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Quality assessment of seismic recording: the Tehran Seismic Telemetry Network

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Abstract

The Tehran Seismic Telemetry Network commenced operation in 1996, but it has never published any bulletins and there has been no systematic evaluation of the precision and reliability of its seismic recording. In this paper a standard approach is presented to evaluate the quality of operation of the Network. Our findings show no serious gaps in data coverage and the threshold of completeness is about magnitude 2 within the Network. We show that incorrect phase reading is the major reason for errors in identifying the phases, and the large scatter in arrival times. We propose a number of suggestions for the improvement of network operation.

Keywords: Tehran Seismic Telemetry Network; Quality assessment; Phase picking; Seismic stations

1. Introduction

Following the Manjil-Roodbar catastrophic earthquake (Ms 7.7, determined by USGS) of 1990/6/20, the Institute of Geophysics of the University of Tehran acquired a loan from the World Bank to construct a short period seismic network in Iran. The Iran Seismic Telemetry Network was founded in 1995 and is the first modern seismic network in the country. The Network is equipped with 52 three-component seismometers grouped in nine sub-networks distributed over a large part of the country. These sub-networks cover the areas of Tehran, Tabriz, North of Khorasan, Mashad, Semnan, Esfahan, Mazandaran, Yazd and Shiraz, respectively. Due to earthquake vulnerability of Tehran, the capital of Iran, the Institute of Geophysics initiated its efforts by installation of the first of the sub-networks in the Tehran region in 1995. The Tehran Network, despite being in operation for 8 years, has had no comprehensive study on the sensitivity in time and space of its recorded data, and the precision and consistency of its operation.

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In 2002, the University of Tehran granted a project to the first author of this paper to construct an online database for the Iran Seismic Telemetry Network (Iranian Earthquake Information Center, web address http://217.218.33.64). In this paper, using the data extracted from this database, we present a standard procedure to evaluate the quality of operation by the Tehran Network. Since all the other sub-networks operate in the same way, the assessment procedure can be directly applied to them as well.

2. The Tehran Seismic Telemetry Network

Fig. 1 shows the setup of the Tehran Network and Table 1 lists station names and coordinates. The Network consists of 12 seismic stations equipped with SS-1 seismometers with eigenfrequency of 1 Hz made by Kinemetrics Co., VHF antenna, Tx transmitters made by Nanometrics of Canada, 24-bit digitizers, and a power supply based on solar energy. The Tehran central station is equipped with VHF antenna and receivers, a computer system to record and process the data, GPS and power supply systems. The center continuously receives the data from the remote stations. The data is recorded on a 50-samples-per-second basis and processed in real time with

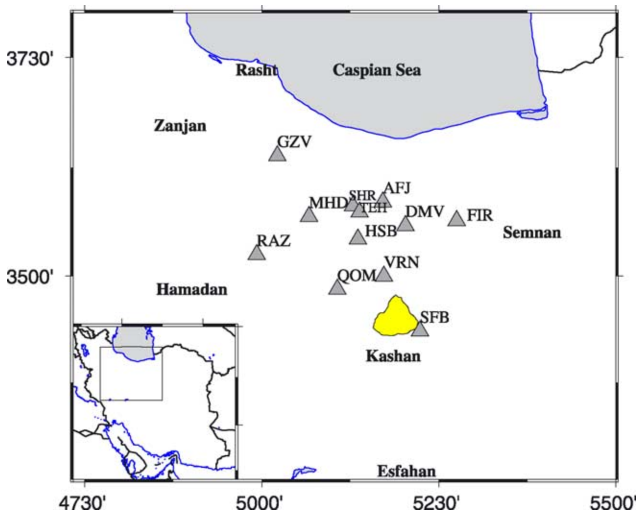

Fig. 1. Location of seismic stations of the Tehran Seismic Telemetry Network. The shaded area marks a salt lake located southeast of Qom. In the text, we refer to the area covered by this figure as the study area.

the Nanometrics Acquisition System (NASQ). After time correction, the data is recorded on a ring buffer that keeps the data for 1 week. When at least four stations detect an event, a triggering system is activated and records the event data permanently on a hard disk. The triggering system is based on an STA/LTA (Short Time Average/Long Time Average) algorithm (Trnkoczy et al., 2002). The raw and processed data are regularly archived on CD.

