AmericanLifelines**Alliance**

A public-private partnership to reduce risk to utility and transportation systems from natural hazards

Seismic Fragility Formulations for Water Systems

Part 2 – Appendices

April 2001

www.americanlifelinesalliance.org

This report was written under contract to the American Lifelines Alliance, a public-private partnership between the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers (ASCE). The report was reviewed by a team representing practicing engineers, academics and water utilit personnel.

Table of Contents

List of Figures

List of Tables

A. Commentary - Pipelines

A.1 Buried Pipeline Empirical Data

Section 4 of the main report provides descriptions and references for empirical damage to buried pipelines from various earthquakes.

Table A.1-1 provides 164 references to damage to buried pipelines from various earthquakes. The references listed in Table A.1-1 are provided in Section 4.8 of the main report.

Depending upon source, some entries in Table A.1-1 represent duplicated data. Also, some data in Table A.1-1 include damage to service laterals up to the customer meter, whereas some data points do not. Also, some data points in Table A.1-1 are based on PGA, some on PGV and some of MMI. Some data points in Table A.1-1 exclude damage for pipes with uncertain attributes. For those data points based on PGA or PGV, some are based on attenuation models which predict median level horizontal motions and some are based on the maximum of two orthogonal horizontal recordings from a nearby instrument.

Table A.1-2 presents the same dataset as in Table A.1-1, but normalized to try to make all data points represent the following condition: damage to main pipes, excluding damage to service laterals up to the utility meter versus median PGV or the average of two horizontal directions.

Table A.1-3 presents damage data for buried pipelines subjected to some form of permanent ground deformations, including liquefaction and ground lurching.

ID	Earthquake	Material Type	Size	Length	Repairs	Rate	Demand	Comment	Source
1001	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.031	PGA = 0.211	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1002	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.207	PGA = 0.306	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1003	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.047	PGA = 0.478	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1004	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.057	PGA = 0.572	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1005	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.227	PGA = 0.595	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1006	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.227	PGA = 0.677	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1007	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.062	PGA = 0.710	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1008	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.202	PGA = 0.792	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1009	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.522	PGA = 0.819	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1010	1995 Hyogoken-nanbu	MX	DS	NR	NR	0.098	PGA = 0.834	Includes DI & CI from 1011 to 1029	Shirozu et al, 1996 (Fig. 15)
1011	1995 Hyogoken-nanbu	DI	DS	NR	NR	0.092	PGA = 0.306		Shirozu et al, 1996 (Fig. 16a)
1012	1995 Hyogoken-nanbu	DI	DS	NR	NR	0.016	PGA = 0.478		Shirozu et al, 1996 (Fig. 16a)
1013	1995 Hyogoken-nanbu	DI	DS	NR	NR	0.02	PGA = 0.572		Shirozu et al, 1996 (Fig. 16a)
1014	1995 Hyogoken-nanbu	DI	DS	NR	NR	0.14	PGA = 0.595		Shirozu et al, 1996 (Fig. 16a)
1015	1995 Hyogoken-nanbu	DI	DS	NR	NR	0.149	PGA = 0.677		Shirozu et al, 1996 (Fig. 16a)
1016	1995 Hyogoken-nanbu	DI	DS	NR	NR	0.027	PGA = 0.710		Shirozu et al, 1996 (Fig. 16a)
1017	1995 Hyogoken-nanbu	DI	DS	NR	NR	0.054	PGA = 0.792		Shirozu et al, 1996 (Fig. 16a)
1018	1995 Hyogoken-nanbu	DI	DS	NR	NR	0.2	PGA = 0.819		Shirozu et al, 1996 (Fig. 16a)
1019	1995 Hyogoken-nanbu	DI	DS	NR	NR	0.065	PGA = 0.834		Shirozu et al, 1996 (Fig. 16a)
1020	1995 Hyogoken-nanbu	CI	DS	NR	NR	0.099	PGA = 0.211		Shirozu et al, 1996 (Fig. 16b)
1021	1995 Hyogoken-nanbu	CI	DS	NR	NR	0.288	PGA = 0.306		Shirozu et al, 1996 (Fig. 16b)
1022	1995 Hyogoken-nanbu	CI	DS	NR	NR	0.252	PGA = 0.478		Shirozu et al, 1996 (Fig. 16b)
1023	1995 Hyogoken-nanbu	CI	DS	NR	NR	0.171	PGA = 0.572		Shirozu et al, 1996 (Fig. 16b)
1024	1995 Hyogoken-nanbu	CI	DS	NR	NR	0.585	PGA = 0.595		Shirozu et al, 1996 (Fig. 16b)
1025	1995 Hyogoken-nanbu	CI	DS	NR	NR	0.441	PGA = 0.677		Shirozu et al, 1996 (Fig. 16b)
1026	1995 Hyogoken-nanbu	CI	DS	NR	NR	0.099	PGA = 0.710		Shirozu et al, 1996 (Fig. 16b)
1027	1995 Hyogoken-nanbu	CI	DS	NR	NR	1.098	PGA = 0.792		Shirozu et al, 1996 (Fig. 16b)
1028	1995 Hyogoken-nanbu	CI	DS	NR	NR	1.458	PGA = 0.819		Shirozu et al, 1996 (Fig. 16b)
1029	1995 Hyogoken-nanbu	CI	DS	NR	NR	0.189	PGA = 0.834		Shirozu et al, 1996 (Fig. 16b)
1030	1994 Northridge	DI	DS	16.1	2	0.0236	PGV = 47.2	LADWP	ALA Report Table 4-10
1031	1994 Northridge	DI	DS	14.4	1	0.0131	PGV = 35.8	LADWP	ALA Report Table 4-10
1032	1994 Northridge	DI	DS	13.4	2	0.0283	PGV = 29.3	LADWP	ALA Report Table 4-10

ID	Earthquake	Material Type	Size	Length	Repairs	Rate	Demand	Comment	Source
1033	1994 Northridge	DI	DS	12.8	6	0.0887	PGV = 22.8	LADWP	ALA Report Table 4-10
1034	1994 Northridge	DI	DS	11.3	1	0.0167	PGV = 17.9	LADWP	ALA Report Table 4-10
1035	1994 Northridge	DI	DS	20.1	3	0.0282	PGV = 14.6	LADWP	ALA Report Table 4-10
1036	1994 Northridge	DI	DS	25.2	2	0.015	PGV = 11.4	LADWP	ALA Report Table 4-10
1037	1994 Northridge	DI	DS	57.9	6	0.0196	PGV = 8.1	LADWP	ALA Report Table 4-10
1038	1994 Northridge	DI	DS	72.9	1	0.0026	PGV = 4.9	LADWP	ALA Report Table 4-10
1039	1994 Northridge	DI	DS	26.4	0	0	PGV = 1.6	LADWP	ALA Report Table 4-10
1040	1994 Northridge	AC	DS	15.8	0	0	PGV = 35.8	LADWP	ALA Report Table 4-9
1041	1994 Northridge	AC	DS	13.4	0	0	PGV = 29.3	LADWP	ALA Report Table 4-9
1042	1994 Northridge	AC	DS	15.2	7	0.0873	PGV = 21.1	LADWP	ALA Report Table 4-9
1043	1994 Northridge	AC	DS	21.3	0	0	PGV = 17.9	LADWP	ALA Report Table 4-9
1044	1994 Northridge	AC	DS	23.6	0	0	PGV = 14.6	LADWP	ALA Report Table 4-9
1045	1994 Northridge	AC	DS	73.6	2	0.0051	PGV = 11.4	LADWP	ALA Report Table 4-9
1046	1994 Northridge	AC	DS	147.2	15	0.0193	PGV = 8.1	LADWP	ALA Report Table 4-9
1047	1994 Northridge	AC	DS	192.4	2	0.002	PGV = 4.9	LADWP	ALA Report Table 4-9
1048	1994 Northridge	AC	DS	98.3	0	0	PGV = 1.6	LADWP	ALA Report Table 4-9
1049	1994 Northridge	CI	DS	78.9	60	0.1441	PGV = 52.1	LADWP	ALA Report Table 4-8
1050	1994 Northridge	CI	DS	84.8	11	0.0246	PGV = 45.6	LADWP	ALA Report Table 4-8
1051	1994 Northridge	CI	DS	101.8	11	0.0205	PGV = 39.0	LADWP	ALA Report Table 4-8
1052	1994 Northridge	CI	DS	117.6	4	0.0064	PGV = 32.5	LADWP	ALA Report Table 4-8
1053	1994 Northridge	CI	DS	87.6	24	0.054	PGV = 27.7	LADWP	ALA Report Table 4-8
1054	1994 Northridge	CI	DS	111.7	39	0.0662	PGV = 24.4	LADWP	ALA Report Table 4-8
1055	1994 Northridge	CI	DS	222.7	87	0.0739	PGV = 21.1	LADWP	ALA Report Table 4-8
1056	1994 Northridge	CI	DS	313.9	56	0.0337	PGV = 17.9	LADWP	ALA Report Table 4-8
1057	1994 Northridge	CI	DS	503.1	59	0.0221	PGV = 14.6	LADWP	ALA Report Table 4-8
1058	1994 Northridge	CI	DS	699.7	111	0.03	PGV = 11.4	LADWP	ALA Report Table 4-8
1059	1994 Northridge	CI	DS	1370.7	166	0.023	PGV = 8.1	LADWP	ALA Report Table 4-8
1060	1994 Northridge	CI	DS	1055.8	44	0.0079	PGV = 4.9	LADWP	ALA Report Table 4-8
1061	1994 Northridge	CI	DS	156.8	0	0	PGV = 1.6	LADWP	ALA Report Table 4-8
1062	1994 Northridge	CP	LG	NR	NR	0.102	PGV = 50.7	Trunk lines	Toprak, 1998 (Fig. 6-30)
1063	1994 Northridge	S	LG	NR	NR	0.0839	PGV = 54.3	Trunk lines	Toprak, 1998 (Fig. 6-30)
1064	1994 Northridge	S	LG	NR	NR	0.0396	PGV = 33.2	Trunk lines	Toprak, 1998 (Fig. 6-30)

ID	Earthquake	Material Type	Size	Length	Repairs	Rate	Demand	Comment	Source
1065	1994 Northridge	S	LG	NR	NR	0.0092	PGV = 19.8	Trunk lines	Toprak, 1998 (Fig. 6-30)
1066	1994 Northridge	S	LG	NR	NR	0.0031	PGV = 13.7	Trunk lines	Toprak, 1998 (Fig. 6-30)
1067	1994 Northridge	S	LG	NR	NR	0.0031	PGV = 9.7	Trunk lines	Toprak, 1998 (Fig. 6-30)
1068	1994 Northridge	AC	DS	NR	NR	0.0183	PGV = 9.8		Toprak, 1998 (Fig. 6-24)
1069	1994 Northridge	AC	DS	NR	NR	0.0031	PGV = 5.9		Toprak, 1998 (Fig. 6-24)
1070	1994 Northridge	DI	DS	NR	NR	0.0122	PGV = 12.5		Toprak, 1998 (Fig. 6-24)
1071	1994 Northridge	S	DS	NR	NR	0.0854	PGV = 21.5		Toprak, 1998 (Fig. 6-25)
1072	1994 Northridge	S	DS	NR	NR	0.0488	PGV = 13.8		Toprak, 1998 (Fig. 6-25)
1073	1994 Northridge	S	DS	NR	NR	0.0549	PGV = 9.9		Toprak, 1998 (Fig. 6-25)
1074	1994 Northridge	S	DS	NR	NR	0.0515	PGV = 5.9		Toprak, 1998 (Fig. 6-25)
1075	1994 Northridge	CI	DS	NR	NR	0.0674	PGV = 29.4		Toprak, 1998 (Fig. 6-8)
1076	1994 Northridge	CI	DS	NR	NR	0.0759	PGV = 25.7		Toprak, 1998 (Fig. 6-8)
1077	1994 Northridge	CI	DS	NR	NR	0.0338	PGV = 21.8		Toprak, 1998 (Fig. 6-8)
1078	1994 Northridge	CI	DS	NR	NR	0.0213	PGV = 17.8		Toprak, 1998 (Fig. 6-8)
1079	1994 Northridge	CI	DS	NR	NR	0.0031	PGV = 13.7		Toprak, 1998 (Fig. 6-8)
1080	1994 Northridge	CI	DS	NR	NR	0.0241	PGV = 9.8		Toprak, 1998 (Fig. 6-8)
1081	1994 Northridge	CI	DS	NR	NR	0.0061	PGV = 5.9		Toprak, 1998 (Fig. 6-8)
1082	1989 Loma Prieta	S	DS	60	47	0.148	PGV = 17.0	EBMUD	ALA Report 9/24
1083	1989 Loma Prieta	S	DS	279	9	0.0061	PGV = 7.0	EBMUD	ALA Report 9/24
1084	1989 Loma Prieta	S	DS	45	2	0.0084	PGV = 5.0	EBMUD	ALA Report 9/24
1085	1989 Loma Prieta	S	DS	374	5	0.0025	PGV = 3.0	EBMUD	ALA Report 9/24
1086	1989 Loma Prieta	AC	SM	46.2	3	0.0123	PGV = 17.0	EBMUD	ALA Report 9/24
1087	1989 Loma Prieta	AC	SM	438	2	0.0009	PGV = 7.0	EBMUD	ALA Report 9/24
1088	1989 Loma Prieta	AC	SM	79.5	1	0.0024	PGV = 5.0	EBMUD	ALA Report 9/24
1089	1989 Loma Prieta	AC	SM	445	8	0.0034	PGV = 3.0	EBMUD	ALA Report 9/24
1090	1989 Loma Prieta	CI	DS	20.6	10	0.0919	PGV = 17.0	EBMUD	ALA Report 9/24
1091	1989 Loma Prieta	CI	DS	879	24	0.0052	PGV = 7.0	EBMUD	ALA Report 9/24
1092	1989 Loma Prieta	CI	DS	123	8	0.0123	PGV = 5.0	EBMUD	ALA Report 9/24
1093	1989 Loma Prieta	CI	DS	473	14	0.0056	PGV = 3.0	EBMUD	ALA Report 9/24
1094	1989 Loma Prieta	S	DS	NR	NR	0.097	PGV = 16.0	EBMUD	Eidinger et al, 1995
1095	1989 Loma Prieta	S	DS	NR	NR	0.0052	PGV = 7.0	EBMUD	Eidinger et al, 1995
1096	1989 Loma Prieta	S	DS	NR	NR	0.0031	PGV = 2.5	EBMUD	Eidinger et al, 1995

