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CORRELATION FOR EARTHQUAKE-RELATED DEFORMATION OF EMBANKMENTS

Debatosh DAS[1], Raghvendra SINGH[2], and Debasis ROY[3]

ABSTRACT

Seismic design of earth dams and embankments are mainly controlled by the permanent deformation likely to be induced directly or indirectly by the design earthquake. Procedures developed by Yegian et al. (1991), Hynes-Griffin and Franklin (1984), Makdisi and Seed (1978), and Sarma (1975) are often used for estimating permanent earthquake-induced deformation of earth dams and embankments. Checking of these procedures against 122 published records on response of earth dams and embankments to earthquakes indicates that these procedures underestimate permanent deformations. Nevertheless, the observed, permanent deformations were found to relate to the ratio of yield acceleration and the peak horizontal ground acceleration. There was some scatted in the data, based on which the relationship was developed. The scatter was partially due to the variations in the ratio of the fundamental (elastic) period of the earth structure and the predominant period of earthquake ground motion, and the magnitude of the earthquake.

Keywords: Yield acceleration, peak horizontal ground acceleration, fundamental period, predominant period and average permanent deformation.

INTRODUCTION

Simple procedures and design charts are available for obtaining preliminary estimates of permanent, earthquake-induced deformation of earth dams and embankments, e.g., Yegian et al. (1991), Hynes-Griffin and Franklin (1984), Makdisi and Seed (1978), and Sarma (1975). To check their efficacy, a database of 122 published case histories has been assembled documenting performance of earth embankments and dams during past earthquakes (Table 1). The database includes earthquakes of magnitudes between 4.5 and 8.1, and peak horizontal ground accelerations between 0.02g and 0.90g. These case histories also include a wide variety of earth structures such as single zone earth embankments, multi-zone earth- and rock-fill dams, and tailings dams. Permanent earthquake-induced deformations reported in these case histories, in general, exceeded the predictions of Yegian et al. (1991), Hynes-Griffin and Franklin (1984), Makdisi and Seed (1978), and Sarma (1975).

An alternative correlation has been proposed to relate the average, earthquake-induced, permanent deformation of the embankment, D_{avg}, to the ratio of yield acceleration, a_y, and the peak horizontal ground acceleration due to earthquake at the elevation of the toe of the dam or embankment, $a_{\max}$, based on case history observations. As is well known, yield acceleration is, in essence, the horizontal

[1] Former undergraduate student, Dept. of Civil Engrg., IIT Kharagpur, WB 721302, India
[2] Ph.D Candidate, Dept. of Civil Engrg., IIT Kharagpur, WB 721302, India
[3] Asstt. Prof., Dept. of Civil Engrg., Dept. of Civil Engrg., IIT Kharagpur, WB 721302, India. E-Mail: debasis@civil.iitkgp.ernet.in