The location of the stations was chosen based on geographical and topographical criteria, easy accessibility and the need for smaller number of repeater stations (personal communication with the network management). Station spacing varies from 35 to 125 km, with closer spacing in the vicinity of Tehran. Although prior geological and seismic noise studies had been carried out, there is no report indicating their use in the site selection procedure. Our noise study shows that the Tehran (TEH) and the Shahran (SHR) stations have a very high level of seismic noise. Seismic noise in other stations is either very low or at an acceptable level, compared with the global maximum and minimum noise spectra (Peterson, 1993). Station SHR is located within a noisy area and is on top of soft weathered bedrock. Due to the high noise level, it was permanently closed in 2001. The noisy TEH is still in operation, but its records are mostly not taken into account in the calculation of magnitude and event location. The Network reports magnitudes using two magnitude formulas, a local formula, and a Nuttli (1973) formula given by

$$\mathrm{Mn} = \log\left(\frac{v}{2\pi}\right) + 1.66\log(d) - 0.1$$

where v is displacement velocity in nm s^{-1}, and d is the epicentral distance in km. Over 96% of magnitude determinations have used the Nuttli formula. Therefore in this paper we do not differentiate between the two methods, but refer to all magnitude values as Mn.

The total number of events up to 2003/05/31 located by the Network is 10,624. Unless specified otherwise, henceforth we work with a subset of the data that is within the region shown in Fig. 1, the study area. Fig. 2 shows the epicenters of events larger than Mn 3 and the major faults. Visual inspection of the figure shows that most of the events align along known faults. The total number of recorded events within the study area is 7709, but for visual clarity only a subset of events (752) larger than Mn 3 is shown. The Network stores the waveforms of local and teleseismic events but only locates local events. A total number of 4573 teleseismic events have been recorded.

During the above mentioned period, a total of 122,559 phase, and 6994 polarity readings were made (for details of phase readings see Table 3). A team of analysts manually picks the phases. In order to increase its azimuthal coverage, the Network has also used a total of 6433 phase readings from 61 stations of other seismic networks of the country. The ratio of the number of polarity readings to the number of events for different stations is around 12%. The Tehran station (TEH), due to its very high noise level, has a significantly lower ratio, while QOM has the largest ratio of polarity-to-event-number.

Table 1
Specification of the seismic stations shown in Fig. 2

Station code	Station name	Latitude Deg.	Longitude Deg.	Elevation (m)
AFJ	Afjeh	35.856	51.7125	2740
DMV	Damavand	35.5772	52.0322	2300
FIR	Firuzkooh	35.6415	52.7536	2380
GZV	Gazvin	36.3859	50.2184	2400
HSB	Hasan-Abad	35.4275	51.3569	1098
MHD	Mahdasht	35.6853	50.6675	1645
QOM	Qom	34.8424	51.0703	975
RAZ	Razeghan	35.4046	49.929	1920
SFB	Sefidaab	34.3539	52.2365	1000
SHR	Shahran	35.8061	51.2889	~1470
TEH	Tehran	35.7367	51.3817	1470
VRN	Varamin	34.9964	51.7278	1120

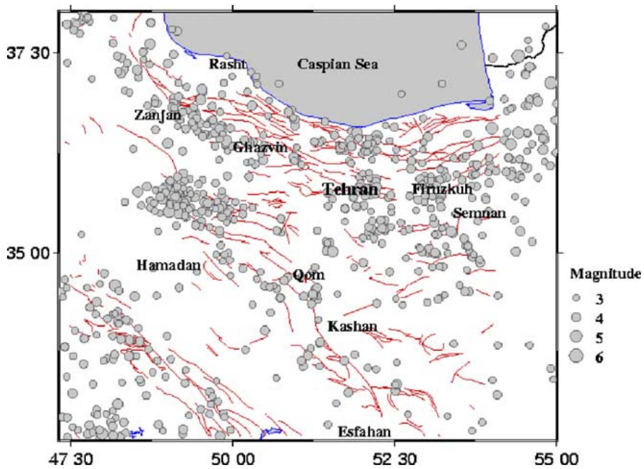

Fig. 2. Epicenters of earthquakes with Mn > 3 (only 752 out of 7709 are shown) recorded by the Tehran Network from 1996/01/01 to 2003/05/31. The lines show fault traces.