ID	Earthquake	Material Type	Size	Length	Repairs	Rate	Demand	Comment	Source
1097	1989 Loma Prieta	AC	DS	NR	NR	0.0122	PGV = 16.0	EBMUD	Eidinger et al, 1995
1098	1989 Loma Prieta	AC	DS	NR	NR	0.0012	PGV = 7.0	EBMUD	Eidinger et al, 1995
1099	1989 Loma Prieta	AC	DS	NR	NR	0.0031	PGV = 2.5	EBMUD	Eidinger et al, 1995
1100	1989 Loma Prieta	CI	DS	NR	NR	0.079	PGV = 16.0	EBMUD	Eidinger et al, 1995
1101	1989 Loma Prieta	CI	DS	NR	NR	0.0055	PGV = 7.0	EBMUD	Eidinger et al, 1995
1102	1989 Loma Prieta	CI	DS	NR	NR	0.0061	PGV = 2.5	EBMUD	Eidinger et al, 1995
1103	1989 Mexico	CP	LG	NR	NR	0.0518	PGV = 9.8		O'Rourke & Ayala,1993 (J)
1104	1989 Loma Prieta	CI	DS	1080	15	0.0026	PGV = 5.3	San Francisco non- liq. Areas	Toprak, 1998 (Table 2-1)
1105	1987 Whittier	CI	DS	110	14	0.0241	PGV = 11.0		Toprak, 1998 (Table 2-1)
1106	1985 Mexico City	CP	LG	NR	NR	0.457	PGV = 21.3		O'Rourke & Ayala, 1993 (I)
1107	1985 Mexico City	MX	LG	NR	NR	0.0031	PGV = 4.3	Mix of CI, CP, AC	O'Rourke & Ayala, 1993 (H)
1108	1985 Mexico City	MX	LG	NR	NR	0.0213	PGV = 4.7	Mix of CI, CP, AC	O'Rourke & Ayala, 1993 (G)
1109	1985 Mexico City	MX	LG	NR	NR	0.137	PGV = 18.9	Mix of CI, CP, AC	O'Rourke & Ayala, 1993 (F)
1110	1983 Coalinga	AC	SM	NR	NR	0.101	PGV = 11.8		O'Rourke & Ayala, 1993 (K)
1111	1983 Coalinga	CI	SM	NR	NR	0.24	PGV = 11.8	Corrosion issue	O'Rourke & Ayala, 1993 (E)
1112	1979 Imperial Val.	AC	DS	NR	NR	0.0183	PGV = 23.7		Toprak, 1998 (Fig. 6-24)
1113	1979 Imperial Val.	CI	DS	11.5	19	0.314	MMI = 7	Corrosion issue	Toprak, 1998 (Table 2-3)
1114	1972 Managua	AC	SM	205	393	0.363	PGA = 0.41	May include PGD effects	Katayama et al, 1975 (Table 4)
1115	1972 Managua	CI	LG	18.8	11	0.11	PGA = 0.41	May include PGD effects	Katayama et al, 1975 (Table 4)
1116	1972 Managua	CI	SM	55.8	107	0.363	PGA = 0.41	May include PGD effects	Katayama et al, 1975 (Table 4)
1117	1971 San Fernando	CI	SM	52.7	3	0.0122	PGA = 0.27	May include PGD effects	Katayama et al, 1975 (Table 9)
1118	1971 San Fernando	CI	SM	60	5	0.0152	PGA = 0.28	May include PGD effects	Katayama et al, 1975 (Table 9)
1119	1971 San Fernando	CI	SM	52.2	7	0.0244	PGA = 0.29	May include PGD effects	Katayama et al, 1975 (Table 9)
1120	1971 San Fernando	CI	SM	48.8	5	0.0183	PGA = 0.29	May include PGD effects	Katayama et al, 1975 (Table 9)
1121	1971 San Fernando	CI	SM	49.1	6	0.0244	PGA = 0.30	May include PGD effects	Katayama et al, 1975 (Table 9)
1122	1971 San Fernando	CI	SM	50.6	9	0.0335	PGA = 0.31	May include PGD effects	Katayama et al, 1975 (Table 9)
1123	1971 San Fernando	CI	SM	59.8	19	0.061	PGA = 0.32	May include PGD effects	Katayama et al, 1975 (Table 9)
1124	1971 San Fernando	CI	SM	40.1	26	0.122	PGA = 0.33	May include PGD effects	Katayama et al, 1975 (Table 9)
1125	1971 San Fernando	CI	SM	31.9	22	0.131	PGA = 0.34	May include PGD effects	Katayama et al, 1975 (Table 9)
1126	1971 San Fernando	CI	SM	18.6	24	0.244	PGA = 0.35	May include PGD effects	Katayama et al, 1975 (Table 9)
1127	1971 San Fernando	CI	SM	16.1	16	0.189	PGA = 0.36	May include PGD effects	Katayama et al, 1975 (Table 9)
1128	1971 San Fernando	CI	SM	19.6	26	0.253	PGA = 0.38	May include PGD effects	Katayama et al, 1975 (Table 9)

ID	Earthquake	Material Type	Size	Length	Repairs	Rate	Demand	Comment	Source
1129	1971 San Fernando	CI	SM	20.6	77	0.707	PGA = 0.39	May include PGD effects	Katayama et al, 1975 (Table 9)
1130	1971 San Fernando	CI	SM	21.8	35	0.305	PGA = 0.41	May include PGD effects	Katayama et al, 1975 (Table 9)
1131	1971 San Fernando	CI	SM	16.8	43	0.482	PGA = 0.42	May include PGD effects	Katayama et al, 1975 (Table 9)
1132	1971 San Fernando	CI	SM	15	53	0.668	PGA = 0.44	May include PGD effects	Katayama et al, 1975 (Table 9)
1133	1971 San Fernando	CI	SM	17.8	53	0.564	PGA = 0.46	May include PGD effects	Katayama et al, 1975 (Table 9)
1134	1971 San Fernando	CI	SM	19.3	53	0.521	PGA = 0.48	May include PGD effects	Katayama et al, 1975 (Table 9)
1135	1971 San Fernando	CI	SM	9.1	24	0.5	PGA = 0.50	May include PGD effects	Katayama et al, 1975 (Table 9)
1136	1971 San Fernando	CI	DS	333	84	0.0488	MMI = 8		Toprak, 1998 (Table 2-3)
1137	1971 San Fernando	CI	DS	3540	55	0.0029	MMI = 7		Toprak, 1998 (Table 2-3)
1138	1971 San Fernando	CI	SM	NR	NR	0.0073	PGV = 5.9		O'Rourke & Ayala, 1993 (C)
1139	1971 San Fernando	CI	SM	NR	NR	0.0473	PGV = 11.8		O'Rourke & Ayala, 1993 (A)
1140	1971 San Fernando	CI	DS	169	6	0.0067	PGV = 7.1		Toprak, 1998 (Table 2-1)
1141	1971 San Fernando	CI	DS	151	10	0.0125	PGV = 11.8		Toprak, 1998 (Table 2-1)
1142	1969 Santa Rosa	CI	DS	136	7	0.0098	MMI = 7		Toprak, 1998 (Table 2-3)
1143	1969 Santa Rosa	CI	SM	NR	NR	0.0085	PGV = 5.9		O'Rourke & Ayala,1993 (B)
1144	1968 Tokachi-oki	AC	DS	24.8	77	0.589	MMI = 6 - 7	May include PGD effects	Katayama et al, 1975 (Table 3)
1145	1968 Tokachi-oki	MX	DS	83.9	22	0.0488	MMI = 6 - 7	Mix of CI & AC, may include PGD	Katayama et al, 1975 (Table 3)
1146	1968 Tokachi-oki	MX	DS	98.1	16	0.0305	MMI = 7 - 8	Mix of CI & AC, may include PGD	Katayama et al, 1975 (Table 3)
1147	1968 Tokachi-oki	MX	DS	101	16	0.0305	MMI = 6 - 7	Mix of CI & AC, may include PGD	Katayama et al, 1975 (Table 3)
1148	1968 Tokachi-oki	MX	DS	150	116	0.146	MMI = 7 - 8	Mix of CI & AC, may include PGD	Katayama et al, 1975 (Table 3)
1149	1968 Tokachi-oki	AC	DS	13.7	58	0.805	MMI = 7 - 8	May include PGD effects	Katayama et al, 1975 (Table 3)
1150	1968 Tokachi-oki	CI	DS	5.6	7	0.238	MMI = 7 - 8	May include PGD effects	Katayama et al, 1975 (Table 3)
1151	1968 Tokachi-oki	MX	DS	33.5	46	0.259	MMI = 7 - 8	Mix of CI & AC, may include PGD	Katayama et al, 1975 (Table 3)
1152	1968 Tokachi-oki	AC	DS	31.1	13	0.0793	MMI = 7 - 8	May include PGD effects	Katayama et al, 1975 (Table 3)
1153	1968 Tokachi-oki	CI	DS	13.7	29	0.403	MMI = 7 - 8	May include PGD effects	Katayama et al, 1975 (Table 3)
1154	1968 Tokachi-oki	MX	DS	60.9	81	0.369	MMI = 7 - 8	Mix of CI & AC, may include PGD	Katayama et al, 1975 (Table 3)
1155	1965 Puget Sound	CI	DS	69.7	13	0.0366	MMI = 8		Toprak, 1998 (Table 2-3)
1156	1965 Puget Sound	CI	DS	1180	14	0.0022	MMI = 7		Toprak, 1998 (Table 2-3)
1157	1965 Puget Sound	CI	SM	NR	NR	0.0021	PGV = 3.0		O'Rourke & Ayala, 1993 (D)
1158	1964 Niigata	CI	SM	293	215	0.14	PGA = 0.16	Non-liq. Area	Katayama et al, 1975
1159	1949 Puget Sound	CI	DS	52.2	24	0.0884	MMI = 8		Toprak, 1998 (Table 2-3)
1160	1949 Puget Sound	CI	DS	819	17	0.004	MMI = 7		Toprak, 1998 (Table 2-3)

ID	Earthquake	Material Type	Size	Length	Repairs	Rate	Demand	Comment	Source
1161	1948 Fukui	CI	DS	49.7	150	0.579	PGA = 0.51	May include PGD	Katayama et al, 1975
1162	1933 Long Beach	CI	DS	368	130	0.0671	MMI = 7 - 9		Toprak, 1998 (Table 2-3)
1163	1923 Kanto	CI	LG	39.1	10	0.0488	PGA = 0.31		Katayama et al, 1975
1164	1923 Kanto	CI	SM	570	214	0.0671	PGA = 0.31		Katayama et al, 1975

Comments 19525.7 3350

DI = ductile iron. AC = asbestoc cement. S = steel. CP = concrete pipe. MX = combined materials (I.e., mixed)

Size refers to pipe diameter. LG = Large (≥ 12 inches) SM = small (< 12 inches), DS = distirbution system (mostly small diameter, but some large diameter possible)

Length is in miles of pipeline (NR = not reported)

Rate is Repairs per 1,000 feet of pipeline length

Demand is the reported seismic intensity measure associated with the length of pipeline.