Table 1. Dam Performance Database

No.	Dam, type	Earthquake				Dist. (km)	T_D (s)	Disp. (m)		Reference
		Date	M_w	T_P (s)	a_{max} (*g*)			Horz.	Vert.	
1	Anderson, 8	10/17/89	7.0	0.32	0.260	16	1.08	0.021	0.041	Harder 1991
2		4/24/84	6.2	0.32	0.410	16	1.08	0.009	0.014	Bureau *et al*. 1985
3	Artichoke Farm, 2	10/17/89	7.1	0.32	0.330	27	0.08	*0.300*	*0.600*	Miller & Roycroft 2004
4	Austrian, 7	10/17/89	7.0	0.32	0.575	11	0.79	0.305	0.789	Harder 1991
5	Asagawara Reg., 7	10/23/04	6.8	0.32	0.120	24	0.53	0.400	0.700	Yasuda *et al.* 2005
6	Baihe, 7	7/28/76	7.8	0.52	0.200	150	0.89	7.000	2.500	Lingyao 1980
7	Brea, 7	1/17/94	6.9	0.45	0.190	67	0.76	0.001	0.001	Abdel-Ghaffar & Scott 1980
8	Chabbot, 5	4/18/06	8.3	0.32	0.570	32	0.99	0.225	0.450	Makdisi & Seed 1978
9		10/17/89	7.0	0.32	0.100	60	0.99	0.001	0.001	
10	Chang, 7	1/26/01	7.6	0.32	0.500	13	0.25	*6.070*	*2.640*	Singh *et al.* 2005
11	Chofukuji, 7	10/23/04	6.8	0.32	0.100	21	0.38	0.050	0.070	Yasuda *et al.* 2005
12	Chonan, 4	12/17/87	6.7	0.32	0.120	40	0.11	*11.56*	*3.87*	Ishihara *et al*. 1990
13	Cogoti, 9	4/4/43	7.9	0.6	0.190	89	0.83	0.000	0.350	Arrau *et al*.1985
14		3/28/65	7.1	0.55	0.040	153	0.83	0.001	0.001	
15		7/8/75	7.5	0.57	0.050	165	0.83	0.001	0.001	
16		3/8/85	7.7	0.96	0.030	280	0.83	0.001	0.001	
17	Cogswell, 9	10/1/87	6.0	0.25	0.060	29	0.69	0.001	0.001	Boulanger *et al.* 1995
18		6/28/91	5.6	0.25	0.260	4	0.69	0.041	0.016	
19	Demi1, 7	1/26/01	7.6	0.55	0.200	90	0.23	0.100	0.050	Krinitzsky & Hynes 2002
20	Douhe, 4	7/28/76	7.8	0.3	0.900	20	0.22	0.510	1.640	Yan 1991
21	El Cobre, 12	3/28/65	7.2	0.32	0.800	40	0.49	*280.0*	*32.0*	Dobry & Alvarez 1967
22	El Infiernillo D/S, 8	3/14/79	7.6	0.55	0.230	110	1.58	0.034	0.046	Resendiz *et al.* 1982
23	El Infiernillo U/S, 8	3/14/79	7.6	0.55	0.230	110	1.58	0.044	0.128	
24		9/19/89	8.1	0.7	0.200	113	1.58	0.025	0.049	
25		9/21/89	7.2	0.56	0.120	116	1.58	0.033	0.065	
26	El Khattabi, 10	2/24/04	6.4	0.25	0.250	21	0.37	0.010	0.010	EERI 2004
27	Chesbro, 7	10/17/89	7.0	0.32	0.425	13	0.46	0.015	0.113	Harder 1991
28	Fatehgadh, 7	1/26/01	7.6	0.55	0.300	80	0.28	*2.230*	*1.030*	Singh *et al.* 2005
29	Gongen, 8	1/17/95	8.2	0.32	0.107	28	0.4	0.001	0.001	Matsumoto *et al.* 1996
30	Guadalupe, 7	10/17/89	7.0	0.32	0.425	19	0.68	0.045	0.195	Harder 1991
31	Guldurek, 7	6/6/00	5.9	0.27	0.125	19	0.91	0.010	0.020	Ozkan & Aksar 2005
32	Hachiro Gata, 4	5/26/83	7.7	0.6	0.168	95	0.08	*12.23*	*2.54*	Olson 2001
33	Hawkins, 6	10/17/89	7.0	0.32	0.225	34	0.15	0.001	0.001	Harder 1991
34	Hebgen, 7	8/17/59	7.5	0.65	0.700	100	0.47	*5.760*	*1.920*	Seed *et al.* 1978
35	Hokkaido Tailings, 12	5/16/68	7.9	0.6	0.225	180	0.14	*41.10*	*12.50*	Ishihara *et al*.1990
36	Industrial, 2	10/17/89	7.1	0.32	0.330	18	0.12	*0.001*	*0.400*	Miller & Roycroft 2004

Table 1. Continued.