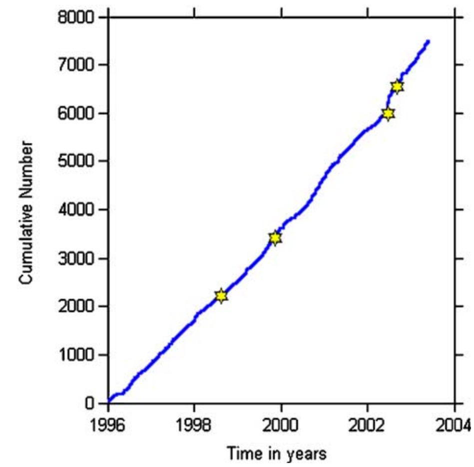

Fig. 3. Cumulative frequency of events versus time. Events larger than Mn 5 are shown by stars.

3. Assessing the quality of seismic recording

In this section, we present the results of a set of statistical analyses to assess the quality of network operation. We first investigate different statistical measures of the input data used in the event location procedure. We then study some statistical measures of the output data obtained from event location. Among the input parameters investigated are, the cumulative number of events detected by the Network and individual stations, the number of read phases, their type, and the number of polarity readings. Studying the cumulative numbers allows one to find possible gaps in data coverage and possible down-time of stations. The output parameters studied are the frequency of events for different magnitude ranges and the threshold of completeness in magnitude. These statistical analyses allow us to assess the detection sensitivity of the Network. In order to find possible errors in event location procedure (e.g. human factors, weak azimuthal coverage, or inappropriate earth model in the inversion method), we study the distribution of errors in geographical coordinates, depth, magnitude, and the distribution of azimuthal coverage of the detected events. We also draw the phase arrival time curves to investigate the correctness of phase pickings. Furthermore, quarry events are differentiated from natural events and are used to assess the precision of event location procedure.

3.1. Completeness of the recorded data in time

To evaluate the quality of operation of the Network as a whole, the cumulative number of events per year has been calculated and is shown in Fig. 3. Any significant slowdown in the rate of event detection can be indicative of incompleteness of the recorded data, usually related to down-time of stations. Fig. 3 shows that the rate of event recording has remained largely constant over the period of operation of the Network. There is only a slight increase in the rate of event recording after the large regional earthquake in 2002.

3.2. Detection threshold of the Network

The threshold of completeness is a bulk indicator of the sensitivity of event detection by a seismic network. In order to find the threshold of completeness (Mc) in the study area as a whole, we calculated the cumulative number of events larger than a given magnitude and found its slope using the weighted residual method. The results are shown in Fig. 4. The cumulative curve (rectangular symbols) deviates significantly from the best-fit line at about Mn 2, indicating a magnitude threshold of that order for the study area. The slope and intercept of the best-fit line are the *a* and *b* coefficients of the Gutenberg–Richter law (Gutenberg and Richter, 1954). For our study area these are 5.56 and 0.89, respectively. The value of coefficient *a* is given for magnitude zero. For events larger than Mn 5 the curve

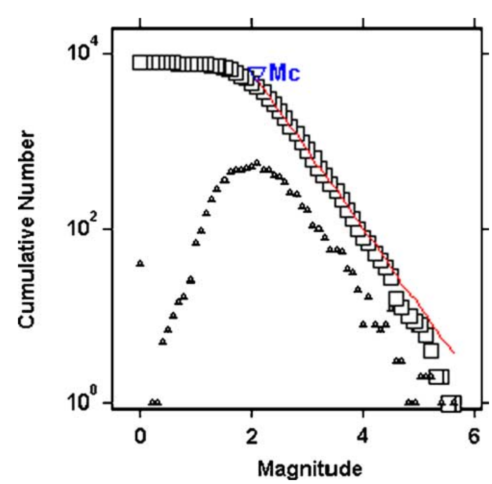

Fig. 4. Cumulative number of events larger than a given magnitude (rectangular symbols). The best-fit line produced by the weighted residual method is also given. The triangles show the number of events for a given magnitude.