PGV = peak ground velocity (inch/second) PGA = peak ground acceleration (g), MMI = modified Mercalli Intensity

Table A.1-1. Pipe Damage Statistics – Wave Propagation

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1001	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.031	0.031	PGA = 0.211	10.5	PGV (c/s)=140xPGA, 0.9xPGV
1002	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.207	0.207	PGA = 0.306	15.2	PGV (c/s)=140xPGA, 0.9xPGV
1003	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.047	0.047	PGA = 0.478	23.8	PGV (c/s)=140xPGA, 0.9xPGV
1004	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.057	0.057	PGA = 0.572	28.4	PGV (c/s)=140xPGA, 0.9xPGV
1005	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.227	0.227	PGA = 0.595	29.6	PGV (c/s)=140xPGA, 0.9xPGV
1006	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.227	0.227	PGA = 0.677	33.6	PGV (c/s)=140xPGA, 0.9xPGV
1007	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.062	0.062	PGA = 0.710	35.3	PGV (c/s)=140xPGA, 0.9xPGV
1008	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.202	0.202	PGA = 0.792	39.3	PGV (c/s)=140xPGA, 0.9xPGV
1009	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.522	---	PGA = 0.819	---	Omit due to possible PGD effects
1010	1995 Hyogoken-nanbu	6.9	MX	DS	NR	NR	0.098	0.098	PGA = 0.834	41.4	PGV (c/s)=140xPGA, 0.9xPGV
1011	1995 Hyogoken-nanbu	6.9	DI	DS	NR	NR	0.092	---	PGA = 0.306	---	Included in 1001 to 1010
1012	1995 Hyogoken-nanbu	6.9	DI	DS	NR	NR	0.016	---	PGA = 0.478	---	Included in 1001 to 1010
1013	1995 Hyogoken-nanbu	6.9	DI	DS	NR	NR	0.02	---	PGA = 0.572	---	Included in 1001 to 1010
1014	1995 Hyogoken-nanbu	6.9	DI	DS	NR	NR	0.14	---	PGA = 0.595	---	Included in 1001 to 1010
1015	1995 Hyogoken-nanbu	6.9	DI	DS	NR	NR	0.149	---	PGA = 0.677	---	Included in 1001 to 1010
1016	1995 Hyogoken-nanbu	6.9	DI	DS	NR	NR	0.027	---	PGA = 0.710	---	Included in 1001 to 1010
1017	1995 Hyogoken-nanbu	6.9	DI	DS	NR	NR	0.054	---	PGA = 0.792	---	Included in 1001 to 1010
1018	1995 Hyogoken-nanbu	6.9	DI	DS	NR	NR	0.2	---	PGA = 0.819	---	Included in 1001 to 1010
1019	1995 Hyogoken-nanbu	6.9	DI	DS	NR	NR	0.065	---	PGA = 0.834	---	Included in 1001 to 1010

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1020	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.099	---	PGA = 0.211	---	Included in 1001 to 1010
1021	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.288	---	PGA = 0.306	---	Included in 1001 to 1010
1022	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.252	---	PGA = 0.478	---	Included in 1001 to 1010
1023	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.171	---	PGA = 0.572	---	Included in 1001 to 1010
1024	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.585	---	PGA = 0.595	---	Included in 1001 to 1010
1025	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.441	---	PGA = 0.677	---	Included in 1001 to 1010
1026	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.099	---	PGA = 0.710	---	Included in 1001 to 1010
1027	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	1.098	---	PGA = 0.792	---	Included in 1001 to 1010
1028	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	1.458	---	PGA = 0.819	---	Included in 1001 to 1010
1029	1995 Hyogoken-nanbu	6.9	CI	DS	NR	NR	0.189	---	PGA = 0.834	---	Included in 1001 to 1010
1030	1994 Northridge	6.7	DI	DS	16.1	2	0.0236	0.0253	PGV = 47.2	47.2	1.07xRate (see Note 7)
1031	1994 Northridge	6.7	DI	DS	14.4	1	0.0131	0.014	PGV = 35.8	35.8	1.07xRate (see Note 7)
1032	1994 Northridge	6.7	DI	DS	13.4	2	0.0283	0.0303	PGV = 29.3	29.3	1.07xRate (see Note 7)
1033	1994 Northridge	6.7	DI	DS	12.8	6	0.0887	0.0949	PGV = 22.8	22.8	1.07xRate (see Note 7)
1034	1994 Northridge	6.7	DI	DS	11.3	1	0.0167	0.0179	PGV = 17.9	17.9	1.07xRate (see Note 7)
1035	1994 Northridge	6.7	DI	DS	20.1	3	0.0282	0.0302	PGV = 14.6	14.6	1.07xRate (see Note 7)
1036	1994 Northridge	6.7	DI	DS	25.2	2	0.015	0.0161	PGV = 11.4	11.4	1.07xRate (see Note 7)
1037	1994 Northridge	6.7	DI	DS	57.9	6	0.0196	0.021	PGV = 8.1	8.1	1.07xRate (see Note 7)
1038	1994 Northridge	6.7	DI	DS	72.9	1	0.0026	0.002	PGV = 4.9	4	Combine w/ 1039, 1.07xRate
1039	1994 Northridge	6.7	DI	DS	26.4	0	0	---	PGV = 1.6	---	

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1040	1994 Northridge	6.7	AC	DS	15.8	0	0	---	PGV = 35.8	---	
1041	1994 Northridge	6.7	AC	DS	13.4	0	0	---	PGV = 29.3	---	
1042	1994 Northridge	6.7	AC	DS	15.2	7	0.0873	0.0216	PGV = 21.1	25.3	Combine w/ 1040, 1041, 1043, 1.07xRate
1043	1994 Northridge	6.7	AC	DS	21.3	0	0	---	PGV = 17.9	---	
1044	1994 Northridge	6.7	AC	DS	23.6	0	0	---	PGV = 14.6	---	
1045	1994 Northridge	6.7	AC	DS	73.6	2	0.0051	0.0042	PGV = 11.4	12.2	Combine w/ 1044, 1.07xRate
1046	1994 Northridge	6.7	AC	DS	147.2	15	0.0193	0.0207	PGV = 8.1	8.1	
1047	1994 Northridge	6.7	AC	DS	192.4	2	0.002	0.0014	PGV = 4.9	3.8	Combine w/ 1048, 1.07xRate
1048	1994 Northridge	6.7	AC	DS	98.3	0	0	---	PGV = 1.6	---	
1049	1994 Northridge	6.7	CI	DS	78.9	60	0.1441	0.1541	PGV = 52.1	52.1	1.07xRate
1050	1994 Northridge	6.7	CI	DS	84.8	11	0.0246	0.0263	PGV = 45.6	45.6	1.07xRate
1051	1994 Northridge	6.7	CI	DS	101.8	11	0.0205	0.0219	PGV = 39.0	39	1.07xRate
1052	1994 Northridge	6.7	CI	DS	117.6	4	0.0064	0.0068	PGV = 32.5	32.5	1.07xRate
1053	1994 Northridge	6.7	CI	DS	87.6	24	0.054	0.0578	PGV = 27.7	27.7	1.07xRate
1054	1994 Northridge	6.7	CI	DS	111.7	39	0.0662	0.0708	PGV = 24.4	24.4	1.07xRate
1055	1994 Northridge	6.7	CI	DS	222.7	87	0.0739	0.079	PGV = 21.1	21.1	1.07xRate
1056	1994 Northridge	6.7	CI	DS	313.9	56	0.0337	0.0362	PGV = 17.9	17.9	1.07xRate
1057	1994 Northridge	6.7	CI	DS	503.1	59	0.0221	0.0236	PGV = 14.6	14.6	1.07xRate
1058	1994 Northridge	6.7	CI	DS	699.7	111	0.03	0.0321	PGV = 11.4	11.4	1.07xRate
1059	1994 Northridge	6.7	CI	DS	1370.7	166	0.023	0.0246	PGV = 8.1	8.1	1.07xRate

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1060	1994 Northridge	6.7	CI	DS	1055.8	44	0.0079	0.0073	PGV = 4.9	4.5	Combine w/ 1061, 1.07xRate
1061	1994 Northridge	6.7	CI	DS	156.8	0	0	---	PGV = 1.6	---	
1062	1994 Northridge	6.7	CP	LG	NR	NR	0.102	0.102	PGV = 50.7	42.3	0.83xPGV (see Note 8)
1063	1994 Northridge	6.7	S	LG	NR	NR	0.0839	0.0839	PGV = 54.3	45.3	0.83xPGV (see Note 8)
1064	1994 Northridge	6.7	S	LG	NR	NR	0.0396	0.0396	PGV = 33.2	27.7	0.83xPGV (see Note 8)
1065	1994 Northridge	6.7	S	LG	NR	NR	0.0092	0.0092	PGV = 19.8	16.5	0.83xPGV (see Note 8)
1066	1994 Northridge	6.7	S	LG	NR	NR	0.0031	0.0031	PGV = 13.7	11.4	0.83xPGV (see Note 8)
1067	1994 Northridge	6.7	S	LG	NR	NR	0.0031	0.0031	PGV = 9.7	8.1	0.83xPGV (see Note 8)
1068	1994 Northridge	6.7	AC	DS	NR	NR	0.0183	---	PGV = 9.8	---	Already in ALA data above
1069	1994 Northridge	6.7	AC	DS	NR	NR	0.0031	---	PGV = 5.9	---	Already in ALA data above
1070	1994 Northridge	6.7	DI	DS	NR	NR	0.0122	---	PGV = 12.5	---	Already in ALA data above
1071	1994 Northridge	6.7	S	DS	NR	NR	0.0854	0.0914	PGV = 21.5	17.9	1.07xRate, 0.83xPGV
1072	1994 Northridge	6.7	S	DS	NR	NR	0.0488	0.0522	PGV = 13.8	11.5	1.07xRate, 0.83xPGV
1073	1994 Northridge	6.7	S	DS	NR	NR	0.0549	0.0587	PGV = 9.9	8.3	1.07xRate, 0.83xPGV
1074	1994 Northridge	6.7	S	DS	NR	NR	0.0515	0.0551	PGV = 5.9	4.9	1.07xRate, 0.83xPGV
1075	1994 Northridge	6.7	CI	DS	NR	NR	0.0674	---	PGV = 29.4	---	Already in ALA data above
1076	1994 Northridge	6.7	CI	DS	NR	NR	0.0759	---	PGV = 25.7	---	Already in ALA data above
1077	1994 Northridge	6.7	CI	DS	NR	NR	0.0338	---	PGV = 21.8	---	Already in ALA data above
1078	1994 Northridge	6.7	CI	DS	NR	NR	0.0213	---	PGV = 17.8	---	Already in ALA data above
1079	1994 Northridge	6.7	CI	DS	NR	NR	0.0031	---	PGV = 13.7	---	Already in ALA data above

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1080	1994 Northridge	6.7	CI	DS	NR	NR	0.0241	---	PGV = 9.8	---	Already in ALA data above
1081	1994 Northridge	6.7	CI	DS	NR	NR	0.0061	---	PGV = 5.9	---	Already in ALA data above
1082	1989 Loma Prieta	6.9	S	DS	60	47	0.148	0.148	PGV = 17.0	17	Supersedes 1094 to 1096
1083	1989 Loma Prieta	6.9	S	DS	279	9	0.0061	0.0061	PGV = 7.0	7	Supersedes 1094 to 1096
1084	1989 Loma Prieta	6.9	S	DS	45	2	0.0084	0.0084	PGV = 5.0	5	Supersedes 1094 to 1096
1085	1989 Loma Prieta	6.9	S	DS	374	5	0.0025	0.0025	PGV = 3.0	3	Supersedes 1094 to 1096
1086	1989 Loma Prieta	6.9	AC	SM	46.2	3	0.0123	0.0123	PGV = 17.0	17	Supersedes 1097 to 1099
1087	1989 Loma Prieta	6.9	AC	SM	438	2	0.0009	0.0009	PGV = 7.0	7	Supersedes 1097 to 1099
1088	1989 Loma Prieta	6.9	AC	SM	79.5	1	0.0024	0.0024	PGV = 5.0	5	Supersedes 1097 to 1099
1089	1989 Loma Prieta	6.9	AC	SM	445	8	0.0034	0.0034	PGV = 3.0	3	Supersedes 1097 to 1099
1090	1989 Loma Prieta	6.9	CI	DS	20.6	10	0.0919	0.0919	PGV = 17.0	17	Supersedes 1100 to 1102
1091	1989 Loma Prieta	6.9	CI	DS	879	24	0.0052	0.0052	PGV = 7.0	7	Supersedes 1100 to 1102
1092	1989 Loma Prieta	6.9	CI	DS	123	8	0.0123	0.0123	PGV = 5.0	5	Supersedes 1100 to 1102
1093	1989 Loma Prieta	6.9	CI	DS	473	14	0.0056	0.0056	PGV = 3.0	3	Supersedes 1100 to 1102
1094	1989 Loma Prieta	6.9	S	DS	NR	NR	0.097	---	PGV = 16.0	---	
1095	1989 Loma Prieta	6.9	S	DS	NR	NR	0.0052	---	PGV = 7.0	---	
1096	1989 Loma Prieta	6.9	S	DS	NR	NR	0.0031	---	PGV = 2.5	---	
1097	1989 Loma Prieta	6.9	AC	DS	NR	NR	0.0122	---	PGV = 16.0	---	
1098	1989 Loma Prieta	6.9	AC	DS	NR	NR	0.0012	---	PGV = 7.0	---	
1099	1989 Loma Prieta	6.9	AC	DS	NR	NR	0.0031	---	PGV = 2.5	---	