No.	Dam, type	Earthquake				Dist. (km)	T_D (s)	Disp. (m)		Reference
		Date	M_w	T_P (s)	a_{max} (g)			Horz.	Vert.	
37	Ishibuchi, 9	5/26/03	7.1	0.42	0.270	85	0.63	0.001	0.001	Nagayama *et al.* 2004
38	Kalaghoda, 7	1/26/01	7.6	0.47	0.300	65	0.18	0.050	0.025	Krinitzsky & Hynes 2002
39	Kalpong, 9	9/14/02	6.5	0.27	0.100	21	0.35	0.001	0.001	Rai & Murty 2004
40	Kanayatani, 10	10/6/00	7.3	0.32	0.110	14	0.05	1.000	0.750	Matsuo 2000
41	Kashi, 7	8/23/85	7.4	0.32	0.250	21	0.25	0.300	0.400	Chonggang 1988
42		9/12/85	6.8	0.3	0.500	16	0.25	1.000	1.500	
43	Kaswati, 7	1/26/01	7.6	0.6	0.280	110	0.33	*2.400*	*1.210*	Singh *et al.* 2005
44	Kawanishi, 7	10/23/04	6.8	0.32	0.140	17	0.59	0.300	0.300	Yasuda *et al.* 2005
45	Kitayama, 7	1/17/95	7.1	0.32	0.300	31	0.34	0.750	0.750	Sakamoto *et al.* 2002
46	Kodanuma, 4	5/16/68	7.9	0.27	0.225		0.05	*12.36*	*1.290*	Mishima & Kimura 1970
47	Kushiro Dk., 1	1/15/93	7.8	0.32	0.200	19	0.11	*3.000*	*2.000*	Sasaki *et al.* 1995
48	La Marque-sa, 7	3/3/85	7.8	0.4	0.670	45	0.11	*7.900*	*2.050*	de Alba *et al*. 1988
49	La Palma, 7	3/3/85	7.8	0.38	0.460	80	0.12	*1.830*	*0.610*	
50	La Villita, 8	11/15/75	5.9	0.25	0.084	10	0.94	0.012	0.024	Elgamal *et al*. 1990
51		10/11/75	4.9	0.27	0.148	52	0.94	0.012	0.024	
52		3/14/79	7.6	0.55	0.100	11	0.94	0.012	0.013	
53		10/25/81	7.3	0.6	0.174	121	0.94	0.024	0.114	
54		9/19/85	8.1	0.48	0.240	58	0.94	0.102	0.336	
55	Lake Merced, 4	3/22/57	5.3	0.32	0.120	5	0.27	*25.90*	*6.66*	Olson 2001
56	Lexington, 7	10/17/89	7.0	0.32	0.450	10	0.77	0.075	0.259	Harder 1991
57	Long Valley, 7	5/27/80	6.1	0.25	0.200	16	0.52	0.001	0.001	Lai *et al*. 1985
58	Lower Van Norman, 7	2/9/71	6.6	0.27	0.600	13	0.38	0.001	0.144	Chaney 1979
59	Lower San Fernando, 6	2/9/71	6.6	0.27	0.450	8	0.48	*17.36*	*7.95*	Seed *et al.* 1975
60		1/17/94	6.9	0.32	0.320	11	0.48	*0.150*	*0.150*	Bardet & Davis 1986
61	LA Dam, 7	1/17/94	6.9	0.32	0.430	7	0.6	0.024	0.088	Seed *et al.* 1978
62	Makubetsu, 7	9/26/03	8.0	0.5	0.251	141	0.42	0.700	0.500	Nagayama *et al.* 2004
63	Matahina, 8	3/2/87	6.5	0.28	0.241	11	1.08	0.250	0.099	Pender & Robertson 1987
64	May 1 Slide, 11	1/23/89	5.5	0.25	0.150	3	0.37	*18.04*	*5.92*	Ishihara *et al*. 1990
65	Metoki, 4	5/16/68	7.9	0.32	0.225	180	0.14	*32.00*	*5.00*	
66	Miboro, 8	8/19/61	7.0	0.32	0.150	16	1.43	0.052	0.026	Bureau *et al.* 1985
67	Miho, 8	1/29/80	6.6	0.33	0.031	57	1.22	0.001	0.001	Iwashita *et al.* 1995
68		4/14/81	4.5	0.32	0.032	13	1.22	0.001	0.001	
69		8/8/83	6.0	0.25	0.152	12	1.22	0.001	0.001	
70		12/17/87	6.6	0.6	0.011	131	1.22	0.001	0.001	

Table 1. Continued.

