ANALYSIS OF TRAVEL TIME RESIDUA AT POLISH SEISMOLOGICAL STATIONS (1998–2004)

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Analyse des résidus du temps de propagation des ondes aux observatoires sismologiques polonais (1998–2004). *On a analysé le temps de propagation pour tous les tremblements de terre télésismiques enregistrés sous forme digitale aux observatoires sismologiques dans l'intervalle 1996–2004. Les résidus de temps de propagation ont été calculés en utilisant les tableaux. Les différences des rapports dans les tableaux ont été calculées pour chaque station par des intervalles de 5 degrés de distance épicentrale et par des intervalles de 10 degrés de l'azimut inverse. Les résidus démontrent des variations régionales. Bien que les valeurs des résidus soient différentes, dans le cas des stations analysées, les propriétés générales sont similaires. On a considéré plusieurs types d'onde, comme P, PP, PKP, PKIKP, S et SKS, mais une analyse régionale complète a été possible seulement pour les premières phases.*

Key words: seismic stations, wave effects, Poland.

1. INTRODUCTION

Developments of modern seismology since the late 1980s have resulted in a large increase of seismological data and their accuracy. Recording of broadband seismic signals has allowed several reassessments of the long-used classic travel time tables of Jeffreys and Bullen (1940). Discrepancies for these tables, although minor, were pointed out already by the author himself (Jeffreys, 1968). Moreover, the accuracy of source locations today is incomparably greater than those that had been basis for the Jeffreys-Bullen tables. In early 1980s several new travel time tables were proposed making account for different source depths or anisotropy of wave velocity inside the Earth (Dziewonski and Anderson, 1981).

Modern travel time tables are calculated using a scheme described by Buland and Chapman, 1983. The method is called theta-function technique and yields better results than earlier used evaluation of ray integrals or ray tracing, even though it is not so straightforward. The TauP toolkit computer package (Crotwell et al., 1999) allows for calculation of travel time tables according to one of accepted standard models: IASP91 (Kennett and Engdahl, 1991), PREM (Dziewonski and Anderson, 1981), AK135 (Kennett at al., 1995), SP6 (Morelli and Dziewonski, 1993), Herrin (Herrin, 1968) or any model that is given in a predescribed format. The usual procedure is having the tables calculated for a 1 or 0.5 degree grid in epicentral distance and 30 or 50 km grid in source depth. Linear interpolation is then used for hypocentral locations between the grid points. Furtherly, it is also important to account for the Earth's ellipticity e.g. (Dziewonski and Gilbert, 1976), an effect of the order of 0.2 to 0.5 second in case of simple P waves and considerably larger in case of phases multiple reflected off Earth's surface.

In this paper the AK135 model was assumed for two reasons. First, the AK135 is an improved version of the IASP91 that was developed as a joint effort of Subcommission on Earthquake Algorithms of the International Association of Seismology and the Physics of the Earth, based on International Seismological Centre (ISC) data 1964-1987. The IASP91 model is being used by the ISC ever since. The same IASP91 model has been used by National Earthquake Information Center of United States Geological Survey until 2003 when it was decided to switch to the improved AK135 model. Therefore the AK135 is considered today as an improved version of the well established IASP91 model. The differences between the two models are not big for P waves - they don't surpass 0.15 of a second at any epicentral distance and any depth. However, for S waves the difference although it usually keeps to within 0.1 of a second, may reach 0.45 of a second (for deep events at about 45 degree epicentral distance). The biggest differences between the models exist in case of waves reflected from the Earth's surface, such as PP or SS, reaching about 2 seconds at some distances in case of SS and still more in case of multiple-reflected waves. Secondly, the AK135 model comes complete with its ellipticity corrections. Considering the choice of model, it might be worthwhile to notice that for P waves at teleseismic distances AK135 produces arrival times about 1.8 to 1.9 seconds faster than the Jeffreys-Bullen (1940) tables. This might be not the best property of the model, but the alternative model PREM yields still greater discrepancies while other velocity models are less acknowledged.

Seismic stations in Poland exist since almost a century but digital recording of broadband signals has started only in 1995 (Bock *et al.*, 1997), if not counted the short 1989-1991 episode of participation in the GSETT-2 project. However, bulletin phases reported in 1996 and 1997 are mixed those from digital and analogue records, uniform phase picks from digital data start only 1998 and therefore 1998 was taken as the start year for this study, except for KWP which was only installed in 1999 and OJC which has its broadband digital recording started 1999. Phase readings at OJC have been found to contain large number of errors so OJC data had to be picked again for the purpose of this study and has been limited to plain P and S waves only. The stations NIE and RAC are not considered here, because the accuracy of their phase picks is far behind the accuracy at other stations. The temporary seismic station CZA (Wiejacz, 2000) has proven to operate for a too short period of time – total of 19 months during 1997–1999. It has yielded too few phase arrivals to make analysis of regional residua possible and only the biased plain P and plain S wave residua could be calculated for this station.

