Estimation of Characteristic Period for Energy Based Seismic Design

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Abstract. Estimation of input energy using approximate methods has been always a considerable research topic of energy based seismic design. Therefore several approaches have been proposed by many researchers to estimate the energy input to SDOF systems in the last decades. The characteristic period is the key parameter of most of these approaches and it is defined as the period at which the peak value of the input energy occurs. In this study an equation is proposed for estimating the characteristic period considering an extensive earthquake ground motion database which includes a total of 268 far-field records, two horizontal components from 134 recording stations located on firm soil sites. For this purpose statistical regression analyses are performed to develop an equation in terms of a number of structural parameters, and it is found that the developed equation yields satisfactory results comparing the characteristic periods calculated from time history analyses of SDOF systems.

Keywords: predominant period, characteristic period, seismic energy

INTRODUCTION

Estimation of input energy using approximate methods has been always a considerable research topic of energy based seismic design. For SDOF systems, input energy spectrum can be investigated by dividing the spectrum into two characteristic parts (Fig.1). For the systems which have shorter periods than the period at which the peak value of spectral input energy occurs, an ascending-linear spectral shape can be assumed, while a descending-curved spectral shape can be assumed for the systems which have longer periods. Thus, the period at which the peak value of spectral input energy occurs – which is called *characteristic period* in the remaining part of the paper - is the key parameter in such method of approaches.

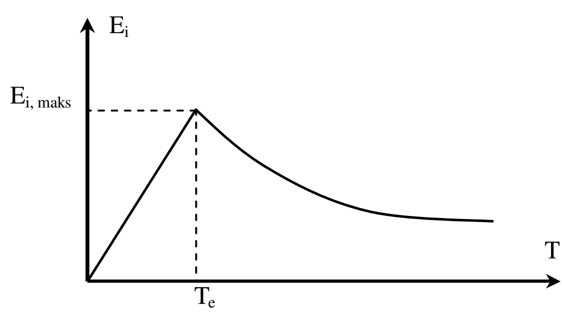

FIGURE 1. Input energy spectrum (drawn schematically).

It is worth to note that the characteristic period can be assumed to coincide with the predominant period of ground motion. Such an approach has also an analytical meaning since it is known that for undamped systems, equivalent input energy velocity spectrum equals to the Fourier amplitude spectrum of the ground acceleration (Eq. 1)[1,2].

$$V_e = \left|FS(\omega)\right| = \sqrt{\frac{2E_i}{m}} \tag{1}$$

However, for a given ground motion, there is no unique characteristic period as it depends on the lateral strength of the system and, to a lesser extent, on the damping of the system [3]. But it is found that the change in lateral strength has not significant affect on characteristic period, thus for the approach proposed in this paper it is neglected and characteristic period is assumed as the period at which the peak value of %5 damped elastic spectral input energy occurs.

Statistical Regression

To obtain a reliable statistical evaluation of characteristic period T_e, regression analyses are carried out considering 268 far-field earthquake ground acceleration records (two horizontal components from 134 recording stations located on firm soil sites) given in detail in Table 1. The best representative equation which allows estimating T_e is obtained with performing following steps:

- An exponential type formulation is adopted:

$$T_e = a \cdot T_s \cdot e^{b \cdot (T_s / T_1)} \tag{2}$$

- A statistical regression is performed comparing the values of T_e obtained by time history analyses of %5 damped SDOF systems with those given by the proposed formulation.
- The best coefficients minimizing the standard error are selected.

Where T_1 is the transition period between the acceleration-controlled and velocity-controlled response spectrum and T_s is the period at which the peak value of %5 damped spectral pseudo velocity occurs.

The transition period T_1 can be estimated by considering relation between idealized pseudo-velocity and pseudo-acceleration response spectra (Fig. 2) [4]. It is clear that the peak values of spectral responses do not always occur at the same period. However, the period obtained from Eq. 3 could take close values with characteristic period.