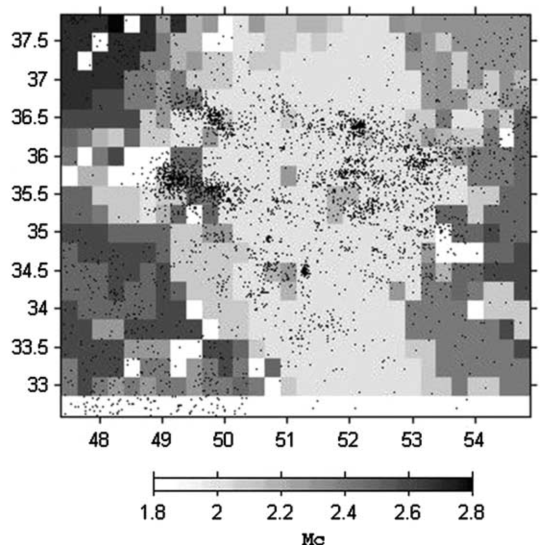

Fig. 5. Threshold of completeness of magnitude across the study area. Dots represent earthquakes. White areas show regions where due to insufficient data, no threshold of completeness could be computed.

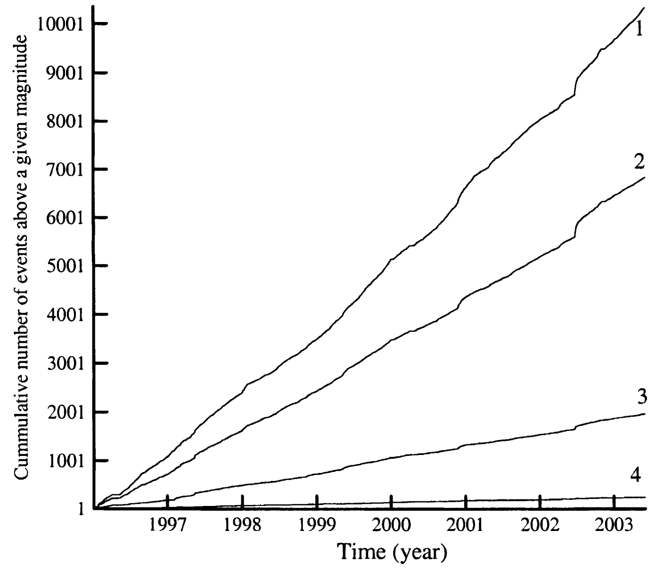

Fig. 6. Cumulative number of events above a given magnitude for the Network as a whole. The numbers on the curves indicate magnitude.

significantly deviates from the best-fit line. This is related to insufficient length of observation time of the Network. De-clustering the data and/or removing explosion-related data did not significantly change values of *a* and *b*.

The spatial distribution of the threshold of completeness of magnitude is an indirect measure of sensitivity and completeness of data. The smaller the Mc values, the more sensitive and complete the data. In order to find the distribution of the Mc values throughout the study area, we divided the region into a grid of 0.25° resolution and calculated the Mc value of each grid cell with the same method as above. A circle was placed at the center of each grid cell and its radius was adjusted so that at least 50 detected events fell inside the circle. Those events where then used to calculate the local Mc value. Fig. 5 shows the result of these calculations. The threshold of completeness is about Mn 2.1 within the Network and increases to more than 2.5 towards the peripheral parts. This shows that the sensitivity of the Network within the study area is at an acceptable level.

To find any changes in the detection threshold of the Network for different magnitude ranges, the cumulative number of events above a given magnitude was calculated for the period of operation. The results are shown in Fig. 6. The figure shows no significant change in the rate of event recording for different magnitude ranges. This implies that the procedure of magnitude calculation has remained unchanged with time. There are two jumps in the number of events larger than a given magnitude at the beginning of 1998 and 2002. Both jumps are related to the two regional earthquakes that occurred in those years.

3.3. Precision of event location

Precision of event location depends on many factors such as, the ratio of secondary to primary phases, the number of unused phase readings, the distance and the azimuth of the used phases, the earth model and the inversion method used, and last but not least, the human factor. We found that the Network has used only one earth model (described in Table 2) throughout its operation period, and only the LOC software developed by the Geological Survey of Canada (DAN User's Guide, 1995) has been used in event locations. Our approach to assess the precision of event location has two steps. In the first step, we evaluate the quality of input parameters in event location (e.g. the number of used phases and their type, and possible time variations in the number of phases). In the second step, we calculate the statistics of errors in the output parameters (e.g. errors in latitude, longitude, depth and magnitude).