No.	Dam, type	Earthquake				Dist (km)	T_D (s)	Disp. (m)		Reference
		Date	M_w	T_P (s)	a_{max} (g)			Horz.	Vert.	
71	Miho, 8	8/5/90	5.1	0.25	0.028	24	1.22	0.001	0.001	Iwashita *et al.* 1995
72		2/2/92	5.7	0.32	0.012	73	1.22	0.001	0.001	
73	Mill Crk., 6	10/17/89	7.0	0.32	0.275	29	0.3	0.007	0.015	Harder 1991
74	Minoogawa, 8	1/17/95	7.1	0.34	0.135	48	0.57	0.001	0.001	Matsumoto *et al.* 1996
75	Mochikoshi 1, 12	1/14/78	7.0	0.32	0.250	8	0.42	*122.5*	*22.75*	Okusa & Anma 1980
76	Mochikoshi 2, 12	1/14/78	7.0	0.32	0.250	8	0.42	*64.70*	*15.90*	
77	Murayama, 7	9/1/23	8.2	0.6	0.800	96	0.52	1.800	1.200	Seed *et al.* 1978
78	Nalband, 4	12/7/88	6.8	0.32	0.750	28	0.24	*2.000*	*3.000*	Yegian *et al.* 1994
79	Newell, 8	10/17/89	7.0	0.32	0.425	10	0.75	0.230	0.011	Harder 1991
80	Niteko L., 3	1/17/95	6.9	0.32	0.400	4	0.21	*0.00*	*2.00*	EERC 1995
81	Niteko M., 3	1/17/95	6.9	0.32	0.400	4	0.17	*22.00*	*2.70*	
82	Niteko U., 3	1/17/95	6.9	0.32	0.400	4	0.17	*22.00*	*2.70*	
83	Niwa Ikum-ine, 7	7/12/93	7.8	0.36	0.280	71	0.23	*0.00*	*1.75*	Tani 1995
84	O' Neil, 3	10/17/89	7.0	0.33	0.110	59	0.37	0.001	0.001	Harder 1991
85	Ono, 7	9/1/23	8.2	0.6	0.800	96	0.52	0.244	0.305	Seed *et al.* 1978
86	Oya, 8	12/8/93	5.0	0.26	0.004	42	0.51	0.001	0.001	Iwashita *et al.* 1995
87		2/16/93	5.0	0.25	0.010	28	0.51	0.001	0.001	
88		2/2/93	4.8	0.25	0.015	9	0.51	0.001	0.001	
89		2/7/93	6.5	0.28	0.067	31	0.51	0.001	0.001	
90		2/8/93	4.9	0.25	0.007	37	0.51	0.001	0.001	
91		6/7/94	4.9	0.25	0.005	40	0.51	0.001	0.001	
92	Oroville, 7	8/1/75	6.0	0.25	0.110	7	2.74	0.001	0.007	Bureau *et al.* 1985
93	Route 272, 4	1/15/93	7.8	0.4	0.380	20	0.13	*26.60*	*5.25*	Miura *et al.* 1995
94	Rudramata, 7	1/26/01	7.6	0.55	0.300	80	0.28	*4.33*	*0.83*	Singh *et al.* 2005
95	San Justo, 8	10/17/89	7.0	0.32	0.260	27	0.51	0.001	0.001	Harder 1991
96	San Luis, 3	10/17/89	7.0	0.33	0.060	54	1.32	0.001	0.001	Harder 1991
97	Sasoi, 7	1/26/01	7.6	0.63	0.200	120	0.27	*0.090*	*0.025*	Krinitzsky & Hynes 2002
98	Shibecha cho, 4	1/15/93	7.8	0.4	0.380	40	0.16	*30.70*	*9.26*	Miura *et al.* 1995
99	Shin Yama-moto Reg, 8	10/23/04	6.8	0.32	0.550	6	0.56	0.020	0.020	Yasuda *et al.* 2005
100	S-T Dk. 1, 1	7/12/93	7.8	0.6	0.184	100	0.09	*5.40*	*2.70*	Ozutsumi *et al.* 2002
101	S-T Dk. 2, 1	7/12/93	7.8	0.6	0.184	100	0.07	*2.40*	*1.26*	
102	S-T Dk. 3, 1	7/12/93	7.8	0.6	0.184	100	0.07	*1.20*	*0.63*	
103	Shivlakha, 7	1/26/01	7.6	0.32	0.450	28	0.26	*3.18*	*1.62*	Singh *et al.* 2005
104	Soda Lake, 13	10/17/89	7.0	0.32	0.325	29	0.19	0.001	0.600	Harder 1991
105	Solfatara, 1	5/18/40	7.1	0.32	0.330	19	0.05	*11.00*	*2.00*	Olson 2001

Table 1. Continued.

No.	Dam, type	Earthquake				Dist (km)	T_D (s)	Disp. (m)		Reference
		Date	M_w	T_P (s)	a_{max} (g)			Horz.	Vert.	
106	South side Levee, 2	10/17/89	7.1	0.32	0.330	18	0.12	*0.001*	*0.500*	Miller & Roycroft 2003
107	Surajbari, 4	1/26/01	7.6	0.32	0.350	40	0.12	*1.00*	*0.30*	EERI 2001
108	Surgu, 8	5/5/86	6.6	0.32	0.210	10	0.72	0.001	0.150	Ozkan *et al.* 1996
109	Suvi, 7	1/26/01	7.6	0.32	0.420	37	0.24	*4.00*	*1.10*	Singh *et al.* 2005
110	Takami, 8	9/26/03	8.0	0.5	0.325	140	1.31	0.001	0.001	Nagayama *et al.* 2004
111	Tapar, 7	1/26/01	7.6	0.32	0.150	43	0.21	*0.500*	*0.800*	Singh *et al.* 2005
112	Tokachi R. Dike Right Bank, 1	9/27/03	8.1	0.7	0.400	125	0.09	*3.65*	*2.00*	Okamura 2003
113	Tokiwa, 7	1/17/95	7.1	0.32	0.200	10	0.49	0.001	0.001	Matsumoto *et al.* 1996
114	Torishima Dike 1, 1	1/17/95	6.9	0.32	0.224	40	0.15	*3.50*	*3.00*	Ozutsumi *et al.* 2002
115	Torishima Dike 2, 1	1/17/95	6.9	0.32	0.224	40	0.14	*0.90*	*0.30*	
116	Tsuboyama , 7	10/23/04	6.8	0.32	0.130	19	0.29	0.070	0.070	Yasuda *et al.* 2005
117	Upper San Fernando, 6	2/9/71	6.6	0.32	0.450	11	0.38	*1.50*	*0.90*	Seed *et al*. 1975
118		1/17/94	6.7	0.27	0.320	11	0.46	*0.200*	*0.150*	Bardet & Davis 1986
119	Vasona, 7	10/17/89	7.0	0.32	0.400	9	0.19	0.027	0.050	Harder 1991
120	Waste Wat. Trt. Plnt., 2	10/17/89	7.1	0.32	0.330	23	0.08	*0.001*	*0.020*	Miller & Roycroft 2004
121	Yamamoto Reg., 7	10/23/04	6.8	0.32	0.550	7	0.38	0.50	0.50	Yasuda *et al.* 2005
122	Yumig., 4	10/6/00	7.3	0.32	0.300	20	0.13	*1.50*	*1.00*	Matsuo 2000