$$T_1 = 2\pi \frac{PSV_{maks}}{PSA_{maks}} \tag{3}$$

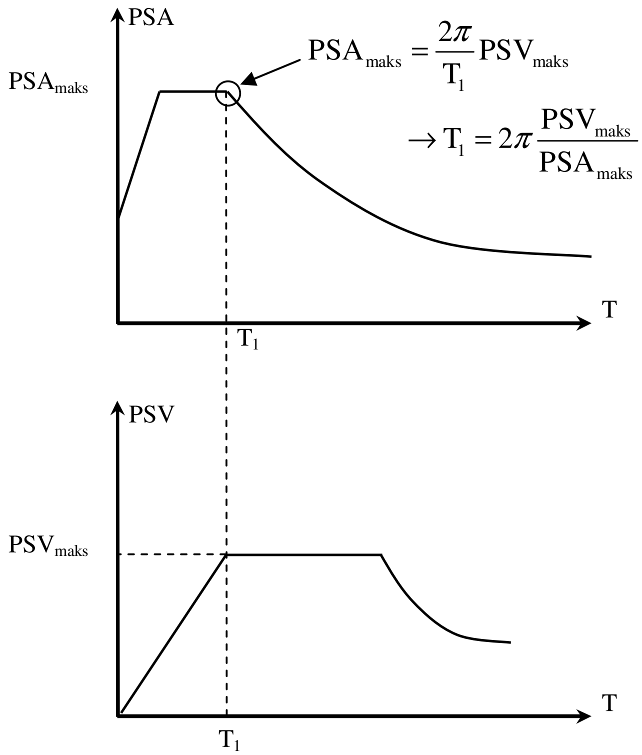

FIGURE 2. Idealized linear elastic response spectra.

TABLE 1. Records used in the regression analysis.

Event		Station name	ID*1	M*2	R_{epc}*3	SC*4	Vs30*5	Owner
Big Bear-01	1992	Rancho Cucamonga - Deer Can	23598	6.5	69	B	822	CDMG
Chi-Chi, Taiwan	1999	TAP065	99999	7.6	173	B	1023	CWB
		TAP077	99999	7.6	170	B	1023	CWB
		TCU085	99999	7.6	107	B	1000	CWB
		TTN042	99999	7.6	105	B	845	CWB
Chi-Chi, Taiwan-05	1999	TTN042	99999	6.2	92	B	845	CWB
Denali, Alaska	2002	Carlo (temp)	Carl	7.9	68	B	964	ANSS/UA
Irpinia, Italy-01	1980	Arienzo	99999	6.9	77	B	1000	ENEL
Loma Prieta	1989	Piedmont Jr High	58338	6.9	92	B	895	CDMG
		Point Bonita	58043	6.9	104	B	1316	CDMG
		SF - Pacific Heights	58131	6.9	96	B	1250	CDMG
		SF - Rincon Hill	58151	6.9	94	B	873	CDMG
		So. San Francisco, Sierra	58539	6.9	84	B	1021	CDMG
Morgan Hill	1984	Gilroy Array #1	47379	6.2	39	B	1428	CDMG
Norcia, Italy	1979	Bevagna	99999	5.9	36	B	1000	ENEL
Northridge-01	1994	Anacapa Island	25169	6.7	77	B	822	CDMG
		Antelope Buttes	24310	6.7	64	B	822	CDMG

Continued.

TABLE 1. *Continued.*

Event		Station name	ID[*1]	M[*2]	R_{epc}[*3]	SC[*4]	Vs30[*5]	Owner
Northridge-01	1994	Lake Hughes #4 - Camp Mend	24469	6.7	50	B	822	CDMG
		Littlerock - Brainard Can	23595	6.7	61	B	822	CDMG
		Mt Wilson - CIT Seis Sta	24399	6.7	46	B	822	CDMG
		Rancho Cucamonga - Deer Can	23598	6.7	90	B	822	CDMG
		Sandberg - Bald Mtn	24644	6.7	62	B	822	CDMG
		Vasquez Rocks Park	24047	6.7	38	B	996	CDMG
		Wrightwood - Jackson Flat	23590	6.7	78	B	822	CDMG
San Fernando	1971	Pasadena - Old Seismo Lab	266	6.6	39	B	969	USGS
Sierra Madre	1991	Vasquez Rocks Park	24047	5.6	40	B	996	CDMG
Whittier Narrows-01	1987	LA - Wonderland Ave	90017	6.0	28	B	1223	USC
		Vasquez Rocks Park	24047	6.0	54	B	996	CDMG
Big Bear-01	1992	Newport Bch	13160	6.5	118	C	405	CDMG
Chi-Chi, Taiwan	1999	HWA029	99999	7.6	77	C	614	CWB
		HWA038	99999	7.6	69	C	643	CWB
		HWA046	99999	7.6	88	C	618	CWB
		ILA031	99999	7.6	132	C	649	CWB
		KAU012	99999	7.6	117	C	474	CWB
		TAP035	99999	7.6	140	C	438	CWB
		TAP052	99999	7.6	148	C	474	CWB
		TAP075	99999	7.6	160	C	553	CWB
		TTN025	99999	7.6	108	C	705	CWB
		TTN032	99999	7.6	90	C	474	CWB
		TTN044	99999	7.6	100	C	474	CWB
		TTN046	99999	7.6	107	C	474	CWB
Drama, Greece	1985	Kavala	99999	5.2	47	C	660	ITSAK
Irpinia, Italy-01	1980	Torre Del Greco	99999	6.9	80	C	660	ENEL
		Tricarico	99999	6.9	72	C	460	ENEL
Kern County	1952	Pasadena - CIT Athenaeum	80053	7.4	126	C	415	CIT
		Santa Barbara Courthouse	283	7.4	88	C	515	USGS
Landers	1992	Arcadia - Campus Dr	90093	7.3	148	C	368	USC
		Glendale-Las Palmas	90063	7.3	165	C	446	USC
		Glendora-N Oakbank	90065	7.3	133	C	446	USC
		LA - Fletcher Dr	90034	7.3	167	C	446	USC
		La Habra - Briarcliff	90074	7.3	145	C	361	USC
		Puerta La Cruz	12168	7.3	100	C	371	CDMG
Landers	1992	Puerta La Cruz	12168	7.3	100	C	371	CDMG
Loma Prieta	1989	Berkeley LBL	58471	6.9	98	C	597	CDMG
		Hayward - BART Sta	58498	6.9	72	C	371	CDMG
		SF - Cliff House	58132	6.9	99	C	713	CDMG

