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Test of ocean tide loading models on the basis of strain data measured at the Vyhne Tidal Station, Slovakia

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Abstract: Tidal strain time series recorded at the Vyhne Tidal Station are used to test thirteen different ocean tide loading models. Ten models have been calculated using SPOTL: EOT11a, HAMTIDE11a, OSU.TPXO72atlas, OSU.TPXO72, TPX070, DTU10, CSR4.0, FES2004, FES95.2.1, SCHW1 and three other models were chosen from the Free Ocean Tide Loading Provider (FOTLP) created by Scherneck and Bos: FES2012, FES2014b, GOT00.2. Hourly sampled strain data, corrected for temperature, were subjected to correction for ocean tide loading. The test of models was focused on the diurnal and semi-diurnal tidal harmonic constituents O1, P1, K1 and M2. A negligible difference between the individual global ocean tide loading models was only found mainly due to using different Earth models and Green functions. The amplitude factors for O1, P1, K1 and M2 derived from the measurements are 1.019, 1.226, 0.842 and 1.131, respectively. The average amplitude factors for these tidal components were obtained after ocean load correction using SPOTL routines: 1.121, 1.332, 0.916, 1.283, and in the case of the three models using FOTLP: 1.046, 1.486, 1.067, 1.317. The corrected amplitude factor became closer to the theoretical value only for K1.

Key words: Earth tide, strain, ocean tide loading

1. Introduction

Ocean tide loading causes deformation of the solid Earth as well as changes of gravity (*Jentzsch, 1997*). Several ocean tide loading models have been developed and tested already by many authors based on gravimetric (e.g., *Baker and Bos, 2003; Boy et al., 2003; Hábel and Meurers, 2014*), GPS (e.g., *Li et al., 2014; Kalita and Rzepecka, 2015; Penna et al. 2015*), tilt

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(e.g., *d'Oreye and Zürn, 2006*), and extensometric (e.g., *Amoruso and Crescentini, 2016; Mentes, 2021*) measurements.

In this paper, we use to test the efficiency of ocean loading corrections using data measured by an extensometer at the Vyhne Tidal Station (VTS) in Slovakia. For the correction, we used the same models as those used by *Mentes (2021)* to correct extensometric data measured at the Sopronbánfalva Geodynamic Observatory (SGO) in Hungary in order to compare the results obtained at the two observatories. The efficiency of ocean loading corrections are compared using thirteen different ocean tide loading models for the diurnal and semi-diurnal tidal harmonic constituents O1, K1, P1 and M2.

2. Measurement site and instrument

The VTS is located in Central Slovakia in the centre of the Štiavnické vrchy Mts. range in the cadastre of the village Vyhne (Fig. 1). The coordinates of the observatory are: latitude $48^\circ\,29'\,52''$ N; longitude $18^\circ\,49'\,48''$ E; the altitude is 420 m a.s.l. The instrument is a 20.5 m long quartz-tube extensometer with capacitive transducer. The azimuth of the extensometer is 55°, and its scale factor is -0.1141 nstr mV^{-1}. The construction of the extensometer is the same as that of the instrument in the SGO and its annual calibration is made with the same calibration device (*Brimich, 1988; Dudášová, 1998; Mentes, 2010*).

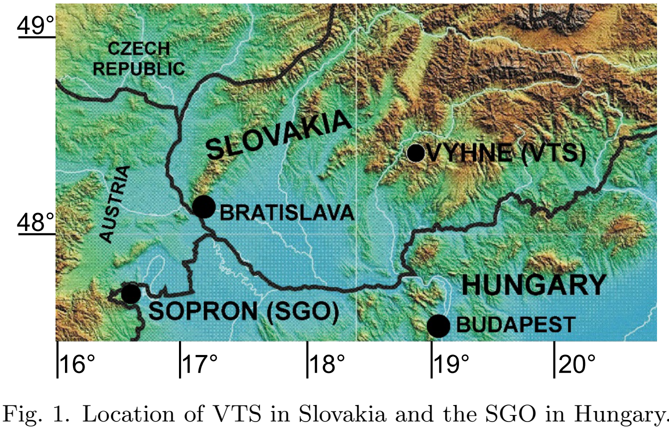

Fig. 1. Location of VTS in Slovakia and the SGO in Hungary.

3. Data processing

Strain, the temperature inside the gallery and the open-air temperature data were recorded with a period of ten minutes. Two strain data series are available. One of them directly sampled each ten minutes. The other one is sampled first with one minute period and then averaged to 10 minutes period. The nine samples of the one-minute sampling are taken symmetrically with respect to the output sample. The calibration pulses are omitted from this process and are being sampled only directly (*Bednárik and Brimich, 2005*). The decimated data have a slightly lower level of noise than the directly sampled and are better suited for further processing.

Data series were despiked and ungapped by the T-soft program (*Van Camp and Vauterin, 2005*) and then the data were low-pass filtered by a LSQ filter with a cut-off frequency of 12 cpd (cycles per day) and decimated to one hour sampling and processed by ETERNA 3.40 Earth tide data processing program package (*Wenzel, 1996*) using the Wahr-Dehant Earth model (*Wahr, 1981; Dehant, 1987*) and the HW95 tidal potential catalogue (*Hartmann and Wenzel, 1995*). Temperature correction was also carried out by ETERNA 3.40. For tidal evaluation and testing the ocean tide loading models strain data measured in 2017 were used.

For ocean load correction of strain data the same ocean tide loading models have been used as used by *Mentes (2021)* in the SGO: ten models from SPOTL (*Agnew, 2013*) and three models from FOTLP created by Scherneck and Bos (`http://holt.oso.chalmers.se/loading/`).