2. METHOD OF ANALYSIS

It is generally assumed (Cleary and Hales, 1966) that for earthquake source s and receiver *r*:

$$\delta t_{rs} = a_{rs} + b_r + d_s \tag{1}$$

where δt_{rs} is observed residuum, a_{rs} is the average difference from the tables for a station at epicentral distance the same as *r*, b_r is station residual and d_s is perturbation caused by conditions peculiar to quake *s*, *i.e.* source term. In case of considering a single station in an attempt to find its residual, there is only one b_r while the a_{rs} is dependent on *s* only. Therefore the source term d_s becomes inseparable from the a_{rs} and the equation (1) can be written as:

$$\delta t_s = c_s + b \tag{2}$$

where c_s is the sum of the inseparable a_s and d_s terms. The method of calculation basically follows the scheme used by Gibowicz, (1970). The first approximate of *b*, b_0 can be calculated as mean of the individual event residua. Following this, one subtracts this constant value from the individual event residua and then it is possible to calculate first estimates of c_s for different epicentral distance ranges, $c_0(\Delta)$:

$$c_0(\Delta)=(\Sigma(\delta t_i - b_0)*f(i,\Delta))/N_c \tag{3}$$

where i numbers the individual events, $f(i,\Delta)$ is 1 if the event's epicentral distance belongs to the epicentral distance cell Δ, otherwise 0, and N_c is the number of events in each cell.

Having calculated the first approximates $c_0(\Delta)$, it is now possible to calculate the second approximate of *b*, b_1. The problem with b_0 is that it is being biased by the aboundance of events at various epicentral distances, accounting for $c_0(\Delta)$ removes that bias, although the bias due to aboundance of events at various back-azimuths still remains. Therefore:

$$b_1 = b_0 + \bar{c}_0(\Delta) \tag{4}$$

where $\bar{c}_0$ denotes the mean of c_0, while the second approximates of $c_1(\Delta)$ are:

$$c_1(\Delta) = c_0(\Delta) - \bar{c}_0(\Delta) \tag{5}$$

The same method can be applied in respect to both epicentral distance and back azimuth, however when considering back azimuth there now happen regions of the Earth without any events for which the finding of the regional effect is not possible. The number of these regions depends on the regional aboundance of earthquakes but also on the density of the epicentral distance and back azimuth φ grid. Thus, finally we arrive at final values of b, $c(\Delta,\varphi)$ and $c(\Delta)$ averages of $c(\Delta,\varphi)$ in each epicentral distance cell, although for grid cells without any events in them these values will remain unresolved.

Of course the lack of information from these regions may bias the final results for average station residua. Therefore it is a matter of weighting out: grid cells too big may weakly bring out the regional effects, while grid cells too small may yield biased results. The analysis performed for a source region discrete grid of 5 degree epicentral distance and 10 degree azimuth for P wave in the epicentral distance range of 15 to 100 degrees has resulted in 36% Earth surface coverage in case of most aboundant in readings station SUW and less for the other stations. In case of CZA only 13% of the cells are covered, therefore it is pointless to discuss such results.

3. RESULTS

The global distribution of individual P-wave travel time residua in respect to the AK135 model for station SUW is shown in Figure 1. Similar figures can be created for other phases and stations, but they are then less aboundant in data while the appropriate figures of P wave at other stations look very similar. One may note already that smaller or larger residua tend to group in various parts of the world. Distinguishing for shallow, intermediate and deep earthquake sources does not change much in this picture.

The method described in section 2 was applied to the phase readings from stations SUW, KWP, WAR, KSP, OJC and the temporary station CZA (1997–1999), in particular to 7 types of phases: P, PKP, PKIKP, PP, S, SKS and SS that are most common in regional or teleseismic quake reports. In case of PKP and SKS phases, the travel time tables have two branches, namely the df and ac (Please define!). In these cases the residua were calculated according to the branch that resulted in smaller residua, since the identification of the branch, whether by numerical procedures or by eye might be ambiguous.

Phase readings for the events at SUW, KWP, WAR, KSP and CZA have been taken from annual reports of Polish Seismological Broadband Stations (Wiejacz and Jankowska, 2000, Jankowska et al., 2001, 2002, 2003, 2004; report for 1998 was not published), while for OJC the P and S phase picks have been done directly on the seismograms. Location of these stations is shown on map in Figure 2.