Continued.

TABLE 1. *Continued.*

Event		Station name	ID[*1]	M[*2]	R_{epc}[*3]	SC[*4]	Vs30[*5]	Owner
Loma Prieta	1989	SF - Diamond Heights	58130	6.9	92	C	583	CDMG
		SF - Presidio	58222	6.9	98	C	594	CDMG
		SF - Telegraph Hill	58133	6.9	97	C	713	CDMG
		Sunol - Forest Fire Station	1688	6.9	62	C	401	USGS
N. Palm Springs	1986	Anza - Tule Canyon	5231	6.1	60	C	685	USGS
		Murrieta Hot Springs	13198	6.1	66	C	685	CDMG
		Puerta La Cruz	12168	6.1	76	C	371	CDMG
		Temecula - 6th & Mercedes	13172	6.1	75	C	371	CDMG
Northridge-01	1994	Glendora - N Oakbank	90065	6.7	62	C	446	USC
		Huntington Beach - Lake St	13197	6.7	79	C	371	CDMG
		Newport Bch - Irvine Ave. F.S	13160	6.7	88	C	405	CDMG
		Newport Bch - Newp & Coast	13610	6.7	87	C	371	CDMG
		Palmdale - Hwy 14 & Palmdale	24521	6.7	57	C	552	CDMG
		Rancho Palos Verdes - Hawth	14404	6.7	53	C	478	CDMG
		Rancho Palos Verdes - Luconia	90044	6.7	56	C	509	USC
		Riverside Airport	13123	6.7	106	C	371	CDMG
		Seal Beach - Office Bldg	14578	6.7	66	C	371	CDMG
San Fernando	1971	Upland - San Antonio Dam	287	6.6	75	C	446	ACOE
		Wrightwood - 6074 Park Dr	290	6.6	72	C	486	USGS
Whittier Narrows-01	1987	Castaic - Old Ridge Route	24278	6.0	77	C	450	CDMG
		Huntington Beach - Lake St	13197	6.0	44	C	371	CDMG
		Leona Valley #5 - Ritter	24055	6.0	63	C	446	CDMG
		Malibu - Las Flores Canyon	90050	6.0	51	C	623	USC
		Moorpark - Fire Sta	24283	6.0	78	C	405	CDMG
		Pacific Palisades - Sunset	90049	6.0	44	C	446	USC
Chi-Chi, Taiwan	1999	CHY065	99999	7.6	116	D	273	CWB
		KAU085	99999	7.6	119	D	261	CWB
		TAP026	99999	7.6	147	D	215	CWB
		TAP090	99999	7.6	156	D	324	CWB
		TAP095	99999	7.6	158	D	215	CWB
Dinar, Turkey	1995	Cardak	99999	6.4	50	D	339	ERD
Friuli, Italy-01	1976	Conegliano	8005	6.5	90	D	275	
Imp. Valley-06	1979	Coachella Canal #4	5066	6.5	84	D	345	USGS
Irpinia, Italy-01	1980	Bovino	99999	6.9	52	D	275	ENEL

Continued.