The Earth models by SPOTL are: the Gutenberg-Bullen Model A average Earth (gbaver) and two models of the Earth's crust and mantle structure (*Harkrider, 1970*), one oceanic (gbocen) and one continental shield (gbcont). The Green functions were calculated by *Farrell (1972).* The 'ce' denotes a reference frame with the center of mass of solid Earth and the 'cm' a reference frame with the common center of mass of the load and the Earth.

In FOTLP models the ocean load was calculated relative to the fixed common mass center of the ocean and the solid Earth (no motion correction) and the moving center of mass of the solid Earth (motion correction). The calculations were carried out using elastic (*Farrell, 1972*) and viscoelastic Earth model STW105 (*Kustowski et al., 2008*).

The ocean loading correction (see Fig. 2) was carried out according to *Neumeyer et al. (2005)* and *Hábel and Meurers (2014).* The L amplitude and λ phase of the ocean tide load vectors $\vec{\mathrm{L}}(\mathrm{L},\lambda)$ were determined from the above mentioned different ocean tide loading models and were subtracted from the observed strain tidal vectors $\vec{\mathrm{A}}(\mathrm{A},\alpha)$ in case of the O1, K1, P1 and M2 tidal waves to obtain the corrected tidal strain vectors $\vec{\mathrm{A}}_c(\mathrm{A}_c,\alpha_c)$.

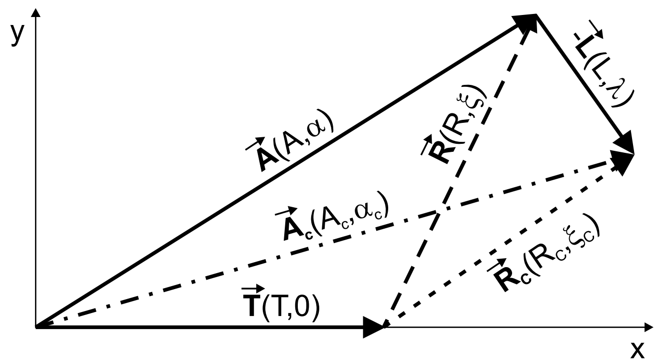

Fig. 2. Outline of tidal ocean loading correction (after *Neumeyer et al., 2005; Hábel and Meurers, 2014; Mentes 2021*). Theoretical tidal vector $\vec{\mathbf{T}}$(T, 0), observed tidal vector $\vec{\mathbf{A}}(\mathrm{A},\alpha)$, observed residual vector $\vec{\mathbf{R}}(\mathrm{R},\xi)$, ocean loading vector $\vec{\mathbf{L}}(\mathrm{L},\lambda)$, corrected tidal vector $\vec{\mathbf{A}}_c(\mathrm{A}_c,\alpha_c)$ and the remaining residual vector after correction $\vec{\mathbf{R}}(\mathrm{R}_c,\xi_c)$. The vectors are defined by their amplitudes (T, A, R, L, A_c and R_c) and phases (0, α, ξ, λ, α_c and ξ_c).

4. Results and discussion

Results of the tidal evaluation of the measured strain data in case of the tidal constituents O1, K1, P1 and M2 are shown in Table 1. The amplitude factor is close to one for O1 and M2, while less than one was obtained for K1 and greater than one for P1.

Tables 2–5 show the amplitudes (L) and phases (λ) of the ocean tide load, the amplitudes (A_c) and phases (α_c) of tidal strain corrected for the ocean tide load, the amplitudes (R_c) and phases (ξ_c) of the remaining residuals after the correction and the corrected amplitude factors (η_c) in case of different Earth and global ocean tide loading models calculated using SPOTL routines. Since each ocean tide loading model gave nearly identical results and the difference was only depending on whether the center of the Earth (ce suffix) or the common center of the load and the Earth (cm suffix) was used for the reference frame, we only used the average corrected amplitude

Table 1. Tidal results calculated from strain data corrected for temperature.

Wave	Theoretical amplitude T [nstr]	Measured amplitude A [nstr]	Measured phase lead α [degree]	Amplitude factor η	Measured residual R [nstr]	Phase of the residual ξ [degree]
O1	6.3006	6.41704	13.4572	1.01848	1.49381	187.085
P1	2.9312	3.59412	0.5300	1.22616	0.66360	177.12831
K1	8.8576	7.46067	15.1724	0.84229	2.56003	130.30197
M2	6.3214	7.14767	6.8420	1.13071	1.15136	132.31231

Table 2. Results of correction of the O1 wave for ocean tide loading derived from 10 ocean loading models with different Earth models calculated by SPOTL routines. The observed values, not corrected for ocean tide loading, are in Table 1.

Earth model	Ocean tide model	Amplitude of the ocean tide load L [nstr]	Phase of the ocean tide load λ [degree]	Corrected strain amplitude A_c [nstr]	Phase of the corrected strain α_c [degree]	Amplitude of the remaining residual R_c [nstr]	Phase of the remaining residual ξ_c [degree]	Corrected amplitude factor η_c
gbocen.ce	eot11a	0.705	151.772	7.076	9.428	1.288	64.102	1.123
	hamtide11a	0.112	151.620	7.074	9.424	1.286	64.173	1.123
	osu.tpxo72atlas	0.702	151.562	7.072	9.427	1.286	64.241	1.122
	tpxo70	0.712	151.431	7.079	9.365	1.284	63.781	1.124
	fes952	0.724	149.179	7.070	9.127	1.255	63.326	1.122
	fes2004	0.707	151.024	7.072	9.358	1.279	64.020	1.122
	osu.tpxo72	0.695	151.792	7.069	9.476	1.289	64.516	1.122
	dtu10tr	0.702	151.834	7.074	9.449	1.289	64.243	1.123
	csr4tr	0.722	151.854	7.090	9.350	1.289	63.341	1.125
	schw1	0.681	150.030	7.044	9.414	1.269	65.221	1.118
gbav.ce	eot11a	0.706	151.744	7.076	9.422	1.288	64.063	1.123
	hamtide11a	0.704	151.597	7.074	9.418	1.286	64.139	1.123
	osu.tpxo72atlas	0.703	151.532	7.072	9.420	1.285	64.203	1.122
	tpxo70	0.713	151.410	7.080	9.359	1.283	63.742	1.124
	fes952	0.726	149.115	7.071	9.114	1.254	63.254	1.122
	fes2004	0.708	150.985	7.072	9.351	1.278	63.987	1.122
	osu.tpxo72	0.696	151.766	7.069	9.470	1.289	64.480	1.122
	dtu10tr	0.702	151.806	7.074	9.443	1.289	64.210	1.123