Notes.
1. Dam types: 1 = 1-zone levee, 2 = Multi zone levee, 3 = 1-zone earth dam, 4 = 1-zone embankment, 5 = 1-zone hydraulic fill dam, 6 = Multi zone hydraulic fill, 7 = Compacted multi zone dam, 8 = Multi zone rock fill dam, 9 = Concrete faced rock fill dam, 10 = Concrete faced decomposed granite or gravel dam, 11 = Natural slope, 12 = Upstream constructed tailings dam, 13 = Downstream constructed tailings dam.
2. Displacements in italics indicate cases involving liquefaction

seismic coefficient needed for a factor of safety of unity in pseudo static limit equilibrium slope stability analysis of the dam or embankment. An attempt has also been made to explain the scatter in the data, based on which the proposed $D_{avg} - a_y / a_{\max}$ relationship is developed.

DATA REDUCTION

A brief summery of the procedures for data analysis and parameter estimation is as follows.

Peak Ground Acceleration

Accelerograms are available from pre-existing instruments downstream of the toe of the dams at a few sites. Peak horizontal ground accelerations were obtained directly from the records of these instruments. In other cases, earthquake-specific attenuation relationships were used for estimating the peak horizontal ground accelerations.

Yield Acceleration

The yield acceleration is estimated from pseudo static slope stability analyses using software package XSTABL (version 5.1) and the Simplified Bishop method. Shear strength and other input parameters for these analyses were estimated as discussed below.

Estimation of Input Parameters

The undrained shear strength and unit weights of soils within and underneath the embankment or dam body were estimated from site-specific Standard Penetration Test (SPT) or Cone Penetration Test (CPT) data for most of the case histories analyzed in this study. However, in a few case histories site-specific SPT or CPT data were not available. In the analyses of these case histories, generic properties were used for the dam or embankment material and foundation soils or rocks. The pre- and post- liquefaction shear strengths were estimated following Olson (2001) for soils characterized with normalized SPT blow count, $(N_1)_{60}$, of up to 12 or normalized cone tip resistance, q_{c1}, of up to 6.5 MPa. For soils characterized with higher values of $(N_1)_{60}$ or q_{c1}, the shear strength was estimated following McGregor and Duncan (1998).

Observed Earthquake-Induced Deformation

For estimating the average, observed earthquake-induced, permanent deformation, D_{avg}, the displacement vector representative of the soil mass that participated in the downslope movement was first estimated. The average deformation was assumed to be the dot product of this displacement vector and the vector aligned along the average inclination of the base of the sliding surface.

Fundamental Elastic Period of Embankment

In only a few case histories, the fundamental elastic period of the dam could be directly obtained from available recordings from small earthquakes from instruments installed at dam crest. Otherwise, the fundamental elastic periods of the dam or embankment were estimated following Gazetas and Dakoulas (1991). Generic values of shear wave velocities representative of the material used in the construction of the dam or embankment were used in these estimations. The geometry of valley was assumed to be between “narrow trapezium” and “wide trapezium” for earth structures other than highway or railway embankments, river dikes and tailings dams. The fundamental elastic periods of highway or railway embankments, river dikes and tailings dams were estimated assuming these structures to be infinitely long.

Predominant Period of Earthquake Ground Motion

In only a few case histories, the predominant period, T_P, of earthquake ground motion could be directly obtained from available recordings from instruments installed downstream of the toe or the abutment of the dam. In other cases, earthquake predominant periods were estimated following Idriss (1991).

COMPARISON BETBEEN OBSERVED AND PREDICTED DEFORMATIONS

Permanent earthquake-induced deformations obtained from semi-empirical procedures developed by Yegian et al. (1991), Makdisi and Seed (1978), Sarma (1975) and the upper bound relationship of Hynes-Griffin and Franklin (1984) were compared with D_{avg} obtained from case history observations (Figure 1). The comparison indicates that the permanent deformations obtained from Yegian et al. (1991), Makdisi and Seed (1978), and Sarma (1975) underestimated observed permanent deformations for 82 to 92 percent of the case histories. The corresponding figure for the Hynes-Griffin and Franklin (1984) upper bound relationship was 67 percent.