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1100	1989 Loma Prieta	6.9	CI	DS	NR	NR	0.079	---	PGV = 16.0	---	
1101	1989 Loma Prieta	6.9	CI	DS	NR	NR	0.0055	---	PGV = 7.0	---	
1102	1989 Loma Prieta	6.9	CI	DS	NR	NR	0.0061	---	PGV = 2.5	---	
1103	1989 Mexico	7.4	CP	LG	NR	NR	0.0518	0.0518	PGV = 9.8	9.8	
1104	1989 Loma Prieta	6.9	CI	DS	1080	15	0.0026	0.0026	PGV = 5.3	5.3	
1105	1987 Whittier	5.9&5.3	CI	DS	110	14	0.0241	---	PGV = 11.0	---	Main and aftershock magnitudes (Note 10)
1106	1985 Mexico City	8.1&7.5	CP	LG	NR	NR	0.457	---	PGV = 21.3	---	Main and aftershock magnitudes (Note 10)
1107	1985 Mexico City	8.1&7.5	MX	LG	NR	NR	0.0031	---	PGV = 4.3	---	Main and aftershock magnitudes (Note 10)
1108	1985 Mexico City	8.1&7.5	MX	LG	NR	NR	0.0213	---	PGV = 4.7	---	Main and aftershock magnitudes (Note 10)
1109	1985 Mexico City	8.1&7.5	MX	LG	NR	NR	0.137	---	PGV = 18.9	---	Main and aftershock magnitudes (Note 10)
1110	1983 Coalinga	6.7	AC	SM	NR	NR	0.101	0.101	PGV = 11.8	11.8	
1111	1983 Coalinga	6.7	CI	SM	NR	NR	0.24	---	PGV = 11.8	---	Corrosion bias
1112	1979 Imperial Val.	6.5	AC	DS	NR	NR	0.0183	0.0183	PGV = 23.7	23.7	
1113	1979 Imperial Val.	6.5	CI	DS	11.5	19	0.314	---	MMI = 7	---	Corrosion bias
1114	1972 Managua	6.3	AC	SM	205	393	0.363	---	PGA = 0.41	---	See Note 9
1115	1972 Managua	6.3	CI	LG	18.8	11	0.11	---	PGA = 0.41	---	See Note 9
1116	1972 Managua	6.3	CI	SM	55.8	107	0.363	---	PGA = 0.41	---	See Note 9
1117	1971 San Fernando	6.7	CI	SM	52.7	3	0.0122	0.0122	PGA = 0.27	13.8	PGV (c/s)=130xPGA per Wald Figs. 1&2
1118	1971 San Fernando	6.7	CI	SM	60	5	0.0152	0.0152	PGA = 0.28	14.3	PGV (c/s)=130xPGA per Wald Figs. 1&2

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1119	1971 San Fernando	6.7	CI	SM	52.2	7	0.0244	0.0244	PGA = 0.29	14.8	PGV (c/s)=130xPGA per Wald Figs. 1&2
1120	1971 San Fernando	6.7	CI	SM	48.8	5	0.0183	0.0183	PGA = 0.29	14.8	PGV (c/s)=130xPGA per Wald Figs. 1&2
1121	1971 San Fernando	6.7	CI	SM	49.1	6	0.0244	0.0244	PGA = 0.30	15.4	PGV (c/s)=130xPGA per Wald Figs. 1&2
1122	1971 San Fernando	6.7	CI	SM	50.6	9	0.0335	0.0335	PGA = 0.31	15.9	PGV (c/s)=130xPGA per Wald Figs. 1&2
1123	1971 San Fernando	6.7	CI	SM	59.8	19	0.061	0.061	PGA = 0.32	16.4	PGV (c/s)=130xPGA per Wald Figs. 1&2
1124	1971 San Fernando	6.7	CI	SM	40.1	26	0.122	0.122	PGA = 0.33	16.9	PGV (c/s)=130xPGA per Wald Figs. 1&2
1125	1971 San Fernando	6.7	CI	SM	31.9	22	0.131	0.131	PGA = 0.34	17.4	PGV (c/s)=130xPGA per Wald Figs. 1&2
1126	1971 San Fernando	6.7	CI	SM	18.6	24	0.244	---	PGA = 0.35	---	See Note 9
1127	1971 San Fernando	6.7	CI	SM	16.1	16	0.189	---	PGA = 0.36	---	See Note 9
1128	1971 San Fernando	6.7	CI	SM	19.6	26	0.253	---	PGA = 0.38	---	See Note 9
1129	1971 San Fernando	6.7	CI	SM	20.6	77	0.707	---	PGA = 0.39	---	See Note 9
1130	1971 San Fernando	6.7	CI	SM	21.8	35	0.305	---	PGA = 0.41	---	See Note 9
1131	1971 San Fernando	6.7	CI	SM	16.8	43	0.482	---	PGA = 0.42	---	See Note 9
1132	1971 San Fernando	6.7	CI	SM	15	53	0.668	---	PGA = 0.44	---	See Note 9
1133	1971 San Fernando	6.7	CI	SM	17.8	53	0.564	---	PGA = 0.46	---	See Note 9
1134	1971 San Fernando	6.7	CI	SM	19.3	53	0.521	---	PGA = 0.48	---	See Note 9
1135	1971 San Fernando	6.7	CI	SM	9.1	24	0.5	---	PGA = 0.50	---	See Note 9
1136	1971 San Fernando	6.7	CI	DS	333	84	0.0488	0.0488	MMI = 8	26	PGV per Wald el al, 1999 Fig. 2
1137	1971 San Fernando	6.7	CI	DS	3540	55	0.0029	0.0029	MMI = 7	9.1	PGV per Wald el al, 1999 Fig. 2
1138	1971 San Fernando	6.7	CI	SM	NR	NR	0.0073	---	PGV =	---	Same data set as 1140 and 1141

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
									5.9		
1139	1971 San Fernando	6.7	CI	SM	NR	NR	0.0473	---	PGV = 11.8	---	Same data set as 1140 and 1141
1140	1971 San Fernando	6.7	CI	DS	169	6	0.0067	0.0067	PGV = 7.1	7.1	
1141	1971 San Fernando	6.7	CI	DS	151	10	0.0125	0.0125	PGV = 11.8	11.8	
1142	1969 Santa Rosa	5.6&5.7	CI	DS	136	7	0.0098	---	MMI = 7	---	Main and aftershock magnitudes (Note 10)
1143	1969 Santa Rosa	5.6&5.7	CI	SM	NR	NR	0.0085	---	PGV = 5.9	---	Main and aftershock magnitudes (Note 10)
1144	1968 Tokachi-oki	7.9	AC	DS	24.8	77	0.589	---	MMI = 6 - 7	---	See Note 9
1145	1968 Tokachi-oki	7.9	MX	DS	83.9	22	0.0488	---	MMI = 6 - 7	---	See Note 9
1146	1968 Tokachi-oki	7.9	MX	DS	98.1	16	0.0305	---	MMI = 7 - 8	---	See Note 9
1147	1968 Tokachi-oki	7.9	MX	DS	101	16	0.0305	---	MMI = 6 - 7	---	See Note 9
1148	1968 Tokachi-oki	7.9	MX	DS	150	116	0.146	---	MMI = 7 - 8	---	See Note 9
1149	1968 Tokachi-oki	7.9	AC	DS	13.7	58	0.805	---	MMI = 7 - 8	---	See Note 9
1150	1968 Tokachi-oki	7.9	CI	DS	5.6	7	0.238	---	MMI = 7 - 8	---	See Note 9
1151	1968 Tokachi-oki	7.9	MX	DS	33.5	46	0.259	---	MMI = 7 - 8	---	See Note 9
1152	1968 Tokachi-oki	7.9	AC	DS	31.1	13	0.0793	---	MMI = 7 - 8	---	See Note 9
1153	1968 Tokachi-oki	7.9	CI	DS	13.7	29	0.403	---	MMI = 7 - 8	---	See Note 9
1154	1968 Tokachi-oki	7.9	MX	DS	60.9	81	0.369	---	MMI = 7 - 8	---	See Note 9
1155	1965 Puget Sound	6.5	CI	DS	69.7	13	0.0366	0.0366	MMI = 8	16.7	PGV per Wald el al, 1999 eqn 2
1156	1965 Puget Sound	6.5	CI	DS	1180	14	0.0022	0.0022	MMI = 7	8.6	PGV per Wald el al, 1999 eqn 2
1157	1965 Puget Sound	6.5	CI	SM	NR	NR	0.0021	---	PGV = 3.0	---	Data included in 1155 and 1156
1158	1964 Niigata	7.5	CI	SM	293	215	0.14	0.14	PGA = 0.16	6	PGV (c/s)=95xPGA per Wald Figs. 3&4

ID	Earthquake	Magnitude	Material Type	Size	Length	Repairs	Raw Rate (rpr / 1,000 ft)	Repair Rate / 1000 ft	Demand	PGV, inch/sec	Comment
1159	1949 Puget Sound	7.1	CI	DS	52.2	24	0.0884	0.0884	MMI = 8	16.7	PGV per Wald el al, 1999 eqn 2
1160	1949 Puget Sound	7.1	CI	DS	819	17	0.004	0.004	MMI = 7	8.6	PGV per Wald el al, 1999 eqn 2
1161	1948 Fukui	7.3	CI	DS	49.7	150	0.579	---	PGA = 0.51	---	See Note 9
1162	1933 Long Beach	6.3	CI	DS	368	130	0.0671	0.0671	MMI = 7 - 9	24.6	PGV per Wald el al, 1999 eqn 2
1163	1923 Kanto	7.9	CI	LG	39.1	10	0.0488	0.0488	PGA = 0.31	11.6	PGV (c/s)=95xPGA per Wald Figs. 3&4
1164	1923 Kanto	7.9	CI	SM	570	214	0.0671	0.0671	PGA = 0.31	11.6	PGV (c/s)=95xPGA per Wald Figs. 3&4

Notes.

1. DI = ductile iron. AC = asbestoc cement. S = steel. CP = concrete pipe. MX = combined materials (I.e., mixed)

2. Size refers to pipe diameter. LG = Large (> about 12 inches) SM = small (≤ about12 inches).

3. DS = distirbution system (mostly small diameter, but some large diameter possible)

4. Repair rate is repairs per 1,000 of pipe

5. Modified Demand, PGA, inches / second. Peak Ground Velocity. Entry of "---" means that the data point was screened out for reasons cited in this table.

6. Wald et al ([1999] equation 2 is as follows: MMI = 3.47 log(PGV) + 2.35, where PGV is in cm / sec.

7. 1.07 x Rate modification is to account for repairs omitted from Toprak [1998] analysis due to lack of some atttributes, but the damage did occur

8. 0.83 x PGV modification is to adjust peak PGV value of two horizontal directions to average horizontal vale of two directions (for Northridge only)

9. Data point screened out due to possible PGD effects. For San Fernando, only point in the northeast part of the valley were screened out per Barenberg [1988] and NOAA [1973].

10. These entries had aftershocks of similar magnitude as the main shock. The data points were screened out as the amount of damage caused by each event cannot be differentiated.

Table A.1-2. Screened Database of Pipe Damage Caused by Wave Propagation

ID	Earthquake	Material Type	Size	Repair Rate / 1000 ft	PGD, inches	Source	Comment
2001	1989 Loma Prieta	CI	DS	3.5	4.6	Porter et al, 1991 (Fig. 9)	
2002	1989 Loma Prieta	CI	DS	3.5	1.3	Porter et al, 1991 (Fig. 9)	
2003	1989 Loma Prieta	CI	DS	2.6	4.6	Porter et al, 1991 (Fig. 9)	
2004	1989 Loma Prieta	CI	DS	2.3	4.5	Porter et al, 1991 (Fig. 9)	
2005	1989 Loma Prieta	CI	DS	2.3	2.8	Porter et al, 1991 (Fig. 9)	
2006	1989 Loma Prieta	CI	DS	2.1	3.8	Porter et al, 1991 (Fig. 9)	
2007	1989 Loma Prieta	CI	DS	2.1	2.3	Porter et al, 1991 (Fig. 9)	
2008	1989 Loma Prieta	CI	DS	1.7	3.7	Porter et al, 1991 (Fig. 9)	
2009	1989 Loma Prieta	CI	DS	1.6	1.1	Porter et al, 1991 (Fig. 9)	
2010	1989 Loma Prieta	CI	DS	1.1	0.6	Porter et al, 1991 (Fig. 9)	
2011	1989 Loma Prieta	CI	DS	0.4	1.4	Porter et al, 1991 (Fig. 9)	
2012	1989 Loma Prieta	CI	DS	0.4	0.8	Porter et al, 1991 (Fig. 9)	
2013	1983 Nihonkai-Chubu	AC	SM	4.6	76.5	Hamada et al, 1986 (Fig. 5-6)	
2014	1983 Nihonkai-Chubu	AC	SM	0.6	48.5	Hamada et al, 1986 (Fig. 5-6)	
2015	1983 Nihonkai-Chubu	AC	SM	3.1	49.5	Hamada et al, 1986 (Fig. 5-6)	
2016	1983 Nihonkai-Chubu	AC	SM	4.2	49.8	Hamada et al, 1986 (Fig. 5-6)	
2017	1983 Nihonkai-Chubu	AC	SM	8.5	41.7	Hamada et al, 1986 (Fig. 5-6)	
2018	1983 Nihonkai-Chubu	AC	SM	11.6	30.4	Hamada et al, 1986 (Fig. 5-6)	
2019	1983 Nihonkai-Chubu	AC	SM	6.9	28.9	Hamada et al, 1986 (Fig. 5-6)	
2020	1983 Nihonkai-Chubu	AC	SM	4.4	30.3	Hamada et al, 1986 (Fig. 5-6)	
2021	1983 Nihonkai-Chubu	AC	SM	1.4	28.1	Hamada et al, 1986 (Fig. 5-6)	
2022	1983 Nihonkai-Chubu	AC	SM	1.6	27.1	Hamada et al, 1986 (Fig. 5-6)	
2023	1983 Nihonkai-Chubu	AC	SM	1.8	25.6	Hamada et al, 1986 (Fig. 5-6)	
2024	1983 Nihonkai-Chubu	AC	SM	1.9	23.4	Hamada et al, 1986 (Fig. 5-6)	
2025	1983 Nihonkai-Chubu	AC	SM	5.3	25.7	Hamada et al, 1986 (Fig. 5-6)	
2026	1983 Nihonkai-Chubu	AC	SM	5.9	14.8	Hamada et al, 1986 (Fig. 5-6)	
2027	1983 Nihonkai-Chubu	AC	SM	2.7	16.1	Hamada et al, 1986 (Fig. 5-6)	
2028	1983 Nihonkai-Chubu	AC	SM	0.5	14.4	Hamada et al, 1986 (Fig. 5-6)	
2029	1983 Nihonkai-Chubu	AC	SM	0.9	13.8	Hamada et al, 1986 (Fig. 5-6)	
2030	1983 Nihonkai-Chubu	AC	SM	3.1	12.1	Hamada et al, 1986 (Fig. 5-6)	
2031	1983 Nihonkai-Chubu	AC	SM	1.5	11.1	Hamada et al, 1986 (Fig. 5-6)	