Table 2. Continued from the previous page.

	csr4tr	0.723	151.822	7.091	9.342	1.288	63.288	1.125
	schw1	0.683	150.041	7.046	9.407	1.269	65.150	1.118
gbcont.ce	eot11a	0.697	152.177	7.072	9.500	1.294	64.451	1.123
	hamtide11a	0.695	152.021	7.070	9.494	1.292	64.513	1.122
	osu.tpxo72atlas	0.694	151.972	7.069	9.499	1.291	64.592	1.122
	tpxo70	0.704	151.809	7.075	9.436	1.289	64.140	1.123
	fes952	0.719	149.053	7.066	9.141	1.254	63.533	1.121
	fes2004	0.699	151.396	7.069	9.425	1.284	64.347	1.122
	osu.tpxo72	0.686	152.229	7.065	9.555	1.295	64.907	1.121
	dtu10tr	0.693	152.239	7.070	9.522	1.294	64.603	1.122
	csr4tr	0.715	152.198	7.087	9.412	1.293	63.638	1.125
	schw1	0.676	149.983	7.040	9.440	1.269	65.473	1.117
Average		0.683	151.300	7.071	9.400	1.283	64.189	1.122
STD		0.107	0.937	0.011	0.104	0.012	0.555	0.002
gbocen.cm	eot11a	0.530	169.623	7.021	11.479	1.471	71.676	1.114
	hamtide11a	0.548	168.219	7.033	11.323	1.461	70.900	1.116
	osu.tpxo72atlas	0.540	166.178	7.018	11.203	1.441	71.110	1.114
	tpxo70	0.551	167.555	7.033	11.265	1.455	70.751	1.116
	fes952	0.565	165.362	7.037	11.060	1.435	70.114	1.117
	fes2004	0.538	167.952	7.023	11.336	1.457	71.273	1.115
	osu.tpxo72	0.537	166.231	7.015	11.219	1.441	71.244	1.113
	dtu10tr	0.531	168.576	7.018	11.402	1.462	71.576	1.114
	csr4tr	0.543	165.180	7.016	11.126	1.432	70.987	1.114
	schw1	0.554	160.121	7.003	10.733	1.384	70.453	1.112
gbav.cm	eot11a	0.530	169.559	7.021	11.473	1.471	71.646	1.114
	hamtide11a	0.548	168.168	7.033	11.317	1.460	70.870	1.116
	osu.tpxo72atlas	0.541	166.115	7.018	11.196	1.440	71.078	1.114
	tpxo70	0.552	167.505	7.033	11.259	1.454	70.717	1.116
	fes952	0.566	165.237	7.037	11.046	1.434	70.057	1.117
	fes	0.539	167.880	7.023	11.329	1.456	71.246	1.115
	osu.tpxo72	0.538	166.178	7.016	11.212	1.441	71.212	1.113
	dtu10tr	0.531	168.518	7.019	11.396	1.462	71.549	1.114
	csr4tr	0.544	165.111	7.017	11.117	1.431	70.945	1.114
	schw1	0.559	159.951	7.007	10.700	1.382	70.242	1.112
gbcont.cm	eot11a	0.629	170.408	7.122	11.216	1.497	67.696	1.130
	hamtide11a	0.626	168.951	7.112	11.109	1.481	67.716	1.129
	osu.tpxo72atlas	0.640	166.915	7.112	10.922	1.461	67.228	1.129
	tpxo70	0.641	168.266	7.123	11.006	1.476	67.086	1.131

Table 2. Continued from the previous page.

	fes952	0.656	165.332	7.125	10.704	1.446	66.212	1.131
	fes2004	0.627	168.657	7.109	11.098	1.478	67.795	1.128
	osu.tpxo72	0.640	167.025	7.112	10.930	1.462	67.238	1.129
	dtu10tr	0.629	169.351	7.114	11.144	1.485	67.743	1.129
	csr4tr	0.623	165.794	7.088	10.904	1.446	67.955	1.125
	schw1	0.601	160.010	7.034	10.577	1.383	68.968	1.116
Average		0.573	166.664	7.050	11.127	1.450	69.843	1.119
STD		0.043	2.650	0.043	0.231	0.027	1.702	0.007

Table 3. Results of correction of the P1 wave for ocean tide loading derived from 10 ocean loading models with different Earth models calculated by SPOTL routines. The observed values, not corrected for ocean tide loading, are in Table 1.