An almost linear increase of the cumulative number of detected events and a low threshold of completeness serve as bulk indicators of satisfactory performance of a network. The sensitivity level of the triggering system for event detection may not be affected much if a few of the stations go off-line. However, the precision of event location will be affected by station down-time, as the number of phases used in event location will be reduced. In order to find periods of station down-time, we drew the cumulative number of events detected by each station (Fig. 7). It can be seen that AFJ, QOM and FIR have had several significant down-times; VRN and DMV have never had any significant

Table 2
The earth model used by the Tehran Network

Layer number	*P* velocity (km s^{-1})	*S* velocity (km s^{-1})	Depth to top of layer (km)
1	3.49	2	0
2	6	3.46	5.5
3	7	4.04	29.5
4	8.1	4.68	49.5

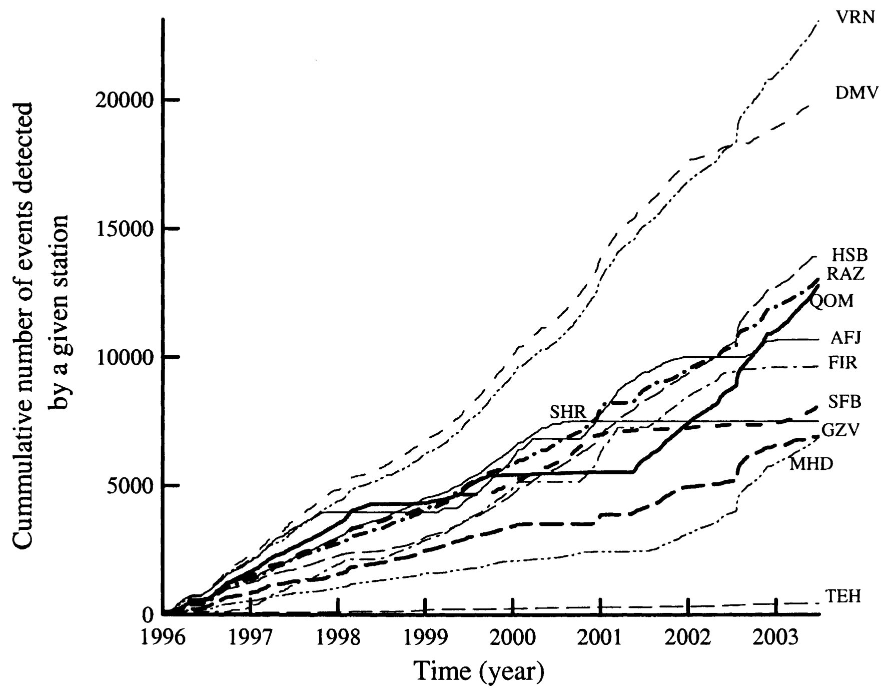

Fig. 7. Cumulative number of events (all magnitudes) detected by individual stations.

down-time; and SHR was shut down in the middle of 2001. We conclude that the precision of event location in time has not been constant because of frequent and long down-time periods for some of the stations.

Table 3 lists the number of amplitude readings (i.e. number of traces) used in magnitude calculations, the number of Pn, Pg, Sn and Sg phase readings, the total number of events detected by individual stations, and the percentage of the phases whose weight have been set to zero or not used in event location procedure. Phase onsets and types are suggested by the automated routine and decided by the analysts. However, it appears that the analysts' judgment is influenced by software suggestions, in particular for secondary phases. The ratio of secondary to primary phase readings has an average of 47% for all stations, a relatively high value.

Location programs and/or the network analysts set the weight of a phase reading used in event location to zero, if the time residual for that reading is too large. The time residual is the difference between the observed arrival time and the theoretical one calculated from the earth model. According to Table 3 about 41% of Pn, 28% of Pg, 34% of Sn, and 97% of Sg phases have not been used in event location. These numbers do not vary between stations, implying that the unacceptable percentage of unused phases is not related to possible site effects. If geology beneath a station is responsible for the station bias and its large time residual, we should always observe large residuals for that station. We observed no significant differences in the average time residuals between the stations, which confirms the absence of any important station bias. In all stations the weight of 0–20% of the phases are manually set to zero. The location program sets the rest. This implies that the network analysts have not tried to improve their inversion results by reducing the number of input phases. The large proportion of unused phases is a strong indicator of incorrect phase picking. This, by itself is not sufficient for proof of human error. The negative effects of human errors will be demonstrated more convincingly in the discussion on arrival times. The percentage of unused phases from other networks was found to be about 30%. These phases are used only for events larger than Mn 3 and are from stations outside the azimuthal coverage of the Network.