ID	Earthquake	Material Type	Size	Repair Rate / 1000 ft	PGD, inches	Source	Comment
2032	1983 Nihonkai-Chubu	AC	SM	0.5	7.6	Hamada et al, 1986 (Fig. 5-6)	
2033	1983 Nihonkai-Chubu	CI	SM	15.2	49.8	Hamada et al, 1986 (Fig. 5-4a)	Gas pipe (note 4)
2034	1983 Nihonkai-Chubu	CI	SM	19	30	Hamada et al, 1986 (Fig. 5-4a)	Gas pipe (note 4)
2035	1983 Nihonkai-Chubu	CI	SM	20.5	25.7	Hamada et al, 1986 (Fig. 5-4a)	Gas pipe (note 4)
2036	1983 Nihonkai-Chubu	CI	SM	14.6	9.5	Hamada et al, 1986 (Fig. 5-4a)	Gas pipe (note 4)
2037	1983 Nihonkai-Chubu	CI	SM	12.1	11.9	Hamada et al, 1986 (Fig. 5-4a)	Gas pipe (note 4)
2038	1983 Nihonkai-Chubu	CI	SM	5.9	9.6	Hamada et al, 1986 (Fig. 5-4a)	Gas pipe (note 4)
2039	1983 Nihonkai-Chubu	CI	SM	0.9	11.2	Hamada et al, 1986 (Fig. 5-4a)	Gas pipe (note 4)
2040	1983 Nihonkai-Chubu	CI	SM	0.9	8.4	Hamada et al, 1986 (Fig. 5-4a)	Gas pipe (note 4)
2041	1983 Nihonkai-Chubu	CI	SM	0.5	6.6	Hamada et al, 1986 (Fig. 5-4a)	Gas pipe (note 4)
2042	1983 Nihonkai-Chubu	S	SM	16.5	76.6	Hamada et al, 1986 (Fig. 5-4b)	Gas pipe (note 4)
2043	1983 Nihonkai-Chubu	S	SM	3	51.4	Hamada et al, 1986 (Fig. 5-4b)	Gas pipe (note 4)
2044	1983 Nihonkai-Chubu	S	SM	2.4	28.6	Hamada et al, 1986 (Fig. 5-4b)	Gas pipe (note 4)
2045	1983 Nihonkai-Chubu	S	SM	2.8	26.6	Hamada et al, 1986 (Fig. 5-4b)	Gas pipe (note 4)
2046	1983 Nihonkai-Chubu	S	SM	1.3	9.7	Hamada et al, 1986 (Fig. 5-4b)	Gas pipe (note 4)
2047	1971 San Fernando	MX	LG	1.2	19.5	Barenberg, 1988 (Fig. 2)	
2048	1971 San Fernando	MX	LG	1.9	25.7	Barenberg, 1988 (Fig. 2)	
2049	1971 San Fernando	MX	LG	2.3	27.4	Barenberg, 1988 (Fig. 2)	
2050	1971 San Fernando	MX	LG	3.7	31.1	Barenberg, 1988 (Fig. 2)	
2051	1971 San Fernando	MX	LG	8.2	41	Barenberg, 1988 (Fig. 2)	
2052	1906 San Francisco	CI	DS	9.3	108	Porter et al, 1991 (Fig. 9)	
2053	1906 San Francisco	CI	DS	6.8	60	Porter et al, 1991 (Fig. 9)	
2054	1906 San Francisco	CI	DS	2.9	60	Porter et al, 1991 (Fig. 9)	
2055	1906 San Francisco	CI	DS	3.9	29	Porter et al, 1991 (Fig. 9)	
2056	1906 San Francisco	CI	DS	3.6	12	Porter et al, 1991 (Fig. 9)	

Notes
1. CI = Cast Iron, AC = Asbestoc Cement, S = steel, MX = mix of CI and S
2. Size refers to pipe diameter. LG = Large (> about 12 inches) SM = small (≤ about12 inches).
3. Rate is reported repairs per 1,000 feet of pipeline.
4. Datapoint notused in statistical analysis

Table A.1-3. Database of Pipe Damage Caused by Permanent Ground Displacements

A.2 Buried Pipeline Empirical Data

A.2.1 San Francisco, 1906

The 1906 San Francisco earthquake (magnitude 8.3) caused failure of the water distribution system, which, in turn, contributed to the four-day-long fire storm that destroyed much of the city [Manson].

About 52% of all pipeline breaks occurred inside or within one block of zones experiencing permanent ground deformations, yet these zones accounted for only 5% of the built up areas in 1906 affected by strong ground shaking [Youd and Hoose, Hovland and Daragh, Schussler].

A.2.2 San Fernando, 1971

The 1971 San Fernando earthquake (magnitude 7.1) caused 23 square miles of residential areas to be without water until 1,400 repairs were made. Over 500 fire hydrants were out of service until 22,000 feet of 6- to 10-inch pipe could be repaired [McCaffery and O’Rourke, O’Rourke and Tawfik].

A.2.3 Haicheng, China, 1975

1975 Haicheng, China earthquake (magnitude 7.3) caused damage to buried water piping to four nearby cities, resulting in an average pipe repair rate of 0.85 repairs per 1,000 feet of pipe [Wang, Shao-Ping and Shije]. The damage was greatest for softer soil sites closer to the epicenter.

A.2.4 Mexico City, 1985

The 1985 Mexico City earthquake (magnitude 8.1) caused about 30% of the 18 million people in the area to be without water immediately after the earthquake [Ayala and O’Rourke, O’Rourke and Ayala]. The aqueduct/transmission system was restored to service about six weeks after the event and repairs to the distribution system took several months.

Two water utilities serve Mexico City. The Federal District system experienced about 5,100 repairs to its distribution system (2- to 18-inch diameter pipe, total length of pipe uncertain), and about 180 repairs to its primary system (20- to 48-inch pipe, 570 km of pipe). The Mexico State water system had more than 1,100 repairs to its piping system in addition to about 70 repairs to the aqueduct system. More than 6,500 total repairs resulted from the earthquake.

A.2.5 Other Earthquakes 1933 - 1989

Table A.2-1 presents summary damage statistics for buried pipe for a variety of historical earthquakes. The data shown is limited wherever possible to damage from ground shaking effects only.

Earthquake	Pipe Material	Pipe Repairs	Pipe Length, km	Notes
1933 Long Beach	Cast Iron	130	592	MMI 7-9
1949 Puget Sound	Cast Iron	17	1,319.2	MMI 7
1949 Puget Sound	Cast Iron	24	84.1	MMI 8
1965 Puget Sound	Cast Iron	14	1,906.7	MMI 7
1965 Puget Sound	Cast Iron	13	112.2	MMI 8
1969 Santa Rosa	Cast Iron	7	54 – 219 ?	
1971 San Fernando	Cast Iron	55	5,700	MMI 7
1971 San Fernando	Cast Iron	84	536.2	MMI 8
1979 Imperial Valley	Cast Iron	19	18.5	El Centro
1979 Imperial Valley	Asbestos Cement	6	100	El Centro
1983 Coalinga	Cast Iron	8	13.8	Corrosion?
1989 Loma Prieta	Cast Iron mostly	15	1,740	SFWD

Table A.2-1. Pipe Damage Statistics From Various Earthquakes

Except for the GIS-based analyses done for the EBMUD water system (1989 Loma Prieta) and the LADWP water system (1994 Northridge), damage statistics for the various past earthquakes all suffer from one or more of the following limitations:

- Accurate inventory of existing pipelines (e.g., lengths, diameters, materials, joinery) were not completely available.
- Limited (or no) strong motion instruments were located nearby, making estimates of strong motions over widespread areas less accurate.
- Accurate counts of damaged pipe locations were not available.

Recognizing these limitations, Toprak [1998] used the available databases to find reliable or semi-reliable estimates of pipe damage from past earthquakes. Table A.2-2 lists these findings. The PGVs in Table A.2-2 are based on interpreted nearby instruments, listing the highest of the two horizontal components. The average of the two horizontal directions of peak ground velocity motion would be about 83% of the maximum in any one direction.

Earthquake	Pipe Material	PGV (peak) (in/sec)	Pipe Length (km)	Repairs per km	Notes
1989 Loma Prieta	Cast Iron (mostly)	5.3	1,740	0.0086	SFWD
1987 Whittier	Cast Iron	11.0	177.1	0.0791	
1971 San Fernando	Cast Iron	11.8	242.6	0.0412	Zone 1
1971 San Fernando	Cast Iron	7.1	271.6	0.0221	Zone 2
1979 Imperial Valley	Asbestos Cement	15.0	100	0.0600	

Table A.2-2. Pipe Damage Statistics From Various Earthquakes [after Toprak]

Table A.2-3 lists the data shown in Figures A-1 and A-2. The PGV values are based on attenuation relationships.

Earthquake	Pipe Material	PGV (in/sec)	Pipe Length (km)	Repairs per km	Notes
1971 San Fernando	Cast Iron 3 to 6"	11.8		0.155	Pt A
1969 Santa Rosa	Cast Iron 3 to 6"	5.9	219	0.028	Pt B
1971 San Fernando	Cast Iron 3 to 6"	5.9		0.024	Pt C
1965 Puget Sound	Cast Iron 8 to 10"	3.0		0.007	Pt D
1983 Coalinga	Cast Iron 3 to 6"	11.8		0.24	Pt E
1985 Mexico City	AC, Conc Cl 20-48"	18.9		0.137	Pt F
1985 Mexico City	AC, Conc Cl 20-48"	4.7		0.0213	Pt G
1985 Mexico City	AC, Conc Cl 20-48"	4.3		0.0031	Pt H
1989 Tlahuac	PCCP 72"	21.3		0.457	Pt I
1989 Tlahuac	PCCP 72"	9.8		0.0518	Pt J
1983 Coalinga	AC 3 to 10"	11.8		0.101	Pt K

Table A.2-3. Pipe Damage Statistics From Various Earthquakes (From Figures A-1 and A-2)

Several issues related to the data in Tables A.2-2 and A.2-3 suggest how this data might be combined with data from Sections A.3.11 and A.3.12. These are as follows:

- No GIS analysis was performed for the pipeline inventories. Thus, differentiation of pipe damage as a function of PGV is much cruder than that available from GIS analysis.
- The data in Table A.2-2 is based on the maximum ground velocity of two horizontal directions for the nearest instrument. The data in Table A.2-3 is based on attenuation functions and is the expected average ground motion in two horizontal directions.
- The data for the 1985 Mexico City earthquake is for an event which had a strong ground motion duration of 120 seconds. This is 3 to 6 times longer than the data from the other earthquakes in the databases. Not surprisingly, damage rates for the 1985/1989 Mexico data are higher than comparable values from California earthquakes. If repair rate is a function of duration, then a magnitude/duration factor might be needed when combining data from separate types of empirical datasets.

A.3 Buried Pipe Fragility Curves – Past Studies

This section summarizes past studies that developed damage algorithms used for the seismic evaluation of water distribution pipes. Many of these past studies are still considered current, but others are no longer considered appropriate since the state-of-the-practice in water distribution seismic performance evaluation is rapidly advancing. The following sections briefly describe these past studies.

A.3.1 Memphis, Tennessee

Since the late 1980s, several universities, the National Science Foundation and the USGS have sponsored studies of seismic pipeline damage for the city of Memphis, Tennessee [Okumura and Shinozuka]. For the most part, the damage algorithms used in these studies were based on expert opinion and a limited amount of empirical evidence.

The damage algorithms used in these studies were based on simple formulae which were easily applied to all pipes within the water distribution system. The algorithms are functions of the following three parameters:

- Level of shaking, as expressed in terms of Modified Mercalli Intensity (MMI). The higher the MMI, the higher the damage rate.
- Pipe diameter. The larger the pipe diameter, the lower the damage rate. The algorithm is based upon limited empirical earthquake damage data available at the time, which tended to show significantly lower damage rates for larger diameter pipe. New empirical data in the 1989 Loma Prieta earthquake confirms the trend of improved performance for large-diameter pipe.
- Ground Condition. The ground condition is based on Uniform Building Code S1, S2, S3 and S4 descriptions. The damage algorithm in very poor soils (S4) was set at 10 times that of stiff soils (S1).