Earth model	Ocean tide model	Amplitude of the ocean tide load L [nstr]	Phase of the ocean tide load λ [degree]	Corrected strain amplitude A_c [nstr]	Phase of the corrected strain α_c [degree]	Amplitude of the remaining residual R_c [nstr]	Phase of the remaining residual ξ_c [degree]	Corrected amplitude factor η_c
gbocen.ce	eot11a	0.405	160.700	3.876	1.481	0.298	19.646	1.322
	hamtide11a	0.397	157.509	3.892	1.741	0.319	21.791	1.328
	osu.tpxo72atlas	0.386	160.266	3.895	1.422	0.315	17.890	1.329
	tpxo70	0.400	158.573	3.886	1.657	0.312	21.145	1.326
	fes952	0.002	-142.960	4.256	-0.476	0.662	-3.061	1.452
	fes2004	0.436	158.635	3.853	1.860	0.286	25.937	1.315
	osu.tpxo72	0.381	160.217	3.900	1.400	0.319	17.388	1.330
	dtu10tr	0.435	160.424	3.849	1.668	0.277	23.868	1.313
	csr4tr	0.417	160.234	3.866	1.592	0.291	21.677	1.319
	schw1	0.393	152.967	3.910	2.125	0.345	24.873	1.334
gbav.ce	eot11a	0.406	160.709	3.875	1.484	0.297	19.729	1.322
	hamtide11a	0.398	157.523	3.891	1.744	0.318	21.856	1.327
	osu.tpxo72atlas	0.387	160.253	3.894	1.428	0.314	17.997	1.328
	tpxo70	0.401	158.557	3.886	1.663	0.311	21.259	1.326
	fes952	0.002	-142.880	4.256	-0.476	0.662	-3.061	1.452
	fes2004	0.437	158.625	3.853	1.866	0.285	26.073	1.314
	osu.tpxo72	0.382	160.206	3.899	1.405	0.318	17.489	1.330

Table 3. Continued from the previous page.

	dtu10tr	0.436	160.417	3.848	1.674	0.276	24.009	1.313
	csr4tr	0.418	160.241	3.865	1.597	0.290	21.804	1.319
	schw1	0.394	152.955	3.909	2.135	0.344	25.039	1.333
gbcont.ce	eot11a	0.403	161.284	3.877	1.413	0.297	18.769	1.323
	hamtide11a	0.395	157.747	3.894	1.703	0.319	21.241	1.328
	osu.tpxo72atlas	0.384	160.820	3.895	1.360	0.314	17.113	1.329
	tpxo70	0.397	158.856	3.888	1.616	0.312	20.558	1.326
	fes952	0.002	-143.006	4.256	-0.476	0.662	-3.061	1.452
	fes2004	0.433	159.078	3.854	1.801	0.285	25.153	1.315
	osu.tpxo72	0.378	160.774	3.901	1.332	0.319	16.501	1.331
	dtu10tr	0.433	160.939	3.849	1.605	0.276	23.030	1.313
	csr4tr	0.415	160.787	3.867	1.523	0.290	20.750	1.319
	schw1	0.390	152.823	3.913	2.115	0.347	24.553	1.335
Average		0.365	128.776	3.918	1.433	0.342	18.932	1.337
STD		0.122	90.603	0.114	0.671	0.108	7.814	0.039
gbocen.cm	eot11a	0.425	168.950	3.840	0.715	0.250	11.046	1.310
	hamtide11a	0.445	163.838	3.831	1.349	0.252	20.940	1.307
	osu.tpxo72atlas	0.418	168.003	3.848	0.792	0.260	11.835	1.313
	tpxo70	0.437	164.937	3.836	1.194	0.254	18.345	1.309
	fes952	0.002	-140.384	4.256	-0.476	0.662	-3.061	1.452
	fes2004	0.464	167.028	3.806	1.062	0.222	18.500	1.298
	osu.tpxo72	0.413	167.869	3.854	0.789	0.265	11.571	1.315
	dtu10tr	0.468	168.683	3.799	0.878	0.212	15.920	1.296
	csr4tr	0.444	168.506	3.822	0.822	0.234	13.541	1.304
	schw1	0.002	-140.467	4.256	-0.476	0.662	-3.061	1.452
gbav.cm	eot11a	0.426	168.944	3.839	0.718	0.249	11.122	1.310
	hamtide11a	0.445	163.841	3.830	1.352	0.252	21.024	1.307
	osu.tpxo72atlas	0.419	167.976	3.848	0.798	0.259	11.949	1.313
	tpxo70	0.438	164.911	3.835	1.200	0.253	18.478	1.308
	fes952	0.002	-140.165	4.256	-0.476	0.662	-3.061	1.452
	fes2004	0.465	167.003	3.805	1.068	0.222	18.659	1.298
	osu.tpxo72	0.414	167.843	3.853	0.795	0.264	11.677	1.314
	dtu10tr	0.469	168.661	3.798	0.884	0.212	16.075	1.296
	csr4tr	0.445	168.494	3.821	0.827	0.233	13.669	1.304
	schw1	0.431	163.084	3.846	1.365	0.267	20.057	1.312
gbcont.cm	eot11a	0.424	169.542	3.840	0.646	0.250	9.982	1.310
	hamtide11a	0.442	164.088	3.833	1.310	0.253	20.251	1.308
	osu.tpxo72atlas	0.416	168.551	3.849	0.729	0.259	10.885	1.313

Table 3. Continued from the previous page.

	tpxo70	0.435	165.232	3.838	1.152	0.255	17.630	1.309
	fes952	0.002	-140.154	4.256	-0.476	0.662	-3.061	1.452
	fes2004	0.462	167.480	3.806	1.003	0.222	17.467	1.299
	osu.tpxo72	0.410	168.439	3.856	0.721	0.266	10.522	1.315
	dtu10tr	0.467	169.187	3.799	0.814	0.212	14.783	1.296
	csr4tr	0.442	169.067	3.823	0.753	0.234	12.379	1.304
	schw1	0.426	163.069	3.851	1.345	0.271	19.500	1.314
Average		0.380	126.069	3.888	0.773	0.301	12.852	1.326
STD		0.149	104.493	0.145	0.537	0.143	7.121	0.050

Table 4. Results of correction of the K1 wave for ocean tide loading derived from 10 ocean loading models with different Earth models calculated by SPOTL routines. The observed values, not corrected for ocean tide loading, are in Table 1.