TABLE 1. *Continued.*

Event		Station name	ID*1	M*2	R_{epc}*3	SC*4	Vs30*5	Owner
Irpinia, Italy-02	1980	Mercato San Severino	99999	6.2	48	D	350	ENEL
Kern County	1952	LA-Hollywood S.FF	24303	7.4	118	D	316	CDMG
Kobe, Japan	1995	HIK	99999	6.9	136	D	256	
Kocaeli, Turkey	1999	Atakoy	99999	7.5	100	D	275	ITU
		Botas	99999	7.5	171	D	275	KOERI
		Cekmece	99999	7.5	108	D	346	KOERI
		Fatih	99999	7.5	94	D	339	KOERI
		Zeytinburnu	99999	7.5	95	D	275	ITU
Landers	1992	Amboy	21081	7.3	75	D	271	CDMG
		Boron Fire Station	33083	7.3	143	D	345	CDMG
		Burbank - N Buena Vista	90012	7.3	174	D	271	USC
		Compton - Castlegate St	90078	7.3	166	D	309	USC
		Fort Irwin	24577	7.3	121	D	345	CDMG
		Fountain Valley - Euclid	90002	7.3	149	D	270	USC
		LA - Obregon Park	24400	7.3	162	D	349	CDMG
		LB - Orange Ave	90080	7.3	164	D	270	USC
		Lakewood - Del Amo Blvd	90084	7.3	158	D	235	USC
		Pomona - 4th & Locust FF	23525	7.3	122	D	230	CDMG
		San Bernardino - E & Hospitality	23542	7.3	80	D	271	CDMG
		Tarzana - Cedar Hill	24436	7.3	193	D	257	CDMG
Lazio-Abruzzo, Italy	1984	Garigliano-Centrale Nucleare	99999	5.8	51	D	200	ENEL
Loma Prieta	1989	Oakland - Outer Harbor Wharf	58472	6.9	94	D	249	CDMG
		Oakland - Title & Trust	58224	6.9	92	D	306	CDMG
		Olema - Point Reyes Station	68003	6.9	138	D	339	CDMG
		Richmond City Hall	58505	6.9	107	D	260	CDMG
Manjil, Iran	1990	Rudsar	99999	7.4	87	D	275	BHRC
Morgan Hill	1984	Los Banos	56012	6.2	80	D	271	CDMG
		SF Intern. Airport	58223	6.2	71	D	190	CDMG
N. Palm Springs	1986	Anza Fire Station	5160	6.1	50	D	339	USGS
		Colton Interchange - Vault	754	6.1	64	D	275	CDOT
		Indio - Coachella Canal	12026	6.1	53	D	345	CDMG
Northridge-01	1994	Anaheim - W Ball Rd	90088	6.7	70	D	235	USC
		Baldwin Park - N Holly	90069	6.7	55	D	309	USC
		Brea - S Flower Av	90087	6.7	69	D	309	USC
		Featherly Park - Maint	13122	6.7	86	D	309	CDMG
		Hemet - Ryan Airfield	13660	6.7	151	D	339	CDMG
		Huntington Bch - Waikiki	90083	6.7	71	D	235	USC
		San Bernardino	23542	6.7	117	D	271	CDMG
		San Jacinto-CDF Fire Sta	12673	6.7	154	D	271	CDMG

Continued.

TABLE 1. *Continued.*

Event		Station name	ID*1	M*2	R_{epc}*3	SC*4	Vs30*5	Owner
Northridge-01	1994	Tustin - E Sycamore	90089	6.7	86	D	235	USC
		Loma Linda; VA Hospital, North Freefield	5229	6.7	121	D	275	USGS
		Loma Linda; VA Hospital, South Freefield	5229	6.7	121	D	275	USGS
San Fernando	1971	Gormon - Oso Pump Plant	994	6.6	50	D	308	CDWR
Whittier Narrows-01	1987	Lancaster - Med Off FF	24526	6.0	71	D	271	CDMG
		Rosamond - Goode Ranch	24274	6.0	88	D	271	CDMG

*1 ID: Station ID number
*2 M: Moment magnitude of earthquake
*3 R_{epc}: Distance from the recording site to epicenter
*4 SC: NEHRP Site Classification
*5 Vs30: Average shear wave velocity down to 30m depth (m/s)

Examples of the computation of the periods T_1 and T_s for a ground acceleration record (Gilroy Array #1 ground acceleration record – G01230 horizontal component, Morgan Hill Earthquake, 1984) are shown in Fig. 3. Characteristic period is computed T_e=0.24s by performing time history analysis to SDOF systems while the transition period estimated by Eq. 3 is T_1=0.16s and the period at which the peak value of spectral pseudo velocity occurs is T_s=0.32s.