Fig. 8 shows the phase diagrams for different phases. Only events larger than Mn 3 and with root mean square (RMS) of time residuals less than 0.2 s have been used. The only exception was the Sg phase where due to lack of sufficient data all events were used. There is a very large scatter for all phases. The scattering did not decrease when we used only phases related to larger events ($>$Mn 4) within the area. From the figure we can see Pn and Sn first arrivals at distances smaller than 200 km and Pg and Sg first arrivals at distances greater than 200 km. Assuming a maximum crustal thickness of 50 km, Pn and Sn should only appear as first onsets at distances greater than 200 km (Havskov et al., 2002). This wide overlap between direct and Moho phases is not acceptable and some of the phase readings must be wrong or misinterpreted. The observed wide scatters must be, in large part, due to inappropriate phase picking.

We used these time arrivals to obtain an estimate on a one-layer crustal structure. Because of the unreliable scatters, we chose to draw the best-fitted lines in Fig. 8 by hand. The slopes of theses lines give crustal *P* and *S* velocities of 6.0 ± 0.2 and 3.5 ± 0.2 km s^{-1}, and Moho P

Table 3
Statistics for different phase types of all events detected by the stations of the Tehran Network

Station	# of traces	% of traces not used	# of Pn	% of Pn not used	% of Pn manually not used	# of Pg	% of Pg not used	% of Pg manually not used	# of Sn	% of Sn not used	% of Sn manually not used	# of Sg	% of Sg not used	% of Sg manually not used	Ratio of secondary to primary phases	Total # of traces and phases	Total # of located events
AFJ	4180	2	2514	40	10	1695	23	5	1201	34	2	948	98	1	51	10538	4560
DMV	7529	3	4566	41	11	3238	26	10	2729	39	3	1883	97	2	59	19945	8630
FIR	3699	3	2158	42	9	1757	25	2	971	36	3	938	97	2	48	9523	4273
GZV	2885	3	1735	49	19	1062	35	15	748	33	2	461	98	3	43	6891	3203
HSB	5581	3	3362	42	11	2276	27	7	1566	34	4	971	97	3	44	13756	6113
MHD	2853	3	1522	45	17	1322	31	12	632	36	3	541	97	2	41	6870	3145
QOM	5060	3	3721	36	8	1338	28	8	2026	30	2	645	96	4	52	12790	5454
RAZ	5134	2	3628	41	8	1574	31	9	1902	37	3	708	97	3	50	12946	5831
SFB	3208	2	2456	36	5	825	23	2	1208	29	0	331	96	1	46	8028	3717
SHR	2992	0	1789	31	0	1445	18	0	662	32	0	502	99	0	35	7390	3568
TEH	181	2	101	37	7	68	33	4	43	23	4	25	96	0	40	418	237
VRN	8772	3	5814	39	11	3004	22	5	3496	32	2	1859	96	1	60	22945	9422

The percentages of unused phases are also listed. The percentages of phases whose weight is set to zero in event location by operators are given in separate columns.

and S velocities of 8.1 ± 0.2 and 4.7 ± 0.2 km s^{-1}, respectively. The 4-layer earth model employed by the Network (Table 2) has an average crustal *P* velocity of 6.13 km s^{-1}, an average crustal *S* velocity of 3.53 km s^{-1}, a Moho *P* velocity of 8.1 km s^{-1}, and a Moho *S* velocity of 4.68 km s^{-1}. This clearly shows that although the velocities of the model sub-layers may not be properly defined, the model on the average is a good approximation of the real earth. From these velocities we calculated a crustal thickness of 48 ± 3 km for the study area. This result is in broad agreement with those of other studies (Dehghani and Makris, 1983; Sodoudi et al., 2003).

All events are located using the LOC program. The program gives different error measures for the calculated occurrence time and location of events. These measures are quantitative indicators of the precision of event location procedure carried out by network operators. It is not necessarily a measure of the true accuracy of event location. We have investigated the distribution of errors in latitude, longitude, depth, and magnitude, as well as distribution of RMS of time residuals. Computed error in latitude and longitude for all events is always less than 1 km. The RMS of time residuals for 99% of events is less than 0.1 s. This very low value is not a fortunate sign and is an artifact of high proportion of unused phases in event location. The standard deviation of errors in magnitude using all events of the catalogue is 0.1888. Generally, the errors in depth are significant and sometimes unrealistically large. Again this is mainly related to inappropriate phase picking and also due to the fact that most of the events are outside the Network and that station spacing is not dense enough to allow for a precise depth determination (Havskov et al., 2002). If depth error is unrealistically large, sometimes the practice is to fix the depth value to a sensible value determined by local geology. The Network does not pursue this practice.