Earth model	Ocean tide model	Amplitude of the ocean tide load L [nstr]	Phase of the ocean tide load λ [degree]	Corrected strain amplitude A_c [nstr]	Phase of the corrected strain α_c [degree]	Amplitude of the remaining residual R_c [nstr]	Phase of the remaining residual ξ_c [degree]	Corrected amplitude factor η_c
gbocen.ce	eot11a	1.337	160.522	7.998	-10.865	1.557	-75.391	0.903
	hamtide11a	1.323	160.559	8.011	-10.886	1.566	-74.982	0.904
	osu.tpxo72atlas	1.314	159.967	8.023	-10.800	1.560	-74.418	0.906
	tpxo70	1.312	159.989	8.024	-10.806	1.562	-74.376	0.906
	fes952	1.268	157.134	8.080	-10.416	1.539	-71.620	0.912
	fes2004	1.327	159.153	8.013	-10.652	1.537	-74.393	0.905
	osu.tpxo72	1.302	160.136	8.033	-10.840	1.570	-74.158	0.907
	dtu10tr	1.331	160.244	8.005	-10.826	1.556	-75.068	0.904
	csr4tr	1.311	159.930	8.026	-10.797	1.561	-74.313	0.906
	schw1	1.187	154.321	8.172	-10.142	1.552	-67.928	0.923
gbav.ce	eot11a	1.340	160.531	7.995	-10.863	1.556	-75.489	0.903
	hamtide11a	1.326	160.567	8.008	-10.884	1.564	-75.079	0.904
	osu.tpxo72atlas	1.317	159.966	8.020	-10.796	1.558	-74.508	0.905
	tpxo70	1.315	159.992	8.021	-10.803	1.560	-74.465	0.906
	fes952	1.271	157.101	8.077	-10.406	1.536	-71.694	0.912
	fes2004	1.329	159.153	8.011	-10.649	1.536	-74.475	0.904

Table 4. Continued from the previous page.

	osu.tpxo72	1.305	160.134	8.031	-10.837	1.568	-74.241	0.907
	dtu10tr	1.334	160.248	8.002	-10.823	1.554	-75.161	0.903
	csr4tr	1.314	159.935	8.023	-10.795	1.559	-74.411	0.906
	schw1	1.191	154.314	8.169	-10.134	1.550	-68.014	0.922
gbcont.ce	eot11a	1.332	161.141	8.000	-10.972	1.572	-75.542	0.903
	hamtide11a	1.317	161.166	8.015	-10.991	1.581	-75.100	0.905
	osu.tpxo72atlas	1.308	160.568	8.026	-10.903	1.575	-74.548	0.906
	tpxo70	1.303	160.588	8.031	-10.912	1.578	-74.405	0.907
	fes952	1.257	157.059	8.091	-10.421	1.545	-71.276	0.913
	fes2004	1.321	159.670	8.017	-10.743	1.550	-74.488	0.905
	osu.tpxo72	1.294	160.758	8.039	-10.948	1.586	-74.215	0.908
	dtu10tr	1.327	160.815	8.006	-10.923	1.568	-75.238	0.904
	csr4tr	1.303	160.470	8.031	-10.893	1.576	-74.343	0.907
	schw1	1.172	154.234	8.188	-10.158	1.563	-67.507	0.924
Average		1.300	159.346	8.040	-10.729	1.560	-73.695	0.908
STD		0.043	1.983	0.051	0.245	0.013	2.212	0.006
gbocen.cm	eot11a	1.438	168.491	7.884	-12.201	1.683	-81.669	0.890
	hamtide11a	1.461	167.514	7.860	-12.021	1.652	-82.135	0.887
	osu.tpxo72atlas	1.438	167.084	7.884	-11.944	1.650	-81.236	0.890
	tpxo70	1.438	167.522	7.884	-12.024	1.661	-81.367	0.890
	fes952	1.347	165.032	7.977	-11.610	1.643	-77.628	0.901
	fes2004	1.416	167.169	7.905	-11.963	1.660	-80.570	0.892
	osu.tpxo72	1.426	167.228	7.895	-11.972	1.658	-80.906	0.891
	dtu10tr	1.430	167.956	7.891	-12.104	1.673	-81.265	0.891
	csr4tr	0.159	167.392	7.914	-12.003	1.669	-80.365	0.893
	schw1	1.335	161.368	7.997	-11.006	1.575	-75.736	0.903
gbav.cm	eot11a	1.441	168.482	7.881	-12.200	1.682	-81.765	0.890
	hamtide11a	1.465	167.507	7.857	-12.020	1.651	-82.234	0.887
	osu.tpxo72atlas	1.441	167.067	7.881	-11.941	1.649	-81.331	0.890
	tpxo70	1.441	167.510	7.881	-12.022	1.659	-81.457	0.890
	fes952	1.350	164.981	7.974	-11.600	1.640	-77.708	0.900
	fes2004	1.419	167.154	7.903	-11.960	1.659	-80.653	0.892
	osu.tpxo72	1.429	167.212	7.893	-11.969	1.657	-80.992	0.891
	dtu10tr	1.433	167.944	7.888	-12.101	1.672	-81.355	0.891
	csr4tr	1.411	167.379	7.911	-12.001	1.667	-80.466	0.893
	schw1	1.339	161.324	7.993	-10.995	1.572	-75.840	0.902
gbcont.cm	eot11a	1.435	169.086	7.887	-12.309	1.698	-81.754	0.890
	hamtide11a	1.458	168.086	7.864	-12.128	1.667	-82.185	0.888

Table 4. Continued from the previous page.