It is therefore apparent that the existing procedures for estimating earthquake-induced, permanent deformations of dams and embankments were found to underestimate the observed deformations, although the performance of the Hynes-Griffin and Franklin (1984) upper bound relationship was better in comparison with other available procedures in this regard. The fact that the semi-empirical procedures evaluated here are based on rigid-plastic material behavior is likely to be the main reason for the general underestimation of deformation for dams and embankments constructed mainly from flexible soil and rock fill materials.

Arguably, the procedures examined here are, strictly speaking, not applicable to cases involving liquefaction. However, as is apparent from the results presented in Figure 1, removal of case histories involving limited or significant extents of liquefaction from the database of dam performance case histories before making the comparison does not appear to improve the performance of any of the procedures being examined.

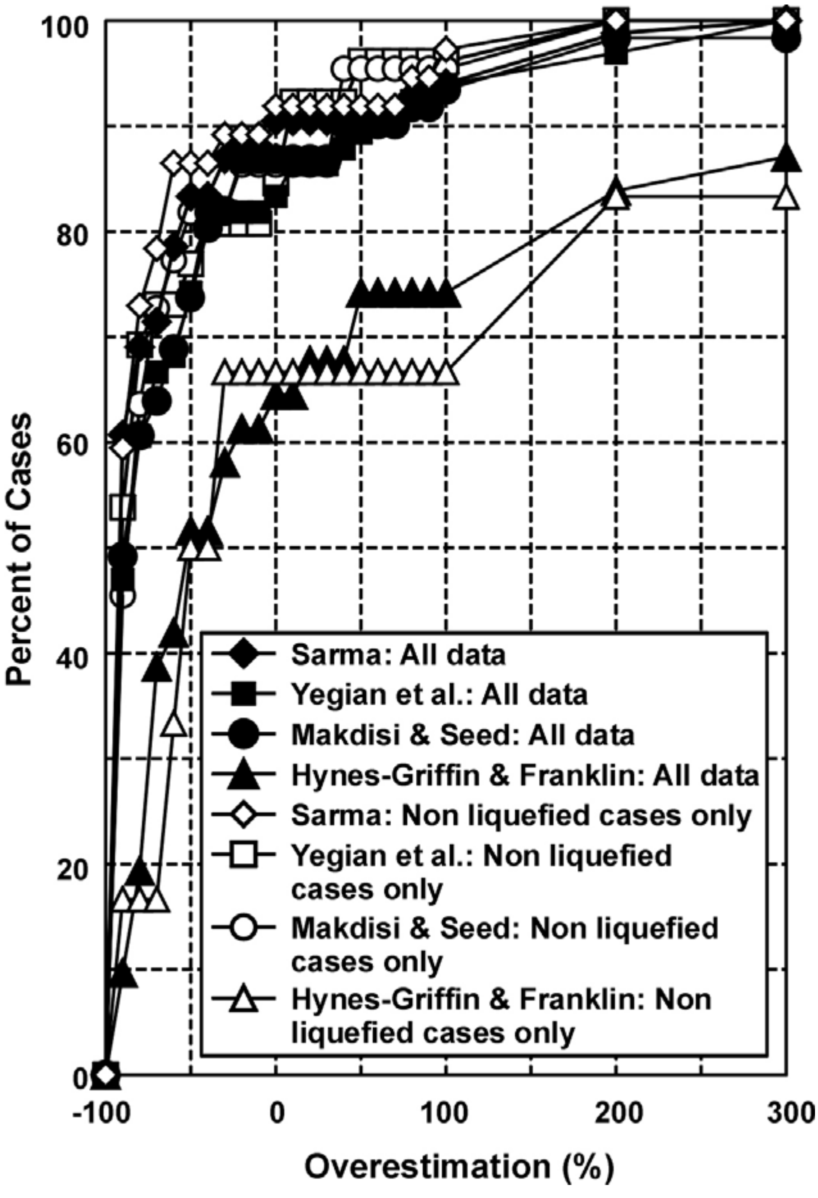

Figure 1. Comparison of Observed and Predicted Deformations

A CORRELATION FOR D_{avg} BASED ON CASE HISTORY OBSERVATIONS

As is apparent from the previous section, existing semi-empirical procedures for estimation of earthquake-induced, permanent deformation of dams and embankments by and large underestimate observed deformations. Here we attempt to develop alternative correlations for estimating D_{avg} purely on observations from the case history database assembled in this study.

Figure 2 shows a plot between D_{avg} and $a_y/a_{\max}$. In this figure, the symbols representing individual case histories are marked with numerals for cross-referencing against the case history serial number entered in the first column of Table 1. A non-linear relationship between the logarithms of D_{avg} and $a_y/a_{\max}$ apparent from these data is shown on Figure 2 ($r^2 = 0.73$). An "upper bound" relationship representing 80% prediction limit is also included on Figure 2 for possible use in relatively critical projects. Data with $a_y/a_{\max} \geq 4$ were not considered while developing these correlations.

