4) is condered to be real, including also the location of the latest aftershock (June 25, 1997, Ms 5.9), which could be correlated with a surface rupture.

Fastan Iran is a wide zone of active deformation related to the collision between the Arabian Plate and the Eurasian Plate. The overall shear across the zone is accommodated on both strike-slip and thrust faults in complex geometries. The major earthquakes in the northeast of Iran are associated with E-Wrunning thrust and left-lateral strike-slip faults. To the south of these faults is a set of right-lateral strike-slip faults running N-S and extending to the Makran region in the south. Seismicity decreases dramatically east of the Iran-Afghanistan border, and geological structures in eastern Iran are aligned in a N-S direction. The combination of the dominant E-W left-lateral faults and the subordinate N-Sright-lateral strike-slip faults with thrust faults trending NW-SE indicates that the eastern part of the Iranian plateau is undergoing a structural rotation as it is being compressed against the stable blocks of western Afghanistan and Turkmenistan. The rotation results in a lateral movement of material away from the compression zone and towards the Makran region in the south along the strike-slip faults [8].

For earthquakes of the size like the Ghaen-Birjand, the focal mechanisms are often very complicated and the results derived from far field stations were used to interpret the rupture procedure. The source mechanism of the main shock proposed by Harvard University indicates a right-lateral fault. This agrees with field results of the active fault survey teams.

Based on P wave first motion polarity, recorded at local and regional stations, an attempt has been made for calculating fault plane solution of some larger aftershocks. The results of this procedure are presented in Table (2) and from these it can be observed that some of the fault planes exhibit nodal planes that strike in a *N-NW* to *S-SE* direction, in accordance with the main fault and the general geological structural trend. The obtained focal mechanisms do however clearly demonstrate that the aftershock sequence is complicated, and do not adjust on a well-defined rupture plane.

## **5.** Errors in Location

The location errors of aftershocks in latitude, longitude and depth are displayed in Figure (6), with a dashed line drawn at the important GT5 level



Figure o. Locatike errors in latitude, longitude and depth (in km) for the aen-Birjand 1997 aftershock sequence, and elocation with improved crustal model following the V\_LEST inversion.

**Table 2.** Fault plane solutions of some larger aftershocks based on F rave first motion analysis, recorded at local and regional stations. In this table SK, DA, SA, AZ and PL are able viate s for strike, dip angle, slip angle, azimuth and plunge respectively.

Event	SK1	DA1	SA1	SK2	DA2	Б. <del>–</del>		P-axis		T-axis		xis	Projection
(Location)							AZ	PL	AZ	PL	AZ	PL	5
1997/06/20													(
00:32:57.7					$\mathbf{V}$								$\langle \cdot \rangle$
	240	77	-121	129	32	-24	117	49	354	26	248	30	1 5
Lat: 33.85N													1/ *** 9 1
Long: 59.95E													
Depth: 10													
ML: 3.2			. 44										
1997/06/20				2									
12:57:49.2	226		1	125	72	22	01	25	170	10	202	52	
Lat: 22 20N	220	20	-1	123	/3	-33	82	33	1/9	10	282	33	- X
Lat. $33.291$ Long: 60.11E													1. A. S. 1
Denth: 25													X Y
ML: 4.9													
1997/06/21													1
08:45:26.9													
	40	65	156	299	68	27	350	2	259	34	84	56	$\sim 1$
Lat: 33.30N													-1, <b>*</b> X +
Long: 60.01E													X /o Y
Depth: 12													$\sim$
ML: 4.2													
1997/06/22													A
22:52:57.8													$\langle - \rangle$
	271	54	29	163	67	140	220	8	122	44	318	45	
Lat: 33.46N													1 4 . 1
Long: 59.65E													
Depth: 16													$\sim$
ML: 4.3													_4
1997/06/23													
22.23.10.0	44	84	175	134	85	6	260	1	350	8	170	82	$\wedge$
Lat: 33 50N		04	175	134	05	U	209	1	559	0	170	02	
Long: 59 98E													
Depth: 13													$\vee$ $\vee$
ML: 4.0													$\sim$
							·						

(hypocenter uncertainty less than or equal to 5km). Since it is well known that small standard errors can also be caused by using small number of stations (and readings) and thereby not expressing the real precision, in Figure (7) the situation for the present database was clarified. The left part of Figure (7) shows that *RMS* could be controlled by using 6 to 10 stations generally in use (with both *P* and *S* readings from each one). Figure (7 right) shows the *RMS* time residual distribution indicating satisfactory values. It must be noted that the events with *RMS* above 0.6 were excluded from the database of aftershocks.