	osu.tpxo72atlas	1.434	167.655	7.887	-12.049	1.665	-81.303	0.890
	tpxo70	1.431	168.110	7.891	-12.131	1.677	-81.326	0.891
	fes952	1.336	165.025	7.988	-11.614	1.648	-77.287	0.902
	fes2004	1.412	167.680	7.909	-12.054	1.674	-80.609	0.893
	osu.tpxo72	1.420	167.832	7.902	-12.081	1.674	-80.893	0.892
	dtu10tr	1.428	168.501	7.893	-12.202	1.687	-81.372	0.891
	csr4tr	1.401	167.931	7.920	-12.099	1.683	-80.342	0.894
	schw1	1.320	161.352	8.011	-11.018	1.583	-75.280	0.904
Average		1.371	166.819	7.910	-11.911	1.656	-80.301	0.893
STD		0.229	2.049	0.043	0.341	0.030	1.974	0.005

Table 5. Results of correction of the M2 wave for ocean tide loading derived from 10 ocean loading models with different Earth models calculated by SPOTL routines. The observed values, not corrected for ocean tide loading, are in Table 1.

Earth model	Ocean tide model	Amplitude of the ocean tide load	Phase of the ocean tide load	Corrected strain amplitude	Phase of the corrected strain	Amplitude of the remaining residual	Phase of the remaining residual	Corrected amplitude factor
		L [nstr]	λ [degree]	A_c [nstr]	α_c [degree]	R_c [nstr]	ξ_c [degree]	η_c
gbocen.ce	eot11a	0.403	57.744	8.153	-3.598	1.114	-27.347	1.290
	hamtide11a	0.397	58.043	8.149	-3.627	1.111	-27.634	1.289
	osu.tpxo72atlas	0.386	58.393	8.141	-3.689	1.108	-28.205	1.288
	tpxo70	0.373	55.415	8.152	-3.838	1.127	-28.964	1.290
	fes952	0.234	46.119	8.113	-4.838	1.159	-36.167	1.283
	fes2004	0.435	57.591	8.169	-3.408	1.118	-25.744	1.292
	osu.tpxo72	0.367	57.096	8.140	-3.834	1.115	-29.205	1.288
	dtu10tr	0.405	57.418	8.156	-3.598	1.116	-27.290	1.290
	csr4tr	0.414	57.751	8.158	-3.534	1.115	-26.816	1.291
	schw1	0.324	5.392	8.285	-5.696	1.371	-36.861	1.311
gbav.ce	eot11a	0.401	60.036	8.138	-3.558	1.098	-27.397	1.287
	hamtide11a	0.395	60.413	8.133	-3.587	1.095	-27.695	1.287
	osu.tpxo72atlas	0.385	60.850	8.126	-3.646	1.092	-28.251	1.285
	tpxo70	0.370	57.890	8.137	-3.799	1.111	-29.037	1.287
	fes952	0.227	49.579	8.097	-4.819	1.145	-36.453	1.281
	fes2004	0.433	59.707	8.154	-3.367	1.102	-25.760	1.290

Table 5. Continued from the previous page.

	osu.tpxo72	0.365	59.617	8.124	-3.793	1.099	-29.271	1.285
	dtu10tr	0.402	59.674	8.141	-3.558	1.100	-27.337	1.288
	csr4tr	0.412	59.932	8.143	-3.494	1.099	-26.848	1.288
	schw1	0.309	6.968	8.269	-5.658	1.354	-37.026	1.308
gbcont.ce	eot11a	0.399	59.922	8.138	-3.574	1.098	-27.511	1.287
	hamtide11a	0.392	60.429	8.132	-3.606	1.095	-27.854	1.286
	osu.tpxo72atlas	0.378	60.878	8.123	-3.687	1.091	-28.600	1.285
	tpxo70	0.362	57.772	8.133	-3.850	1.111	-29.449	1.287
	fes952	0.200	48.109	8.086	-4.994	1.148	-37.799	1.279
	fes2004	0.432	59.863	8.153	-3.370	1.101	-25.808	1.290
	osu.tpxo72	0.356	59.481	8.121	-3.858	1.100	-29.786	1.285
	dtu10tr	0.399	59.775	8.138	-3.581	1.099	-27.543	1.287
	csr4tr	0.409	59.962	8.142	-3.513	1.099	-27.006	1.288
	schw1	0.292	2.671	8.256	-5.834	1.356	-38.224	1.306
Average		0.369	52.483	8.150	-3.960	1.135	-29.630	1.289
STD		0.059	16.227	0.044	0.712	0.077	3.877	0.007
gbocen.cm	eot11a	0.507	72.345	8.084	-2.623	0.999	-21.735	1.279
	hamtide11a	0.495	73.438	8.072	-2.685	0.990	-22.446	1.277
	osu.tpxo72atlas	0.482	74.566	8.060	-2.756	0.982	-23.235	1.275
	tpxo70	0.488	73.530	8.070	-2.733	0.990	-22.862	1.277
	fes952	0.397	68.957	8.079	-3.420	1.036	-27.730	1.278
	fes2004	0.539	72.849	8.088	-2.395	0.992	-19.912	1.279
	osu.tpxo72	0.477	75.213	8.053	-2.784	0.978	-23.584	1.274
	dtu10tr	0.521	71.666	8.094	-2.538	1.004	-20.906	1.280
	csr4tr	0.535	75.039	8.067	-2.384	0.972	-20.193	1.276
	schw1	0.409	55.920	8.167	-3.607	1.127	-27.120	1.292
gbav.cm	eot11a	0.509	74.163	8.069	-2.581	0.983	-21.698	1.276
	hamtide11a	0.497	75.328	8.057	-2.643	0.974	-22.427	1.274
	osu.tpxo72atlas	0.486	76.498	8.044	-2.711	0.966	-23.200	1.273
	tpxo70	0.490	75.417	8.054	-2.691	0.974	-22.842	1.274
	fes952	0.396	71.212	8.064	-3.398	1.020	-27.930	1.276
	fes2004	0.541	74.544	8.073	-2.352	0.976	-19.837	1.277
	osu.tpxo72	0.480	77.122	8.038	-2.741	0.962	-23.562	1.272
	dtu10tr	0.523	73.416	8.079	-2.496	0.988	-20.854	1.278
	csr4tr	0.538	76.700	8.053	-2.342	0.956	-20.121	1.274
	schw1	0.406	58.339	8.151	-3.565	1.110	-27.173	1.289
gbcont.cm	eot11a	0.506	74.134	8.069	-2.597	0.983	-21.829	1.276
	hamtide11a	0.494	75.432	8.055	-2.662	0.973	-22.604	1.274