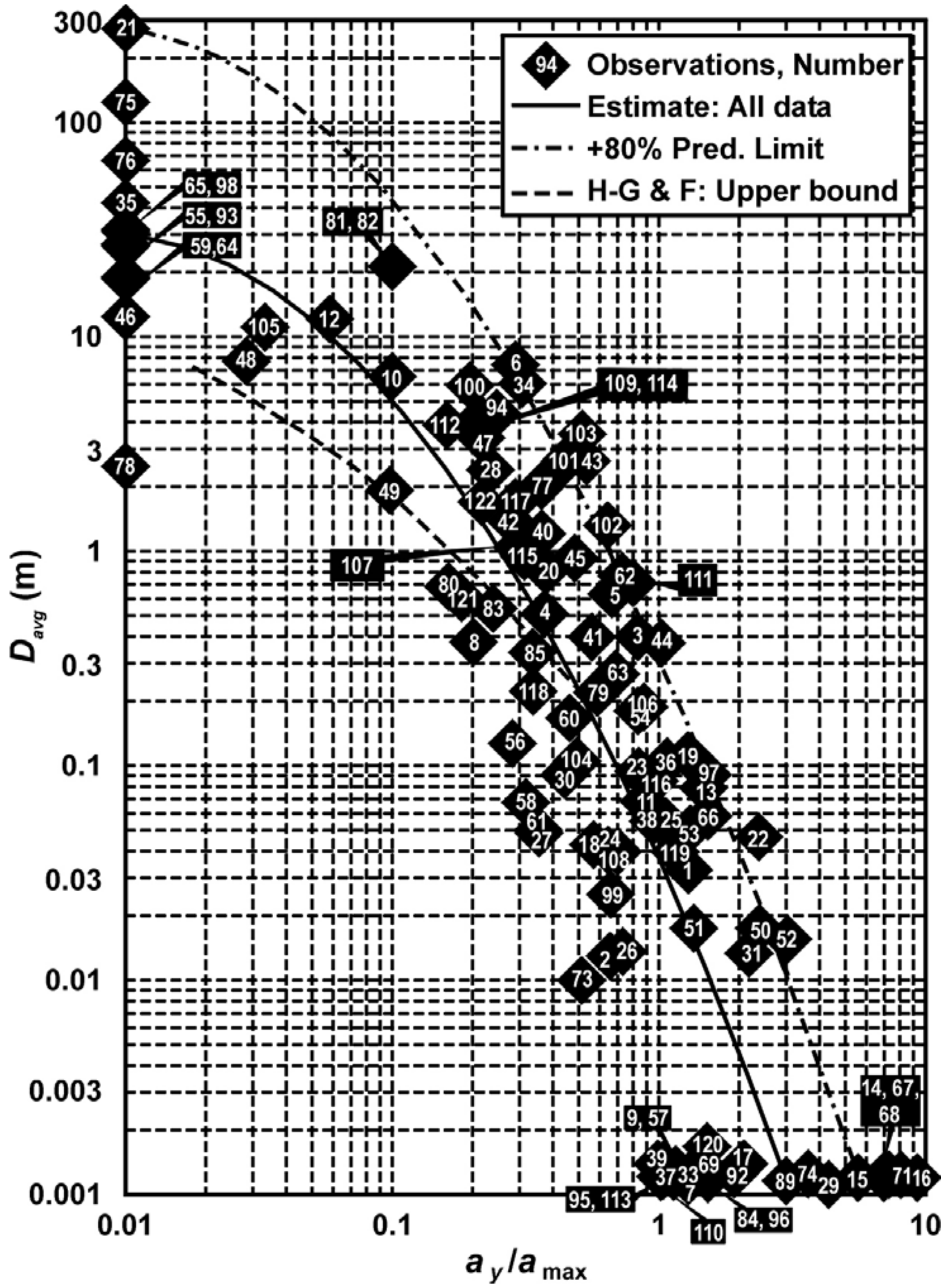

Figure 2. Observed Displacements and Proposed Correlations

(Note: Labeling on the symbols represents case history number found on column 1 of Table 1)

For comparison, the upper bound relationship of Hynes-Griffin and Franklin (1984) is plotted in Figure 2 using dashed line. The fact that Hynes-Griffin and Franklin (1984) upper bound relationship underestimates the observed deformation is apparent from this comparison once again.