The incidence of breaks is assumed to be a Poisson process and the damage algorithm is as follows:

$$n = C_d \, C_g \, 10^{0.8(MMI-9)} \qquad [A\text{-}1]$$

where

n = the occurrence rate of pipe failure per kilometer; MMI = Modified Mercalli Intensity; and

$$C_d = \begin{cases} 1.0 \text{Diameter } D < 25 \text{ cm} \\ 0.525 \bullet D < 50 \text{ cm} \\ 0.250 \bullet D < 100 \text{ cm} \\ 0.0100 \bullet D \end{cases}$$

$$C_g = \begin{cases} 0.5 \text{Soil S1} \\ 1.0 \text{Soil S2} \\ 2.0 \text{Soil 3S} \\ 5.0 \text{Soil S4} \end{cases}$$

The probability of a major pipe failure (i.e., complete break with total water loss) is calculated as:

$$P_{f_{major}} = 1 - e^{-nL} \qquad [A\text{-}2]$$

where

L = the length of pipe and n is defined by the equation above.

The occurrence rate of leakage is assumed to be:

$$P_{f_{minor}} = 5 \, P_{f\ major} \qquad [A\text{-}3]$$

The above damage algorithms are very simple, and capture several of the key features of how seismic hazards affect pipe. Although these damage algorithms are simple to use, they are not considered suitable for “modern” loss estimation efforts as they are based on the MMI scale instead of PGV and PGD, and omit factors such as pipe construction material, corrosion and amounts, if any, of ground failures.

A.3.2 University-based Seismic Risk Computer Program

Researchers at Princeton University have developed a program [Sato and Myurata] using the same damage algorithm as that used for Memphis, except that the Cg factor, ranging from 1.0 to 0.0, depending on ground conditions, is omitted.

The damage algorithm presented in Table A.3-1 below is taken from that reference. Note how the pipe failure rate strongly depends on seismic intensity and pipe diameter. For the same reasons described for the Memphis algorithms, these damage algorithms are not considered suitable for use in “modern” loss estimation studies.

MMI Scale	D < 25 cm	25 ≤ D < 50 cm	50 ≤ D < 100 cm	100 ≤ D
VI	0.003	0.001	0.000	0.000
VII	0.025	0.012	0.005	0.000
VIII	0.158	0.079	0.031	0.000
IX	1.000	0.500	0.200	0.000
X	6.309	3.154	1.261	0.000

Table A.3-1. Occurrence Rate of Pipe Failure (per km)

A.3.3 Metropolitan Water District

In a 1978 study on large-diameter (40- to 70-inch) welded seamless pipe for the Los Angeles area Metropolitan Water District (MWD) [Shinozuka, Takada and Ishikawa], a set of damage algorithms was developed based upon analytical calculations of strain levels in the pipe. These algorithms were then applied to the MWD water transmission network.

For wave propagation, the structural strains in the pipe were calculated based upon the free field soil strains. For segments of pipe that cross through areas where soil liquefaction or surface fault rupture are known to occur, the pipe strains are computed using formulas by [Newmark and Hall] or [in ASCE, 1984]. A series of damage probability matrices were developed for the various units of soil conditions that the large diameter pipe traverses. A typical damage probability matrix is as follows:

MMI Scale	Minor Damage	Moderate Damage	Major Damage
VI	1.00	0.00	0.00
VII	0.96	0.04	0.00
VIII	0.18	0.71	0.11
IX	0.00	0.11	0.89

Table A.3-2. Damage Probability Matrix

This table applies for pipe with curves and connections in poor soil conditions. For Intensity VIII, such pipe will have an 18% chance of being undamaged (minor damage), a 71% chance of leakage (moderate damage) and an 11% chance of a total breakage (major damage).

These algorithms introduce the concept of uncertainty into the analysis. For example, given Intensity IX, there is some uncertainty whether the damage rates will be “moderate” or “major.” The uncertainty arises both from imperfect knowledge of the capacity of individual pipe strengths and the randomness of the earthquake hazard levels.

A.3.4 San Francisco Auxiliary Water Supply System

The damage algorithms suggested by Grigoriu et al [Grigoriu, O’Rourke, Khater] were used in a study on pipeline damage of the Auxiliary Water Supply System (AWSS) for the city of San Francisco, California. The AWSS consists of about 115 miles of pipelines with diameters in the range of 10 to 20 inches.

For modeling the expected damage from traveling waves, the authors used a simpler version of the Memphis model. For the AWSS, they adopted the following model:

$$P_f = 1 - e^{-nL} \qquad [A-4]$$

where

P_f = probability that a pipe will have no flow (i.e., complete failure);

n = the mean break rate for the pipe; and

L = the length of the pipe.

No damage algorithms were provided for other seismic hazards (e.g., landslides, surface faulting or liquefaction, although the San Francisco Liquefaction study described below considers liquefaction effects on this system). To obtain the mean break rate, the authors of this study summarized pipeline damage statistics for traveling wave effects from five past earthquakes.

All pipes, independent of size, age, kind or location, were modeled with the same mean break rate value. No “leakage” failure modes were adopted. The range of break rates studied was from 0.02 breaks per kilometer to 0.325 breaks per kilometer with six intermediate values. The authors suggest that a break rate of 0.02/km corresponds to about Intensity VII, and a break rate of 0.10/km corresponds to about Intensity VIII.

A.3.5 Seattle, Washington

This USGS-sponsored study for Seattle, Washington explicitly differentiates between pipe damage caused by ground shaking and soil failure due to liquefaction [Ballantyne, Berg, Kennedy, Reneau and Wu]. This is a major refinement as compared to some earlier efforts.

The following damage algorithms are used for ground shaking effects:

$$n = a\, e^{b(MMI - 8)} \qquad [A-5]$$

where

n = repairs per kilometer, and a and b are adjusted to fit both the scatter in empirical evidence of damage from selected past earthquakes and engineering judgment. The results are shown in Figure A-3.

The damage algorithm for buried pipelines which pass through liquefied soil zones is described in Table A.3-3. This is also shown graphically in Figure A-4. Figures A-4 and A-5 show the suggested landslide and fault crossing algorithms, respectively.

Pipe Kind	Repairs (Breaks or Leaks) per km
Asbestos Cement	4.5
Concrete	4.5
Cast Iron	3.3
PVC	2.6
Welded Steel with Caulked Joints	2.6
Welded Steel with Gas or Oxyacetylene Welded Joints	2.4
Ductile Iron	1.0
Polyethylene	0.5
Welded Steel with arc-welded joints	0.5

Table A.3-3. Pipe Damage Algorithms Due to Liquefaction PGDs

In application, the authors compute the damage rate using equation A-5 based on MMI and the liquefaction-zone rate based on soil description. The higher of the two rates is applied to the particular pipe if the pipe is located in a liquefaction zone.

This study also refined some of the historical repair damage statistics to allow differentiation between leak and break damage. Undifferentiated damage is denoted as repairs.

- A leak represents joint failures, circumferential failures or round cracks, corrosion-related failures or pinholes and small blow-outs.
- A break represents longitudinal cracks, splits and ruptures. A full circle break of cast iron or asbestos cement pipe, for example, would also be defined as a break.

By reviewing the damage and repair data from the 1949 and 1969 Seattle, 1969 Santa Rosa, 1971 San Fernando Valley, 1983 Coalinga, and 1987 Whittier Narrows earthquakes, the following observations were made:

- In local areas subjected to fault rupture, subsidence, liquefaction or spreading ground, approximately 50% of all recorded repairs or damage have been breaks. The remaining 50% of all repairs or damage have been leaks.
- In local areas only subjected to traveling wave motions, approximately 15% of all recorded repairs or damage have been breaks. The remaining 85% of all repairs have been leaks.

A.3.6 Empirical Vulnerability Models

In this National Science Foundation sponsored study performed by the J. H. Wiggins Company [Eguchi et al], empirically based damage algorithms were developed for pipe in ground shaking, fault rupture, liquefaction and landslide areas. They were based on review of actual pipe damage from the 1971 San Fernando, 1969 Santa Rosa, 1972 Managua and the 1979 El Centro earthquakes. The algorithms are statistical in nature and compute the number of pipe breaks per 1,000 feet of pipe. The algorithms denote different break rates according to pipe type. Asbestos cement pipe generally had the poorest performance and welded steel had the best. The study also indicates that corroded pipe has break rates about three times those of uncorroded pipe.

This empirical evidence forms the basis of some of the more recent efforts, including the Seattle damage algorithms described above. The increased repair rate for corroded pipes also serves as partial basis for the pipeline fragility curves in the current study.

A.3.7 San Francisco Liquefaction Study

In this study [Porter et al] the repair rate per 1,000 feet of pipe was related to magnitude of permanent ground deformation (PGD). Data from the 1989 Loma Prieta, Marina District and the 1906 San Francisco, Sullivan Marsh and Mission Creek District earthquakes were used to develop a damage algorithm, as shown in Figure A-6. A key feature is that the repair rate is proportional, at least in some increasing fashion, to the PGD magnitude. Most of the San Francisco pipe which broke in liquefied areas in 1906 and 1989 was cast iron.

A.3.8 Empirical Vulnerability Model – Japanese and US Data

This 1975 study [Katayama, Kubo and Sito] developed an empirical pipeline damage model based on observed repair rates from actual earthquakes. Several of these earthquakes were in Japan: 1923 Kanto-Tokyo, 1964 Nigata, 1968 Tokachi-Oki.

The repair rate is related to soil condition and peak ground acceleration. It does not distinguish between damage caused by ground shaking and permanent ground deformations such as liquefaction, landslides or fault crossing. Figure A-7 shows the algorithm.

A key conclusion drawn from Figure A-7 is that “poor” to “good” soil conditions bear a critical relationship to overall pipe repair rates. Repair rates in “poor” soils are an order of magnitude higher than repair rates in better soils. Another facet is that this early effort tried to relate peak ground acceleration to pipe repair rates. More recent efforts have shown that peak ground acceleration is not a good predictor of actual energies that are damaging to pipes. Peak ground velocity (PGV) is a better predictor. PGVs are further discussed in the Barenberg work described below.

A.3.9 Wave Propagation Damage Algorithm - Barenberg

This 1988 study [Barenberg] computes a relationship between buried cast iron pipe damage, measured in breaks/km, observed in four past earthquakes, and peak ground velocities experienced at the associated sites. The relationship is for damage caused by transient ground motions only (i.e., wave propagation effects). Figure A-1 shows the algorithm.

This study makes a major improvement over previous studies. Empirical pipe damage is related to actual levels of ground shaking at peak ground velocity rather than indirectly and imperfectly at Modified Mercalli Intensity (MMI) levels. MMIs were often used in the past when no seismic instruments were available to record actual ground motions. The MMI scale relates observed items like broken chimneys to ground shaking levels. With the vastly increasing number of seismic instruments installed, each future earthquake will add to the empirical database of actual ground motions versus actual observed damage rates.

Another important reason to adopt peak ground velocity as the predictor of ground-shaking induced pipe repairs is that there are mathematical models to relate ground velocities to strains induced in pipes. This mathematical model states that peak seismic ground strain is directly proportional to the peak ground velocity. The pipes conform to ground movements up to very high strain levels, and the strain/deformation in the pipe is correlated to the ground strain. Hence, empirical relations relating damage to peak ground velocity have a better physical basis than those using MMI.

A.3.10 Wave Propagation Damage Algorithm – O'Rourke and Ayala

This 1988 study [Barenberg] computes a relationship between buried cast iron pipe damage observed in four past earthquakes and peak ground velocities experienced at the associated sites. The relationship is for damage caused by transient ground motions only (i.e., wave propagation effects). Figure A-2 shows the algorithm.

A subsequent work [O'Rourke, M., and Ayala, G., 1994] provides additional empirical data points for pipe damage versus peak ground velocity that were not included in the Barenberg work. The additional data is for large-diameter (20- and 48-inch diameter) asbestos cement, concrete, prestressed concrete, as well as distribution diameter cast iron and asbestos cement pipe types that were subjected to pipe failures in the 1985 Mexico City, 1989 Tlahuac and 1983 Coalinga earthquakes.

Some detailed pipe data was lost in the 1985 Mexico earthquake because the water company's facility collapsed and records were lost. However, it appears that the bulk of the large diameter transmission pipe that is represented by the data in Figure A-2 is for segmented AC and concrete pipe. Joints were typically cemented. A least squares regression line ($R^2 = 0.71$) is plotted for convenience.

The following observations are made:

1. The empirical evidence (Figures A-1 and A-2) does not clearly suggest a "turn over" point in the damage algorithm as is suggested in the Seattle study (Figure A-3) at MMI = VIII, or PGV = 20 inches/second after conversion.

2. The empirical data is more severe at very low levels of shaking than is suggested in the Seattle study. The differences are smaller at strong levels of shaking. In practice, this may not be of great concern, as being greatly off at very low levels of shaking probably does not meaningfully change the level of overall system damage.