Table 5. Continued from the previous page.

	osu.tpxo72atlas	0.479	76.731	8.041	-2.753	0.965	-23.590	1.272
	tpxo70	0.482	75.617	8.051	-2.743	0.974	-23.313	1.274
	fes952	0.369	72.000	8.052	-3.572	1.020	-29.457	1.274
	fes2004	0.540	74.691	8.071	-2.354	0.975	-19.880	1.277
	osu.tpxo72	0.471	77.384	8.034	-2.806	0.961	-24.153	1.271
	dtu10tr	0.519	73.596	8.076	-2.519	0.987	-21.078	1.278
	csr4tr	0.535	76.815	8.051	-2.360	0.956	-20.298	1.274
	schw1	0.378	58.415	8.137	-3.740	1.107	-28.636	1.287
Average		0.483	72.703	8.072	-2.785	0.996	-23.140	1.277
STD		0.050	5.399	0.031	0.410	0.044	2.753	0.005

factors for different centers of mass to compare the corrections. Table 6 summarizes the results of correction obtained from FOTLP. It can be seen that the results obtained are nearly identical, regardless of what kind of Earth model was used. Only small differences are between the amplitude factors calculated with and without a motion correction (see Table 6). The average amplitude factors were also calculated obtained with FOTLP for the sake of comparability of the measured and the averages of the corrected amplitude factors. These values are summarized in Table 7. In case of SPOTL, the corrected amplitude factor of the K1 wave came closer to one, while that of the O1, P1, and M2 waves increased compared to the measured one and thus became worse. In case of FOTLP, the O1 and K1 waves, became near to one, while the other waves increased significantly compared to the measured ones.

5. Conclusions

Strain measurement was used to test thirteen global ocean tide loading models. Tidal parameters corrected for ocean tide loading were calculated. The test of models was carried out in the case of the diurnal and semi-diurnal tidal harmonic constituents O1, P1, K1 and M2. It was only found a negligible difference between the individual global ocean tide loading models mainly due to using different Earth models and Green function. The measured amplitude factors for O1, P1, K1 and M2 are 1.019, 1.226, 0.842, 1.131, respectively. The average amplitude factors for these tidal components were

Table 6. Results of correction of the O1, P1, K1, M2 waves for ocean tide loading derived from three ocean loading models with different Earth models calculated by the FOTLP. L amplitude of the ocean tide load, λ phase of the ocean tide load, A_c corrected strain amplitude, α_c phase of the corrected strain, R_c amplitude of the remaining residual, ξ_c phase of the remaining residual, η_c corrected amplitude factor. The observed values, not corrected for ocean tide loading, are in Table 1.

Tidal wave		Ocean tide model	Earth model	Motion correction	L [nstr]	λ [degree]	A_c [nstr]	α_c [degree]	R_c [nstr]	ξ_c [degree]	η_c
O1		FS2012	Elastic Farrel	No	0.178	59.720	6.607	-11.762	1.347	-87.850	1.049
		FS214b			0.156	79.913	6.606	-11.716	1.342	-87.850	1.048
		GOT00.2			0.151	75.692	6.608	-11.783	1.350	-87.850	1.049
		FS2012	Visco-elastic		0.158	76.349	6.606	-11.722	1.342	-87.850	1.048
		FS214b			0.149	79.417	6.608	-11.778	1.349	-87.850	1.049
		GOT00.2			0.164	78.647	6.604	-11.657	1.335	-87.850	1.048
	Average				0.159	74.956	6.607	-11.736	1.344	-87.850	1.049
	STD				0.010	6.985	0.001	0.044	0.005	0.000	0.000
		FS2012	Elastic Farrel	Yes	0.636	58.334	6.538	-9.051	1.029	-87.850	1.038
		FS214b			0.710	57.731	6.531	-8.750	0.994	-87.850	1.037
		GOT00.2			0.342	0.000	6.658	-13.416	1.545	-87.850	1.057
		FS2012	Visco-elastic		0.636	58.334	6.538	-9.051	1.029	-87.850	1.038
		FS214b			0.710	57.731	6.531	-8.750	0.994	-87.850	1.037
		GOT00.2			0.337	0.000	6.657	-13.406	1.544	-87.850	1.057
	Average				0.562	38.688	6.576	-10.404	1.189	-87.850	1.044
	STD				0.160	27.358	0.058	2.130	0.252	0.000	0.009
P1		FS2012	Elastic Farrel	No	0.064	13.209	4.319	-0.497	0.725	-2.963	1.473
		FS214b			0.050	0.000	4.307	-0.491	0.713	-2.963	1.469
		GOT00.2			0.050	26.060	4.301	-0.487	0.708	-2.963	1.467
		FS2012	Visco-elastic		0.062	13.739	4.316	-0.496	0.723	-2.963	1.472
		FS214b			0.050	0.000	4.307	-0.491	0.713	-2.963	1.469
		GOT00.2			0.048	8.778	4.304	-0.489	0.711	-2.963	1.468
	Average				0.054	10.298	4.309	-0.492	0.716	-2.963	1.470
	STD				0.006	8.974	0.006	0.004	0.006	0.000	0.002

Table 6. Continued from the previous page.