The three selected aftershocks that were recorded both on local and regional stations relocated using only the data from temporal networks. A main source of uncertainty in the relocation was the focal depth. In this area the depth of earthquakes are generally less than 30km and most probably between 9 to 15km for the recent events [5]. Based on spectral analysis of 24 Ghaen-Birjand aftershocks with magnitude above 3.0, it has been observed that the most energetic events occurred in northern parts of the fault (near the main shock) and the depth of these events is less than 30km [7].



Figure 7. Number of stations used and RMS of travel me residuals for the Ghaen-Birjand 1997 aftershock sequence, after relocation with improved crustal model.

Low *RMS* alone does not as alre dy noted, guarantee a reliable solution. To wer, the low average values indicate that station min<sub>0</sub> for the two networks involved is reliable.

It is notable that the m gr. des for most of the better located aftershocks. Too small to be useful as ground truth (GT) refer to events, since they should not be expected to record at sufficiently enough stations at regional distances. In order to face this challenge, three of the larger aftershocks listed in Table (3) as candidates.

For the event of May 10, 1997 (main shock) the determined depth by *ISC* was 6.7km based on routine inversion methods and *pP*\_Depth was 20.25km. The *ISC* reports of focal depth for the three aftershocks are as follows:

- ✤ 1997/06/21, Depth 23.3km.
- ✤ 1997/06/22, Depth 43.2km (pP\_Depth: 16.06).
- ✤ 1997/06/25, Depth 35.0km (pP Depth: 14.27).

In the routine location procedures, the error ellipsoid is computed from the partial derivatives of travel times with respect to latitude, longitude and

 Table 3. Three of the Ghaen-Birjand 1997 relocated aftershocks, with time, location (with uncertainties), RMS, different magnitudes and number of stations contribute to ISC solutions.

Date	Time	Lat.	Long.	Depth	No.	RMS	ML	Mb	Ms	Mw	No.
		Ν	Е	Km	P&S	Sec				HRV	ISC
1997/06/21	08:45:26.9	33.299	60.008	12	14	0.79	4.2	4.2	3.7	-	48
Error (km)		5	10	0							
1997/06/22	22:52:57.8	33.461	59.651	16	18	0.48	4.3	4.3	3.9	-	73
Error (km)		1	3	0							
1997/06/25	19:38:42.8	33.946	59.606	14	21	0.48	5.3	5.4	5.9	6.0	541
Error (km)		2	3	0							

depth, evaluated at the final hypocenter determined for the earthquake. The travel times are not linear. Consequently, the error ellipsoid is an appropriate measure of the errors only to the extent that the partial derivatives are linear in the region nearby the final location and that there is only one spatial minimum of *RMS* residual. But often there is a minimum in *RMS* residual at two different depths, and sometimes neither minimum is significantly lower than the other.

For the aftershock of June 21 it was difficult to determine focal depth reliably only from the first arrivals. The station *HAJ* recorded the event at 26km epicentral distance, and the record shows two secondary phases arriving 2.2 and 3.3 seconds after the first *P* arrival, see Figure (8). The first of these match a reflection from the 23km crustal interface if the focal depth was around 12km, while the second



Figure 8. Recording from the h. 'st. on indicating the secondary arrivals.

phase match a Moho election if the focal depth was around 34 km is show in Figure (9). This figure shows the predict and observed relative arrival time and the corresponding focal depths. It is seen that the secondary arrivals match with two modelled focal depths of around 12 and around 35km. Considering the tectonics of the region and the focal depth of the other aftershocks we are confident that the real focal depth is around 12km and it is fixed to that depth in the database. For the second and third events the depths were fixed to calculated pP depth. The resulting locations were based on these fixed depth values, which is shown in Table (3).

Table (3) shows the parameters of three aftershocks of Ghaen-Birjand earthquake, which is assigned as potential GT5 to GT10 candidates with date, time of day, latitude, longitude, depth, No. of P



Figure 9. Modelled and observed relative arrival times used for the determination of focal depth for the June 21, 1997, Ghaen-Birjand aftershock. The boxed areas indicate where the possible focal depths match with observed secondar ses.

and S phr read 2s (No. P and S), time residual RMS, local homitu e ML, mb (ISC), MS (ISC) and MW (HRV). The local magnitude (ML) calculated according Eq. (2) which was developed by rarabbod et r.1 [7]:

$$= 2.2log (F-P) + 0.0002 \, \mathbf{D} - 0.38 \tag{2}$$

1. which F-P (P time to Final time) is given in scores and **D** is epicentral distance in km.