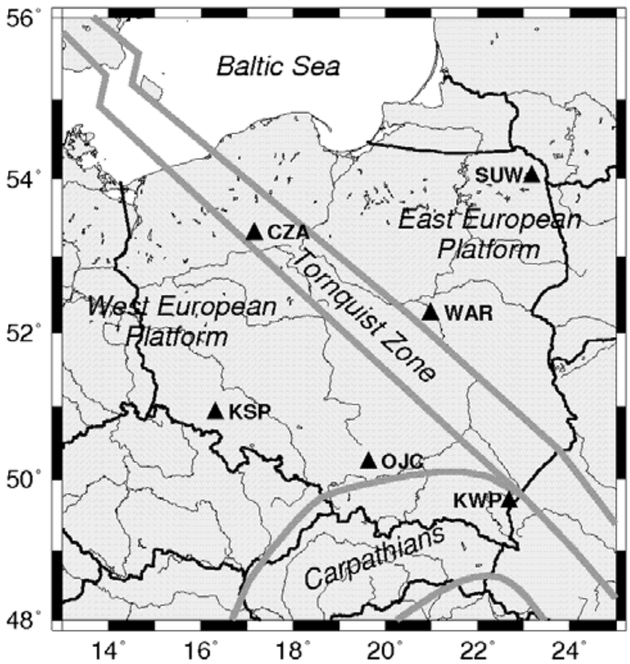

Fig. 2 – Map of Poland and surrounding area, showing the main tectonic units and the locations of seismic stations covered by this study.

The source locations were taken from National Earthquake Information Center (NEIC) of U.S. Geological Survey (USGS) determinations of epicenters available from the internet that later become basis for the final International Seismological Centre's (ISC) earthquake catalogue. Travel time residua were calculated in respect to the AK135 model. The general results obtained for the station residua b (of formulae 1 and 2) are given in the Table 1:

Table 1

Calculated phase residua

Phase	Station	No. of phases	Plain b	Dist. corrected b	Reg. corrected b	Std error of b
P	SUW	2481	1.61	1.60	1.51	0.03
	KWP	2026	2.68	2.52	2.34	0.03
	WAR	957	2.40	2.25	1.87	0.05
	KSP	2845	2.43	2.27	2.04	0.02
	OJC	293	2.55	2.37	2.28	0.05
	CZA	172	2.48	not calculated		0.09
PKP	SUW	200	0.89	not calculated		0.10
	KWP	333	1.86			0.07
	WAR	151	2.24			0.11
	KSP	681	1.55			0.08

Table 1 (continued)

PKIKP	SUW	70	2.31	not calculated		0.24
	KWP	35	3.27			0.22
	WAR	39	3.07			0.22
	KSP	57	3.00			0.19
PP	SUW	479	0.91	0.47	0.50	0.19
	KWP	298	2.08	1.69	1.45	0.22
	WAR	305	1.45	1.67	1.76	0.22
S	SUW	647	1.62	1.55	1.49	0.16
	KWP	378	2.77	2.94	2.98	0.20
	WAR	495	2.41	2.09	1.75	0.19
	OJC	148	3.10	3.60	3.54	0.27
	CZA	41	3.57	not calculated		0.56
SKS	SUW	63	1.39	not calculated		0.77
	KWP	39	2.44			0.98
	WAR	46	1.14			0.91
SS	SUW	97	3.72	3.16	not calculated	0.76
	KWP	48	4.72	4.34		1.15
	WAR	92	3.16	4.23		0.96

As it can be seen, the epicentral distance and regional analyses have not been possible in case of core phases. This is not only because of smaller number of these phases but also due to the regional distribution of the quakes, namely that most of the sources producing core phase onsets at Polish seismological stations group in just a few regional epicentral distance-back azimuth cells. With less than 25% coverage of the regional cells in the epicentral distance range relevant to given phase arrivals, the regional analysis has not been attempted. An intermediate situation exists with the SS phase onsets where many epicentral distance cells are filled and epicentral distance analysis was possible but the regional analysis was not.

The regional distributions of travel time residua for P waves (stations SUW, KWP, WAR, KSP) and S waves (stations SUW, KWP, WAR) are shown in Figures 2 and 3. These figures depict the positive (red) or negative (blue) differences of the observed travel time residua from the final values of the residua as given in Table 1.

As it can be seen, the results for the stations are similar. In all cases one can see the negative residua in back azimuths in southerly direction. This seems to be in accord with the fact that in the southerly direction vs. Poland there is the Mediterranean zone of contact between tectonic plates. As a collision type contact, the material deep down in the Earth is understood cooler than average, therefore the seismic waves travel faster, waves arrive earlier resulting in negative residua. Conversely, positive residua exist in the westerly direction from where the seismic waves travel through the warm region underneath the Atlantic Ridge. In a warm region the seismic wave velocities are lower, leading to positive station residua. Another direction of positive residua is the east-northeast direction. Sources of waves coming from that direction are in Southeast Asia and seismic waves travel under the Eurasian Plate. The Baikal rift zone along their way could be an explanation of this observation.