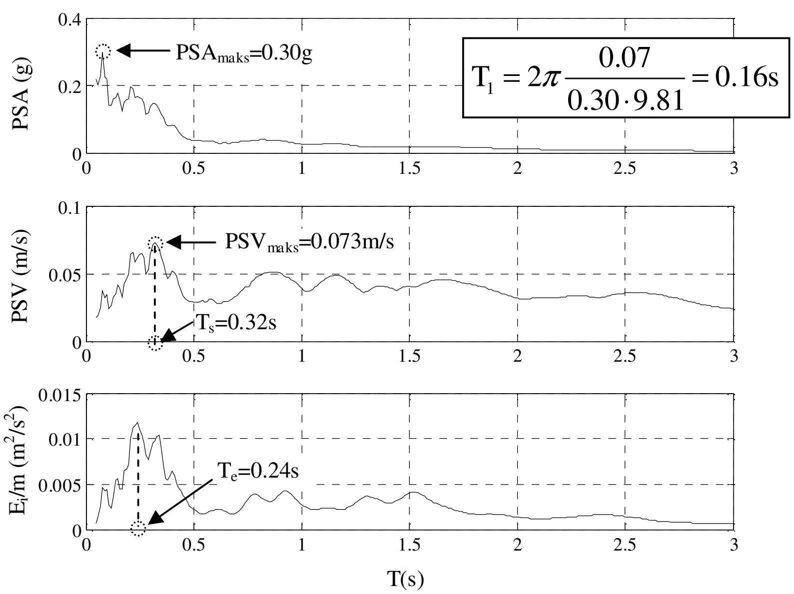

FIGURE 3. Response spectra for Gilroy Array #1 ground acceleration record (G01230 horizontal component, Morgan Hill Earthquake, 1984), ξ=0.05.

As a result of regression analysis, Eq. 4 which estimates T_e is obtained. The proportion of variance accounted for proposed equation is R^2=0.82 and the standard error is SE=0.23. The coefficients are given in Table 2 with their standard errors and the predicted and observed values are drawn in Fig. 4.

$$T_e = 1.23 \cdot T_s \cdot e^{-0.18 \cdot (T_s / T_1)} \tag{4}$$

TABLE 2. Statistical parameters.

Coefficient	Predicted value	Standard Error	t-value
a	1.23	0.039	31
b	-0.18	0.016	-11

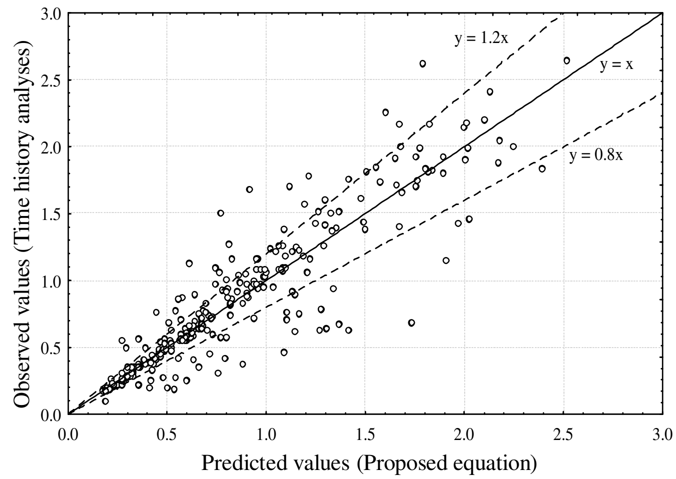

FIGURE 4. T_e values.

Comparison with Different Approaches

Chai et al. [3] assumed that the characteristic period corresponds to the transition period T_1, and they estimated the transition period by Eq. 5 proposed by Vidic et al. [5].

$$T_1 = 2\pi \frac{c_v}{c_a} \frac{PGV}{PGA} \tag{5}$$

Where c_v corresponds to the ratio of the spectral elastic response velocity to peak ground velocity in the velocity-controlled (medium) period range, and c_a corresponds to the ratio of the spectral elastic response acceleration to peak ground acceleration in the acceleration-controlled (short) period range. Chai et al. [3] assumed c_a and c_v as 2.0 and 2.5, respectively, proposed by Chai et al. [6]. Furthermore, many researchers [3,6,7,8] have estimated seismic energy by assuming that the transition period proposed by Vidic et al [5] can be considered as the characteristic period at which the peak value of input energy occurs. Thus, the proposed equation in this paper is needed to compare with the Eq. 5 proposed by Vidic et al. [5].