In Table (3), standard error estimates in latitude, longitude and depth, in km, are given below each of the corresponding values in italics. "No. *ISC*" indicates number of stations that contribute to the *ISC* solutions. The key parameters in consideration of the events in Table (3) as *GT5* to *GT*10 candidates are the standard errors, indicating that the last two of these, seem to have the best locations. With a magnitude of *Ms* 5.9 which recorded on 541 stations worldwide, the largest aftershock is clearly also large enough in magnitude to serve as a *GT* event.

# 6. Origin Time Uncertainty for Ghaen-Birjand Aftershocks

The three Ghaen-Birjand aftershocks were located using data (readings) from integrated local networks. The epicentral distances vary from 4km up to 120km for the local stations, and the azimuths have an acceptable but not very good coverage as shown in Figure (10). With the given distance distribution, the main contributor to the origin time uncertainty is the local velocity model used.

To investigate the effect of the velocity model on the origin time, the three events were located with two alternative velocity models for Iran, Moazami-Goudarzi [12] and Sweeney and Walter [16]).



Figure 10. Distance-azimuth distribution for the three Ghaen-Birjand aftershocks. Note that only the stations in the temporary networks were used in the location.

The impacts of the different models are estimated and the maximum differences between origin times assigned as time uncertainty as shown in Table (4).

**Table 4.** Estimated origin time uncertainty for the three Ghaen-Birjand aftershocks.

Event	Origin Time	Estimated Origin Time Uncertainty
Aftershock 1, June 21	08:45:26.87	0.18 (sec)
Aftershock 2, June 22	22:52:57.85	0.74 (Sec)
Aftershock 3, June 25	19:38:42.75	0.40 (Sec)

## 7. Summary and Conclusions

Following the May 10, 1997, Ghaen-F rjand, arthquake, two independent tempor  $1 \text{ nc}^{+}$  vor. acquired data from aftershocks for a period. Call ut 2 months. The data from these networ! we successfully merged, and 215 aftershocks that were recorded on both networks in the local mag. de range of 2.5 to 5.3 were located in and cound the larger rupture zone. The aftershocks panned in an area of around 100km length and 30lm y dth.

The aftershocks that occurred close to the fault trace show concentration in two "pockets" of enhanced seismicity, and in general the aftershock activity is more pronounced in the southern end of the ruptured fault. The largest earthquakes occurred near the northern end of the ruptured fault.

Based on this aftershock database a Vp/Vs ratio of 1.85 was confirmed for the region, and based on studies from adjacent regions [4] we have substantiated that this value may be representative for the crust in eastern Iran.

A new velocity model was established through joint inversion for hypocenters and crustal velocity

structure. The in: ion we based on a high quality subset of the dat, as and led to an overall improvement in verse MS of travel time residual as compared with  $\Rightarrow$  original crustal model.

The  $_{1}$  crustal model for the Ghaen-Birjand area reduces the average *RMS* for locating the whole events in the database (215 aftershocks) from 0.381 for t. model of eastern Iran [3] to 0.329. Based on the following reasons, this new model is a preferred one or the eastern Iran:

- ✓ It improved the initial model for eastern Iran by changing the body wave velocities and the thickness of layers. In the old model, surface wave dispersion data were used for determining the thickness of each layer, Moho depth and velocities. Therefore, by using the data of body waves in local distances through minimizing the average *RMS* and *VELEST* algorithm of Kissling [9] better values for velocity and thickness of each layer in the upper crust were obtained.
- 2. The extent of aftershock distribution is about 100km in length and 30km in width, so the obtained model is not constrained to a very small area.

As for the Vp/Vs ratio we believe that also the obtained crustal velocity model is applicable for larger areas in eastern Iran.

For some events in this aftershock database focal mechanisms could be computed. The focal mechanisms show preferences for strike slip mechanisms in accordance with the main rupture. However, the components of both thrust and normal faulting indicate a complex deformation pattern in the larger volume around the main fault.

Finally, three of the aftershocks have been

investigated with respect to its usefulness for calibrating travel times over large regions (defining the hypocenters with high precision). The three events that were recorded on a large number of regional stations could be located with the temporal networks and the new velocity model to Ground Truth locations better than 5 to 10km. The relocation results of three selected aftershocks with new crustal model regarded as the best parameters of these events in contrast of considerable azimuthal gaps.

While we regard the above as useful and important results that contribute both in seismicity location related problems of the region and to the tectonic understanding, the database also highlights some problems that an aftershock campaign may encounter. Firstly, it was realized that the distribution of instruments is severely dependent on accessibility and security for the instruments. As for the Ghaen-Birjand region this caused an uneven distribution of the temporal network stations to the west of the main rupture zone. Secondly, it became clear how vulnerable such temporal networks are to technical problems. Even with the significant station redundancy in the two networks the data acquisition suffered severely under technical problems, and this entailed that many events were recorded on few stations.

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