S wave regional residua follow a similar pattern as P wave residua. Since the amount of data is somewhat lower, the regional residua in each cell result from a smaller number of earthquakes. This effects in a greater scatter of the results in that the residua in neighbouring cells often differ more than the respective residua calculated for P waves.

4. DISCUSSION

There are several issues to the travel time residua that have to be considered.

The calculated value of the station residuum in respect to a given velocity model depends mostly on two factors: the characteristics of the specific location of the station such as geological layers or elevation and the relative aboundance of quakes in different areas of the world relative to that station. This second factor can be removed using the technique described in section 2. It may be however of issue if the removal is complete since there are many areas of the world where strong quakes do not happen and many regional distance-azimuth cells are devoid of data. In fact, if the world is divided into 5 degree epicentral distance and 10 degree azimuth cells, even in the most aboundant case of P waves recorded at the longest working station SUW, the coverage of the cells (in the 20 to 100 degree epicentral distance range) is only a little over 36%. Ignoring the void cells is an assumption that their mean value is zero.

The station residua are assumed to depend on the station location, in particular whether it is located on slow or fast geological layers and the thicknesses of these layers. Elevation is also another factor. Here should have small effect since the highest KWP is only 448 m, however the two highest located stations – KWP and OJC show greater residua than the other. As the body waves at teleseismic distance emerge generally from below, the local site effect should be similar for all P arrivals and similar for all S arrivals. This however does not appear so. The residua for different types of P waves and different types of S waves take on different values. The reason may be that different datasets are used to compute P, PKP, PKIKP and PP residua . This is especially important in case of core phases that come generally from just a few areas of the world and the result value may thus be biased.

Considering P and S waves, from a given source to a given station they follow a similar path - actually the path would have been identical had there not been partial melting in the mantle. Therefore, should these waves encounter a slower or faster region along their way, this should affect both waves regardless of whether the effect is near the source, near the station or mid way. Moreover, since in rigid media the S wave velocity is by $\sqrt{3}$ factor smaller than P wave velocity, the S wave discrepancies from theoretical arrival times should be by factor of $\sqrt{3}$

greater than those of P. Statistically this should result in greater calculated values of residua. What is interesting is that in case of SUW station the P and S residua are almost equal and in case of WAR their difference is very small. In case of KWP and OJC some part of the residua may be attributed to elevation while in case of CZA to thick layers of soft sediments underneath the station. Conversely, the residua for SUW are almost always the smallest. This seems understandable in view of the station location. The station itself is on post-glacial sediments, but below them at few hundred meter depth there are strong granitic rocks of relatively high (as of crust) wave velocities.

KSP station has P wave residuum a little greater than that of WAR. Initially there has been performed study of secondary phase residua at KSP, but these phase residua do not seem to follow any pattern, yielding results very different from all the other stations (e.g., residua of negative values). Therefore it has been decided to omit these phases recorded at KSP from this study.

5. CONCLUSIONS

The station residua have been calculated for those Polish broadband seismological stations that were in operation by the end of 2004 with the exception of GKP which has started only in mid-2004 and yielded too little data. In case of OJC station the teleseismic data 1999-2003 had to be reanalyzed. Analysis of residua for the temporary station CZA, 1997-1999 has proven to yield doubtful results due to the short time of operation and relatively low seismic activity of the Earth within that time.

The performed analysis has also shown discrepancies in phase picking of secondary phases at station KSP. The results obtained for secondary phases for this station should be disregarded and in the future the calculations should get repeated using fresh data.

The calculated residua are all positive and reflect a general rule that the higher the elevation of the station, the greater the residuum. This is best visible in the P and S phase residua. Relatively high values for the temporary station CZA are most likely due to very thick slow sedimentary layers beneath the station. Apart from this, the P wave residua range from 1.51 s at SUW to 2.34 s at KWP while S wave residua range from 1.49 s at SUW to 3.54 s at OJC.

The study has shown that there are regional differences in the observed travel times. Waves coming from the same epicentral distance and source depth arrive faster if they come from the southerly direction, whereas the waves from the northwesterly direction arrive with a delay greater than average. Another source of delayed arrivals - though not so much delayed as those from Central American earthquakes - is the region of Southeast Asia. These directional properties are the same for all the Polish broadband seismic stations that were considered.

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Received: February 2, 2006
Accepted for publication: March 16, 2006