A.3.11 Damage Algorithms – Loma Prieta – EBMUD

This study of the EBMUD water distribution system [Eidinger 1998, Eidinger et al 1995, unpublished work] presents the empirical damage data of more than 3,300 miles of pipelines that were exposed to various levels of ground shaking in the 1989 Loma Prieta earthquake. An effort to collate all pipeline damage from the Loma Prieta and Northridge earthquakes is available from http://quake.abag.ca.gov. Using GIS techniques, the entire inventory of EBMUD pipelines was analyzed to estimate the median level of ground shaking at each pipe location. Attenuation models used in this study were calibrated to provide estimates of ground motions approximately equal to those observed at 12 recording stations within the EBMUD service area. Then, careful review was made of each damage location where pipes actually were repaired in the first few days after the earthquake. See Figure A-8 for a map of damage locations.

PGV/Material	Cast Iron RR/1000 feet	Asbestos Cement RR/1000 feet	Welded Steel RR/1000 feet
3 Inches/sec	0.00560	0.00341	0.00253
5 Inches/sec	0.01230	0.00239	0.00841
7 Inches/sec	0.00517	0.00086	0.00610
17 Inches/sec	0.09189	0.01230	0.14826

Table A.3-4. Pipe Repair Rates per 1,000 Feet, 1989 Loma Prieta Earthquake

The damaged pipe locations were binned into twelve groups, representing four average levels of PGV and three types of pipeline: cast iron, asbestos cement with rubber gasketed joints and welded steel with single lap-welded joints. Repair rates were calculated for each bin. The total inventory of pipelines included about 752 miles of welded steel pipe, 1,008 miles of asbestos cement pipe and 1,480 miles of cast iron pipe. There were 135 pipe repairs to the EBMUD system from the Loma Prieta earthquake. Mains: 52 cast iron, 46 steel, 13 asbestos cement, 2 PVC. Service connections: 22 up to meter, but damage on customer side of the meter was not counted). Tables A.3-4 and A.3-5 show the results.

PGV/Material	Cast Iron Miles of Pipe	Asbestos Cement Miles of Pipe	Welded Steel Miles of Pipe
3 Inches/sec	473.2	444.7	374.2
5 Inches/sec	123.2	79.2	45.0
7 Inches/sec	878.8	438.3	279.3
17 Inches/sec	20.6	46.2	60.0

Table A.3-5. Length of Pipe in Each Repair Rate Bin, Loma Prieta Earthquake

The 12 data points from Table A.3-4 are plotted in Figure A-9. An exponential curve fit is drawn through the data. The scatter shown in this plot is not unexpected, in that damage data for three different kinds of pipe are all combined into one regression curve.

The same data in Figure A-9 is plotted in Figure A-10, but this time using three different regression curves, one for each pipe material. Table A.3-6 provides the coefficients for the regression relationships.

Value/Material	Cast Iron RR/1000 feet	Asbestos Cement RR/1000 feet	Welded Steel RR/1000 feet
a	0.000737	0.000725	0.000161
b	1.55	0.77	2.29
PGV	in/sec	in/sec	in/sec
R^2	0.71	0.26	0.90

Table A.3-6. Regression Curves for Loma Prieta Pipe Damage, RR = a (PGV)^b, R^2

One issue brought out by examining Figures A-9 and A-10 is whether a pipe fragility curve should be represented by:

- RR = k a $(PGV)^b$, where (k) is some set of constants that relate to the specific pipe material, joinery type, age, etc., and (a,b) are constants developed by the entire empirical pipe database as in Figure A-9; or
- RR = a (PGV)^b, where (a,b) are constants specific to the particular pipe type, ideally with all other factors (e.g., joinery, age, etc.) being held constant as in Figure A-10.

The standard error terms (R^2) in the regression relationships in Table A.3-6 seem “better” than those in Figure A-9. However, this might be because the regression relationships in Figure A-10 use fewer data points (4) than the regression line in Table A.3-6 and Figure A-9 (12). Based on engineering judgment, R^2 values like 0.90 for the welded steel pipe curve (Figure A-10) appear to be too high, and are considered more of an artifact of a small data set than being a true predictor of uncertainty. The performance of steel pipe is also known to be dependent on the age, corrosive soils, quality of construction of the welds, diameter, and other factors, none of which are accounted for in the two parameter regression models in Figures A-9 or A-10.

Another key observation from Figure A-10 is that asbestos cement pipe (with gasketed joints) appears to perform better than cast iron or welded steel pipe, at least for damage induced by ground shaking. This is in contrast to Figure A-3, which ranks welded steel better than cast iron, and asbestos cement the worst. As also demonstrated in Section A.3.12, the same trend is seen in the 1994 Northridge earthquake, where asbestos cement pipe performed better than ductile iron pipe or cast iron pipe. Based on the rigor of the analyses for the Loma Prieta and Northridge data sets, it would appear that the trend for asbestos cement pipe in Figure A-3 is wrong. This might be due to a reliance on engineering judgment for the performance of rubber gasketed AC pipe, as the empirical evidence of AC pipe performance from Loma Prieta and Northridge was not available when Figure A-3 was developed.

Some researchers that have suggested that pipe damage rates seem to be a function of pipe diameter (see Section 4.4.7).

Tables A.3-7, A.3-8 and A.3-9 provide the EBMUD – Loma Prieta database of pipe lengths and pipe repairs for cast iron, welded steel and asbestos cement pipe, respectively. Figure A-11 summarizes the empirical evidence for the 1989 Loma Prieta earthquake. Tables A.3-10 and A.3-11 provide the length of pipe and number of repairs for each data point in Figure A-11.

PGV	Pipe Diameter, Inches																	
inch/sec	4		6		8		10		12		16		20		24		30	
	L	n	L	n	L	n	L	n	L	n	L	n	L	n	L	n	L	n
3	98.32	0	266.07	9	60.73	2	11.59	0	18.22	0	9.5	0	1.9	0	0.35	0	0	0
5	30.16	3	60.87	3	21.25	1	1.35	0	7.79	0	0.46	0	0.28	0	0	0	0.02	0
7	190.28	4	450.57	14	132.05	5	23.84	0	45.55	0	11.23	0	15.13	0	1.93	0	0	0
13	0.47	5	0.79	0	0.49	0	0	0	0.11	0	0.08	0	0	0	0	0	0	0
16	0.6	0	0.32	0	0.83	0	0.7	0	0.62	0	0	0	0.24	0	0	0	0	0
17	1.33	0	3.35	5	2.59	0	1.6	1	2.61	3	0.5	0	0.54	1	0.52	0	0	0
19	0.27	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	321.42	12	782	31	217.94	8	39.08	1	74.8	3	21.77	0	18.09	1	2.8	0	0.02	0
Notes																		
L = length of pipeline in miles within the specified PGV bin																		
n = number of repairs																		
See Section A.3.11 for further description of the data																		

Table A.3-7. Cast Iron Pipe Damage, 1989 Loma Prieta Earthquake, EBMUD

PGV	Pipe Diameter Inches																									
inch/sec	4		6		8		10		12		16		20		24		30		36		42		48		60	
	L	n	L	n	L	n	L	n	L	n	L	n	L	n	L	n	L	n	L	n	L	n	L	n	L	n
3	1.01	0	71.95	2	77.78	0	0.07	0	112.2	2	48.22	0	20.15	1	19.19	0	6.28	0	8.35	0	1.12	0	4.84	0	0.49	0
5	0.11	0	3.96	1	7.75	0	0.03	0	11.53	0	1.79	0	0.33	0	5.45	0	0.93	0	8.66	0	1.17	0	1.87	0	0.64	1
7	1.11	0	25.66	1	45.17	4	0.16	0	61.58	2	44.82	0	15.08	0	17.73	0	19.9	1	29.48	0	4.82	1	6.02	0	4.52	0
13	0.06	0	0.65	0	1.1	0	0	0	0.09	0	0.43	0	0.19	0	0	0	0.23	0	0	0	0	0	0	0	0	0
15	0.04	0	0.8	0	5.06	0	0.01	0	5.9	2	0.65	0	0.41	0	2.1	0	0	0	1.95	0	1.14	0	0	0	0	0
17	0	0	5.58	25	9.21	12	0.06	0	15.14	7	3.42	0	0.03	1	2.03	1	0.62	0	0.44	0	0	0	0	0	0	0
19	0	0	0.25	0	0.68	0	0	0	1.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	2.33	0	108.9	29	146.8	16	0.33	0	207.5	13	99.33	0	36.19	2	46.5	1	27.96	1	48.88	0	8.25	1	12.73	0	5.65	1

Notes
L = length of pipeline in miles within the specified PGV bin
n = number of repairs
See Section A.3.11 for further description of the data

Table A.3-8. Welded Steel Pipe Damage, 1989 Loma Prieta Earthquake, EBMUD

PGV	Pipeline Diameter, Inches									
inch / sec	4		6		8		10		12	
	L	n	L	n	L	n	L	n	L	n
3	7.8	0	299.27	5	124.4	2	0.43	0	12.76	1
5	2.87	0	50.91	0	18.11	1	0	0	7.29	0
7	11.89	0	273.69	2	129.89	0	0.1	0	22.6	0
13	0	0	1.36	0	0.63	0	0	0	0	0
15	0.43	0	3.97	1	5.22	1	0.04	0	2.36	0
17	0.68	0	9.66	0	15.2	1	1.28	0	1.41	0
19	0	0	0.86	0	2.36	0	0	0	0.75	0
21	0	0	0	0	0	0	0	0	0	0
Total	23.67	0	639.72	8	295.81	5	1.85	0	47.17	1

Notes
L = length of pipeline in miles, within the specified PGV bin
n = number of repairs
See Section A.3.11 for further description of the data

Table A.3-9. Asbestos Cement Pipe Damage, 1989 Loma Prieta Earthquake, EBMUD

Nominal Diameter (inches)/Material	Cast Iron Miles of Pipe	Asbestos Cement Miles of Pipe	Welded Steel Miles of Pipe
4	321	–	–
6	784	663	111
8	218	296	147
10 to 12	114	49	208
16 to 20	43	–	136
24 to 60	–	–	151

Table A.3-10. Pipe Lengths, 1989 Loma Prieta Earthquake, By Diameter

Nominal Diameter (inches)/Material	Cast Iron Number of Repairs	Asbestos Cement Number of Repairs	Welded Steel Number of Repairs
4	12	–	–
6	31	8	29
8	8	5	16
10 to 12	4	1	13
16 to 20	1	–	2
24 to 60	–	–	3

Table A.3-11. Pipe Repair, 1989 Loma Prieta Earthquake, By Diameter

The results in Figure A-11 show a clear trend of improvement in welded steel pipe performance with increasing pipe diameter; the trend is lesser for cast iron pipe and this opposite is true for asbestos cement pipe. The following reasons attempt to explain this behavior:

- **Welded steel pipe**. Small-diameter (6" and 8") welded steel pipe is used as distribution lines to customers. The utility uses only this kind of pipe in areas prone to "poor" soil conditions. Examination of the actual damage from the earthquake showed evidence of poor weld quality and corrosion. Smaller diameter pipe tends to get less attention in terms of inspection of welds. Pipe wall thickness for smaller diameter pipe is relatively thinner than for large diameter pipe, and a constant rate of corrosion would affect smaller diameter pipe to a greater degree. Larger diameter pipe of 16" and higher rarely has service taps or hydrants and has fewer valves, making the pipe less constrained and thus easier to accommodate ground movements without induced stress risers in the pipe. Large-diameter pipe tends to be located in areas away from the worst soils. Although the damage data due to liquefaction has been removed from Table 4-7a,b, it is possible that some liquefaction-induced data remains in the data set.

- **Cast iron pipe.** This involves issues similar to those of steel pipe, but without the weld quality factor.

- **Asbestos cement pipe.** There are no weld or corrosion issues related to asbestos cement pipe. The increase in repair rate with increasing diameter might be related to the smaller number of AC pipe repairs in the data set (14 total), or to factors such as different lay lengths between rubber gasketed joints, or to different insertion tolerances for each rubber gasketed joint for different diameter AC pipe. A rigorous analysis of damage rate versus lay lengths and joint geometry has not yet been performed.

To further examine the trends of diameter dependency versus damage rates, the data is recast for cast iron pipe in Figure A-12. No clear trends can be seen in Figure A-12 that would indicate a diameter dependency for cast iron pipe. As indicated in Section A.3.12, the Northridge data tends to show a good diameter dependency for cast iron pipe.

Based on the Loma Prieta and prior earthquake datasets, Eidinger and Avila [1999] presented a simplified way to assess the relative performance of different types of buried pipe due to wave propagation and permanent ground deformation. Tables A3.12 and A.3-13 show the results. The information presented in Tables A.3-12 and A.3-13 was based on the empirical database through the 1989 Loma Prieta earthquake. In Tables A.3-12 and A.3-13, the constants K_1 and K_2 are to be multiplied by the following "backbone" fragility curves:

Ground shaking: n = 0.00032 $(PGV)^{1.98}$, (n = repair rate per 1,000 feet of pipe, PGV in inches per second).

Permanent ground deformation: n = 1.03 $(PGD)^{0.53}$ (n = repair rate per 1,000 feet of pipe, PGD in inches).