Fajfar et al [9] estimated the transition period T_1 by Eq. 6 proposed by Heidebrecht:

$$T_1 = 4.3\frac{PGV}{PGA} \tag{6}$$

Miranda and Garcia [10] estimated the predominant period of ground motion using the approach proposed by Miranda [11] in which the predominant period of the ground motion is defined as the period at which the peak value of spectral velocity occurs.

In Fig. 5, Fig. 6 and Fig. 7, the value of the transition periods calculated by Eq. 5, Eq. 6 and the T_s periods proposed by Miranda are drawn for all records given in Table.1, respectively, in comparison with the values of characteristic periods obtained from time history analyses. Standard errors for each approaches and for proposed equation in this paper is given in Table. 3.

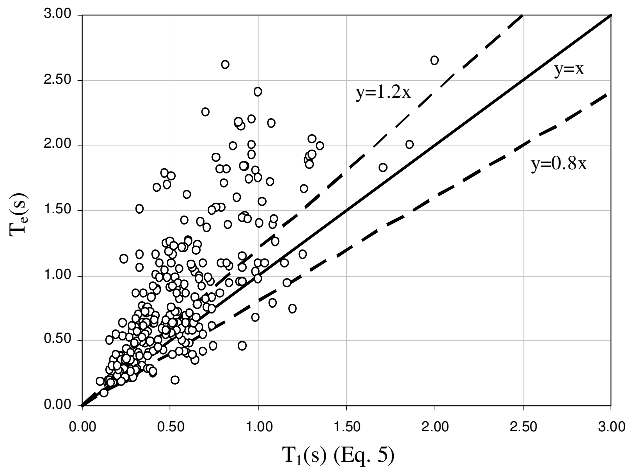

FIGURE 5. T_1 (obtained by Eq. 5) and T_e.

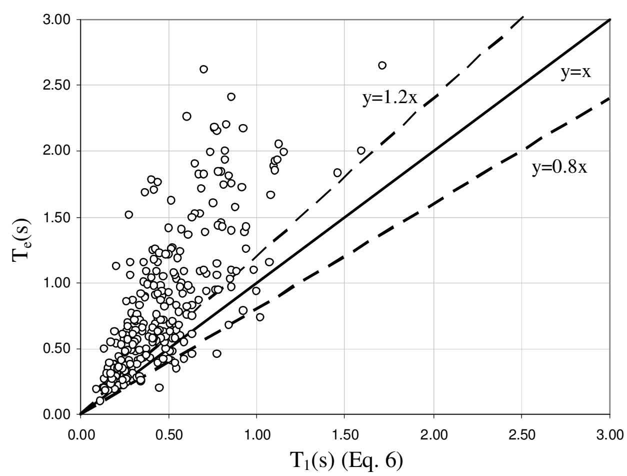

FIGURE 6. T_1 (obtained by Eq. 6) and T_e.

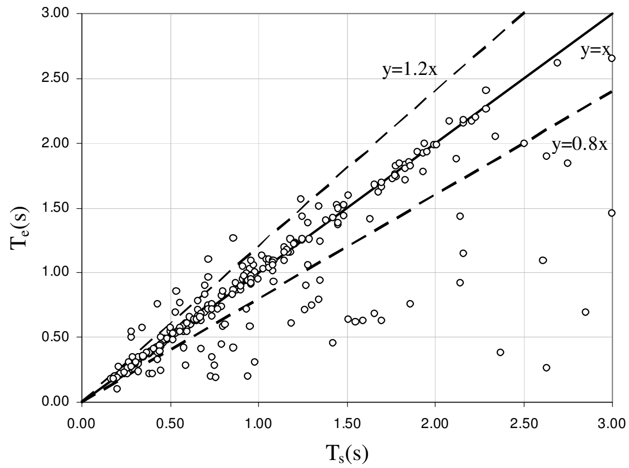

FIGURE 7. T_e vs T_s.

TABLE 3. Standard errors.

	Proposed Eq. 4	**Eq. 5**	**Eq. 6**	**T_s**
Standard Error	0.23	0.38	0.40	0.35

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