Azimuthal coverage of events is another strong factor in determining the quality of event location procedure. We have found that the azimuthal gap is 280° and more for 50% of events. Close to 78% of events have magnitudes less than Mn 3. The azimuthal gap of 50% of events larger than Mn 3 is greater than 300°. This larger gap for larger events is expected since most of them lie outside the Network. The Network has tried to increase its azimuthal coverage for larger events by incorporating readings from other networks. We also calculated the azimuthal gaps for events larger than Mn 3, excluding phase readings from stations of other networks, and found that the azimuthal coverage deteriorated by about 10°. This indicates that the practice of adding phase readings from other networks is either ineffective, or not properly implemented. We should also mention that in this assessment all used, as well as unused phases in event locations were included, and thus the above result underestimates the real azimuthal gaps of located events.

Quarry activity within a seismic network can be a fortunate opportunity to test the accuracy of event location.

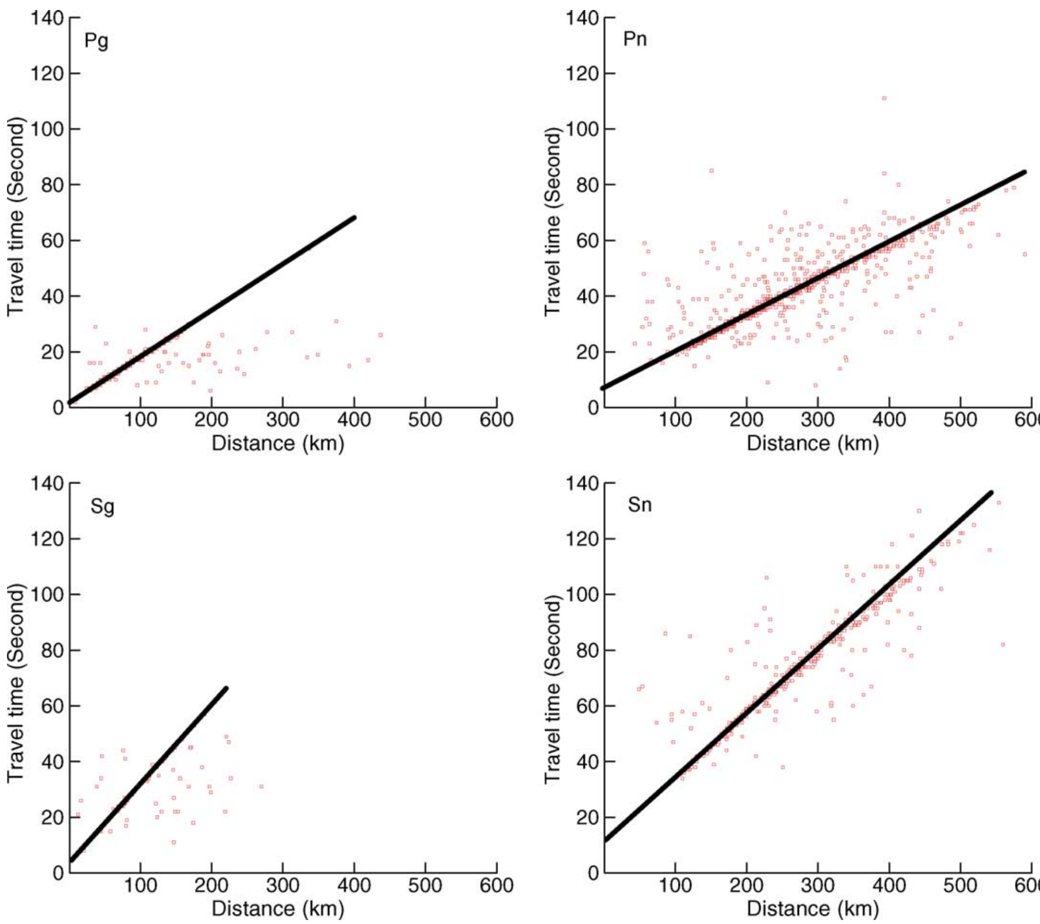

Fig. 8. Travel time curves for Pg, Pn, Sg and Sn phases of events within the study area. In drawing the curves, phases with RMS less than 0.2 s, with the exception of Sg, were used.