		FS2012	Elastic Farrel	Yes	0.150	26.060	4.391	-0.538	0.798	-2.963	1.498
		FS214b			0.153	11.067	4.406	-0.546	0.812	-2.963	1.503
		GOT00.2			0.145	0.000	4.401	-0.544	0.808	-2.963	1.502
		FS2012	Visco-elastic		0.150	26.060	4.391	-0.538	0.798	-2.963	1.498
		FS214b			0.153	11.067	4.406	-0.546	0.812	-2.963	1.503
		GOT00.2			0.142	0.000	4.399	-0.542	0.806	-2.963	1.501
	Average				0.149	12.376	4.399	-0.542	0.806	-2.963	1.501
	STD				0.004	10.679	0.006	0.003	0.006	0.000	0.002
K1		FS2012	Elastic Farrel	No	0.172	17.285	9.379	-12.378	2.632	-49.789	1.059
		FS214b			0.178	11.836	9.392	-12.442	2.650	-49.789	1.060
		GOT00.2			0.170	28.277	9.354	-12.260	2.601	-49.789	1.056
		FS2012	Visco-elastic		0.172	17.285	9.379	-12.378	2.632	-49.789	1.059
		FS214b			0.178	11.836	9.392	-12.442	2.650	-49.789	1.060
		GOT00.2			0.168	15.154	9.381	-12.391	2.636	-49.789	1.059
	Average				0.173	16.946	9.380	-12.382	2.634	-49.789	1.059
	STD				0.004	5.539	0.013	0.061	0.016	0.000	0.001
		FS2012	Elastic Farrel	Yes	0.471	22.859	9.463	-12.767	2.738	-49.789	1.068
		FS214b			0.520	13.021	9.541	-13.121	2.836	-49.789	1.077
		GOT00.2			0.437	0.000	9.562	-13.213	2.862	-49.789	1.080
		FS2012	Visco-elastic		0.471	22.859	9.463	-12.767	2.738	-49.789	1.068
		FS214b			0.520	13.021	9.541	-13.121	2.836	-49.789	1.077
		GOT00.2			0.424	0.000	9.555	-13.180	2.852	-49.789	1.079
	Average				0.474	11.960	9.521	-13.028	2.810	-49.789	1.075
	STD				0.037	9.362	0.042	0.187	0.052	0.000	0.005
M2		FS2012	Elastic Farrel	No	0.527	-51.022	8.369	-8.541	1.678	-47.779	1.324
		FS214b			0.539	-52.002	8.377	-8.588	1.689	-47.779	1.325
		GOT00.2			0.519	-49.577	8.363	-8.507	1.670	-47.779	1.323
		FS2012	Visco-elastic		0.527	-51.022	8.369	-8.541	1.678	-47.779	1.324
		FS214b			0.539	-52.002	8.377	-8.588	1.689	-47.779	1.325
		GOT00.2			0.539	-50.687	8.378	-8.593	1.690	-47.779	1.325
	Average				0.532	-51.052	8.372	-8.560	1.682	-47.779	1.324
	STD				0.008	0.828	0.006	0.032	0.007	0.000	0.001

Table 6. Continued from the previous page.

	FS2012	Elastic Farrel	Yes	0.681	-88.575	8.405	-8.743	1.725	-47.779	1.330
	FS214b			0.769	-86.884	8.475	-9.125	1.815	-47.779	1.341
	GOT00.2			0.040	0.000	7.988	-6.274	1.179	-47.779	1.264
	FS2012	Visco-elastic		0.673	-88.559	8.400	-8.716	1.719	-47.779	1.329
	FS214b			0.769	-86.884	8.475	-9.125	1.815	-47.779	1.341
	GOT00.2			0.035	0.000	7.985	-6.257	1.175	-47.779	1.263
Average				0.495	-58.484	8.288	-8.040	1.571	-47.779	1.311
STD				0.325	41.360	0.215	1.265	0.281	0.000	0.034

Table 7. Measured and the average of corrected amplitude factors calculated by SPOTL and FOTLP using different global ocean tide loading models.

		O1	P1	K1	M2
Measured		1.01848 ± 0.03807	1.22616 ± 0.06997	0.84229 ± 0.02632	1.13071 ± 0.02105
From SPOTL	ce	1.122 ± 0.002	1.337 ± 0.039	0.908 ± 0.006	1.289 ± 0.007
	cm	1.119 ± 0.007	41.326 ± 0.050	0.893 ± 0.005	1.277 ± 0.005
From FOTLP	no motion correction	1.049 ± 0.000	1.470 ± 0.002	1.059 ± 0.001	1.324 ± 0.001
	motion correction	1.044 ± 0.009	1.501 ± 0.002	1.075 ± 0.005	1.311 ± 0.034

obtained after ocean load correction using SPOTL routines: 1.121, 1.332, 0.916, 1.283, and in the case of the three models using FOTLP: 1.046, 1.486, 1.067, 1.317. The corrected amplitude factor became better only for K1. At SGO, the measured average amplitude factors for the tidal components O1, K1, M2 are 0.5323, 0.5283, 1.0036, and the ocean load corrected values are 1.0138, 1.0225, 1.0503. These results show that the effect of the ocean tide loading is greater at Sopronbánfalva, than at Vyhne. One possible explanation for this is that the VTS is further away from the oceans and the Mediterranean than the SGO.

The remaining residues after the correction can be attributed to the local effects (e.g. topographic, cavity) affect the measurement site, which requires further study.

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