FACTORS AFFECTING PROPOSED CORRELATION FOR D_{avg}

There is some scatter in the $D_{avg} - a_y/a_{\max}$ data. Possible causes for this scatter are explored here. Figure 3a presents a bar chart showing the variation of mean D_{avg} with T_D/T_P. A strong influence of T_D/T_P on mean D_{avg} is apparent from these data. Specifically, these data indicate that D_{avg} becomes considerably smaller as T_D/T_P exceeds 1. Figure 3b presents a bar chart showing the variation of mean D_{avg} with M_W. It appears from these data that mean D_{avg} increases somewhat with M_W. For preparing Figure 3, we only considered non-failure cases with $a_y/a_{\max} > 0.01$.

The imprecision in the correlations used for estimating soil properties used in the slope stability computations and the estimates of peak horizontal ground acceleration at the location of dams and embankments, and the fact that the vertical accelerations were neglected in the analyses also likely to have contributed to the scatter in the $D_{avg} - a_y/a_{\max}$ data.

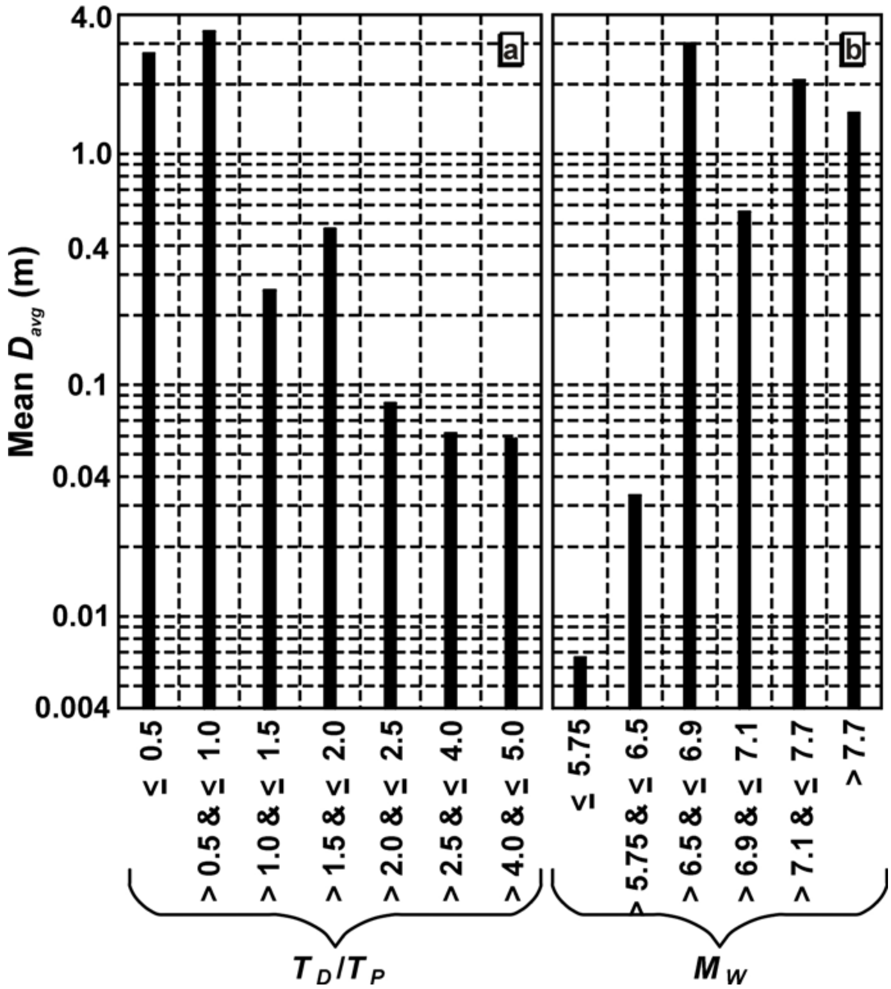

Figure 3. Influence of T_D/T_P and M_W on D_{avg}

CONCLUSIONS

In this study, 122 published case histories documenting response of earth dams and embankments to earthquakes were examined to check the efficacy of a number of commonly used procedures used by geotechnical engineers for estimating earthquake-induced, permanent deformations of dams and embankments. Comparison of the deformations calculated from the procedures developed by Yegian et al. (1991), Hynes-Griffin and Franklin (1984), Makdisi and Seed (1978) and Sarma (1975) with the observed magnitudes of earthquake-induced, permanent deformations indicated that these procedures underestimate the deformation.

The observed, permanent deformations were found to relate to the ratio of yield acceleration and the peak horizontal ground acceleration. A correlation between the earthquake-induced, permanent deformation of dams and embankments has been proposed based on observations from the case history database assembled in this study.

There is some scatter in the $D_{avg} - a_y / a_{\max}$ data, based on which the correlation was developed. The scatter appears to be partially due to the variation in the ratio of the fundamental period of the dam or embankment and the predominant period of the earthquake ground motion and the magnitude of the earthquake.

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