Most of the quarry activity inside the Network is by the Tehran cement production plant, located in the south east of the city. The open mining explosions are carried out from 11:00 to 13:00, local time. This information allows us to easily identify areas with high quarry activity by calculating the day-to-night-time ratio of the number of events. Fig. 9 shows the area with high day-to-night-time event ratio. It shows a dense cluster of events in south east of Tehran, which is shifted a few kilometers from the correct location of the quarry. Given the fact that the explosions take place inside the Network and have high azimuthal coverage, the event locations could have unjustified errors, though at this stage it is difficult to quantify them.

3.4. Accuracy of polarity determination

Polarity reading is one of the important seismic data for studying the mechanism of faulting. The Tehran Network has performed about 6433 polarity readings. The ratio of polarity readings to the number of P phases picked at vertical component is about 11%, a rather low proportion. Even for most of the large earthquakes there are no polarity readings. Our seismic noise study showed that most of the stations have very low to moderate seismic noise. Despite this fact, the ratio of polarity readings to P phases is low. This is possibly related to very inhomogeneous tectonic structure of the study area and possibly to over-cautious approach of network operators in reading phase polarities.

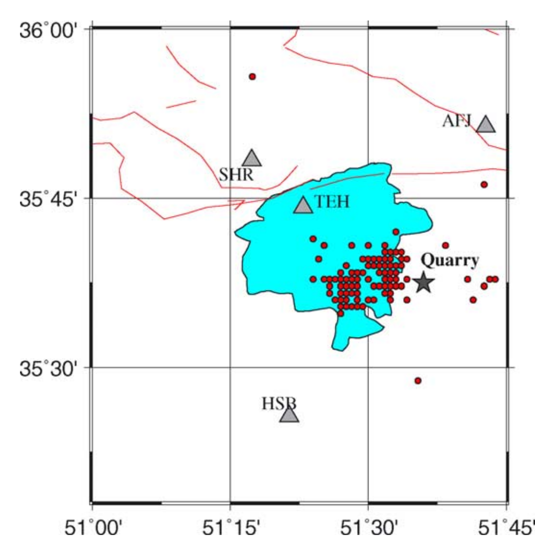

Fig. 9. Locations of explosion events probably related to the Tehran cement production plant. Shaded area denotes the city of Tehran and triangles show nearby seismic stations. Lines are fault traces.

4. Conclusions

In this paper, we have applied standard methods for the assessment of the operation of the Tehran Seismic Telemetry Network. We believe that this kind of investigation is important for identifying shortcomings in procedures of data collection and improvement of the operation of any seismic network that lacks sufficient documentation. One immediate application of our method would be the analysis of operation of other Iranian telemetry networks. We can summarize our findings as follows:

1. The Network shows no serious gaps in its data coverage and the threshold of completeness is about Mn 2 within the Network.
2. The number of rejected phases in event location is very high. This implies incorrect phase pickings and probably too much reliance on the location program. Erroneous phase picking also shows its negative effects in phase diagrams, which show large scatters in arrival times and errors in identifying the first arriving phase.
3. Comparison between the model crustal velocity and thickness and those computed from the phase diagrams shows that the Network earth model has reasonable velocity structure on the average. Although the velocity of some of the model layers may not be appropriate.
4. The practice of including phase readings from other networks to increase the azimuthal coverage seems to have been somewhat ineffective.
5. The true locations and times of man-made events are indicative of a possible systematic epicentral distance error of a few kilometers towards northwest. This can imply lateral velocity heterogeneity and a westward increase of velocities that cannot be accounted for by the one-dimensional earth model.

Based on our findings we propose two suggestions for the improvement of network operation. First and more importantly, phase readings by automated routine should not be allowed to go unchecked by qualified analysts. Second, in order to effectively increase the azimuthal coverage of the Network, the phase readings from other telemetry networks should be directed to a single database and collectively used in event location. This procedure has actually been called for in the original plan of the Iran Seismic Telemetry Network.

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