Pipe Material	Joint Type	Soils	Diam.	K1	Quality
Cast iron	Cement	All	Small	0.8	B
Cast iron	Cement	Corrosive	Small	1.1	C
Cast iron	Cement	Non-corrosive	Small	0.5	B
Cast iron	Rubber gasket	All	Small	0.5	D
Welded steel	Lap - Arc welded	All	Small	0.5	C
Welded steel	Lap - Arc welded	Corrosive	Small	0.8	D
Welded steel	Lap - Arc welded	Non-corrosive	Small	0.3	B
Welded steel	Lap - Arc welded	All	Large	0.15	B
Welded steel	Rubber gasket	All	Small	0.7	D
Asbestos cement	Rubber gasket	All	Small	0.5	C
Asbestos cement	Cement	All	Small	1.0	B
Asbestos cement	Cement	All	Large	2.0	D
Concrete w/Stl Cyl.	Lap - Arc Welded	All	Large	1.0	D
Concrete w/Stl Cyl.	Cement	All	Large	2.0	D
Concrete w/Stl Cyl.	Rubber Gasket	All	Large	1.2	D
PVC	Rubber gasket	All	Small	0.5	C
Ductile iron	Rubber gasket	All	Small	0.3	C

Table A.3-12. Ground Shaking - Constants for Fragility Curve [after Eidinger]

Eidinger suggested a “quality” factor ranging from B to D. ‘B’ suggested reasonable confidence in the fragility curve based on empirical evidence; ‘D’ suggested little confidence.

The empirical evidence from the 1994 Northridge earthquake (see Section A.3.12) suggests that K_1 for small-diameter AC pipe might be about 0.4 times that for cast iron pipe; similarly, K_1 for small-diameter ductile iron pipe might be around 0.55. The K_1 constant for PVC pipe might be similar to that for AC pipe (0.4), still recognizing the lack of empirical data for PVC pipe. The relative performance of different pipe materials in the Kobe earthquake shown in Figure A-17 seems to support that DI pipe has a moderately lower break rate than the “average” pipe material, but possibly only about 50% lower than the average. The poor performance of small-diameter screwed steel pipe in the Northridge earthquake would suggest a K_1 value between 1.1 and 1.5 for that kind of pipe.

Pipe Material	Joint Type	K_2	Quality
Cast iron	Cement	1.0	B
Cast iron	Rubber gasket, mechanical	0.7	C
Welded steel	Arc welded, lap welds	0.15	C
Welded steel	Rubber gasket	0.7	D
Asbestos cement	Rubber gasket	0.8	C
Asbestos cement	Cement	1.0	C
Concrete w/Stl Cyl.	Welded	0.8	D
Concrete w/Stl Cyl.	Cement	1.0	D
Concrete w/Stl Cyl.	Rubber gasket	1.0	D
PVC	Rubber gasket	0.8	C
Ductile iron	Rubber gasket	0.3	C

Table A.3-13. Permanent Ground Deformations - Constants for Fragility Curve [after Eidinger]

A.3.12 Wave Propagation Damage Algorithms – 1994 Northridge – LADWP

A GIS-based analysis of the pipeline damage to the LADWP water system was performed by [after T. O'Rourke and Jeon, 1999]. This GIS analysis is based on the following:

- Data reported here is for cast iron, ductile iron, asbestos cement and steel pipe up to 24" in diameter. The pipeline inventory includes 7,848 km of cast iron pipe, 433 km of ductile iron pipe and 961 km of asbestos cement pipe.

- A total of 1,405 pipe repairs were reported for the LADWP distribution system based on work orders. Of these, 136 were removed from the statistics, either being due to damage to service line connections on the customer side of the meter; non-damage for any other reason (i.e., the work crew could not find the leak after they arrived at the site); duplications; or non-pipe related. An additional 208 repairs were removed from the statistics, being caused by damage to service connections on the utility side of the meter, at locations without any damage to the pipe main. An additional 48 repairs were removed from the statistics for pipes with diameters 24" and larger. Also, 74 repairs were removed from the statistics because the pipe locations, type or size was unknown at these locations This introduces a downward bias in the raw damage rates of 7.9% = 74/939. The remaining pipe data locations are: 673 repairs for cast iron pipe; 24 repairs for ductile iron pipe; 26 repairs for asbestos cement pipe and 216 repairs for steel pipe.

- Note that repair data in Section A.3.11 for Loma Prieta does not remove service line connection repairs, which represent 19.5% (= 22/113) of the repairs due to mains. Repair data in A.3.12 for Northridge does remove service line connection repairs, which represent 20.5% (= 208/1,013) of the repairs due to mains. This suggests that the quantity of repairs to service line connections would be about 20% of that for mains. The Loma Prieta database includes pipe material, diameter and location at every location; the Northridge database has one or more of these attributes missing at 7.9% of all locations and this data was omitted from the statistical analyses. Combining damage data between the two data sets needs to adjust for these differences.

- Damage to steel pipelines in the Northridge database of distribution pipelines was about 216 repairs. The average damage rate for steel pipe was twice as high as that for all other types of pipe combined. The reasons for this are as follows:
  - Steel pipelines are concentrated in hillsides and mountains, owing to a design philosophy that steel pipes should be used rather than cast iron pipes in hillside terrain.
  - Several types of steel pipe are included in the “steel” category, including (as reported by O’Rourke and Jeon): welded joints (43%); screwed joints (9%); elastomeric or victaulic coupling joints (7%); pipes with and without corrosion protection (e.g., coatings, sacrificial anodes, impressed current); pipes using different types of steel, including Mannesman and Matheson steel (30%), which is known to be prone to corrosion; and riveted pipe (1%). Pending more study of the steel pipeline database, repairs to these pipes have not yet been completely evaluated by T. O’Rourke and this data is not incorporated into the fragility formulations in this report. Percentages in this paragraph pertain to the percentage of all steel pipe repairs with the listed attributes. Mannesman and Matheson steel pipes were installed mostly in the 1920s and 1930s without cement lining and coating and have wall thicknesses generally thinner than modern installed steel pipes of the same diameter.
  - 4" diameter steel pipe use screwed fittings; 6" and larger steel pipe use welded slip joints.
- Pipe damage in locales subjected to large PGDs have been “removed” from the database.
- Pipe damage data were correlated (by T. O’Rourke and Jeon) with peak instrumented PGV to the nearest recording. Peak instrumented was the highest of the two orthogonal recorded horizontal motions, not the vector maximum. Most other data in this report is presented with regards to the average of the peak ground velocities from two orthogonal directions. This is commonly the measure of ground velocity provided by attenuation relationships.

A comparison of instrumental records revealed that the ratio of peak horizontal velocity to the average peak velocity from the two orthogonal directions was 1.21. Accordingly, this report presents “corrected” PGV data from the original work. Note that this correction was not applied to the data set used in Appendix G.

Unpublished work suggests that R^2 coefficients are higher if pipe damage from the Northridge earthquake is correlated with the vector maximum of the two horizontal recorded PGVs.

Tables A.3-14, A.3-15 and A.3-16 summarize the results. The data set included 4,900 miles of cast iron pipe of mostly 4", 6" and 8" diameter, and about 15% of the total for 10" through 24" diameter); 270 miles of ductile iron pipe of 4", 6", 8" and 12" diameter; and 600 miles of asbestos cement pipe of 4", 6" and 8" diameter. To maintain a minimum length of pipe for each reported statistic, each reported value is based on a minimum length of about 80 miles of cast iron pipe or 13 miles of ductile iron and asbestos cement pipe. This is done to smooth out spurious repair rate values if the length of pipe in any single bin is very small. At higher PGV values, this required digitization at slightly different PGV values for AC and DI pipe.

PGV (inches/sec)	Cast Iron RR/1000 feet	Cast Iron Miles of Pipe	Cast Iron Repairs
1.6	0.0	156.8	0
4.9	0.0079	1055.8	44
8.1	0.0230	1370.7	166
11.4	0.0300	699.7	111
14.6	0.0221	503.1	59
17.9	0.0337	313.9	56
21.1	0.0739	222.7	87
24.4	0.0662	111.7	39
27.7	0.0540	87.6	24
32.5	0.0064	117.6	4
39.0	0.0205	101.8	11
45.6	0.0246	84.8	11
52.1	0.1441	78.9	60

Table A.3-14. Pipe Repair Data, Cast Iron Pipe, 1994 Northridge Earthquake

PGV (inches/sec)	Asbestos Cement RR/1000 feet	Asbestos Cement Miles of Pipe	Asbestos Cement Repairs
1.6	0.0	98.3	0
4.9	0.0020	192.4	2
8.1	0.0193	147.2	15
11.4	0.0051	73.6	2
14.6	0.0	23.6	0
17.9	0.0	21.3	0
21.1	0.0873	15.2	7
29.3	0.0	13.4	0
35.8	0.0	15.8	0

Table A.3-15. Pipe Repair Data, Asbestos Cement Pipe, 1994 Northridge Earthquake

PGV (inches/sec)	Ductile Iron RR/1000 feet	Ductile Iron Miles of Pipe	Ductile Iron Repairs
1.6	0.0	26.4	0
4.9	0.0026	72.9	1
8.1	0.0196	57.9	6
11.4	0.0150	25.2	2
14.6	0.0282	20.1	3
17.9	0.0167	11.3	1
22.8	0.0887	12.8	6
29.3	0.0283	13.4	2
35.8	0.0131	14.4	1
47.2	0.0236	16.1	2

Table A.3-16. Pipe Repair Data, Ductile Iron Pipe, 1994 Northridge Earthquake

Figure A-13 shows the "backbone" regression curve. The R^2 value is low (0.26), suggesting that by combining all damage data into one plot leads to substantial scatter.

Figure A-14 compares the Loma Prieta (solid line) and Northridge (dashed line) backbone curves. As previously discussed, the Loma Prieta curve includes damage to service connections (about 20%), and the Northridge curve excludes damage due to incompleteness in the damage data set (about 8%). Also, the Loma Prieta database includes cast iron, asbestos cement and steel; the Northridge database include cast iron, asbestos cement and ductile iron. Given these differences, the two curves are not that different; i.e., the curves are mostly within 50% of each other.

A significant concern in developing regression curves of the sort shown in Figures A-9 through A-14 is that the “data points” are based on rates of damage. As such, one data point based on 100 miles of pipe is given the same influence as another data point based on 20 miles of pipe. Also, data points that have ‘0’ repair rate cannot be included in an exponentially based regression curve. One approach to this problem uses a Bayesian form of curve fitting as outlined in Appendix G. Another way to address this is to “weight” the repair data statistics such that each point represents an equal length of pipe. “Weighting” means that the regression analysis is performed with five data points representing a sample with 100 miles of pipe, and one data point representing a sample with 20 miles of pipe. The results of the “weighted” analysis are shown in Figure A-15. In developing Figure A-15, the Loma Prieta and Northridge data are normalized to account for the way the raw data was developed (e.g., service connections, missing main repair data). The main effects of the weighting are as follows:

- The influence of smaller samples of pipe at higher PGV levels has less influence on the regression coefficients.
- The regression curve using a weighted sample is almost linear (power coefficient = 0.99).

Figure A-16 shows a regression analysis for asbestos cement pipe for both the Loma Prieta and Northridge data sets.

Based on comparable levels of shaking, the relative vulnerability of each pipe material in just the Northridge data was evaluated. Table A.3-17 shows the results.

PGV (inch/sec)	Cast Iron RR/1000 feet	Asbestos Cement RR / 1000 feet	Ductile Iron RR/1000 feet	Average RR/1000 feet	CI/ Average	AC/ Average	DI/ Average
5.9	0.0079	0.0020	0.0026	0.0041	1.902	0.476	0.622
9.8	0.0230	0.0197	0.0197	0.0208	1.105	0.948	0.948
13.8	0.0300	0.0052	0.0152	0.0168	1.790	0.307	0.903
17.7	0.0221	–	0.0288	0.0255	0.869	–	1.131
21.7	0.0337	–	0.0167	0.0252	1.338	–	0.662
25.6	0.0739	0.0894	0.0939	0.0857	0.861	1.043	1.096
Average	**–**	**–**	**–**	**–**	**1.311**	**0.693**	**0.894**

Table A.3-17. Pipe Repair Data, 1994 Northridge Earthquake

This suggests the relative vulnerability of these three pipe materials from the Northridge earthquake for areas subjected to ground shaking and no PGDs is as follows:

- Cast iron: 30% more vulnerable than average.
- Asbestos cement: 30% less vulnerable than average.
- Ductile iron: 10% less vulnerable than average.

A.3.13 Relative Pipe Performance – Ballantyne

Ballantyne presents a model to consider the relative performance of pipelines in earthquakes that differentiates the properties of the pipe barrel from the pipe joint.

- Pipe joints usually fail from extension or pulled joints; compression, split or telescoped joints; or bending or rotation.
- Pipe barrels usually fail from shear, bending, holes in the pipe wall or splits.

Holes in pipe walls are usually the result of corrosion. Steel or iron pipe can be weakened by corrosion; asbestos cement pipe, by decalcification; and PVC pipe, by fatigue.

Given these issues, Ballantyne rates various pipe types using four criteria: ruggedness, or strength and ductility of the pipe barrel; resistance to bending failure; joint flexibility; and joint restraint. Table A.3-18 presents these findings as 1 = low seismic capacity and 5 = high seismic capacity.

Material Type/diameter	**AWWA Standard**	**Joint Type**	**Ruggedness**	**Bending**	**Joint Flexibility**	**Restraint**	**Total**
Polyethylene	C906	Fusion	4	5	5	5	19
Steel	C2xx series	Arc Welded	5	5	4	5	19
Steel	None	Riveted	5	5	4	4	18
Steel	C2xx series	B&S, RG, R	5	5	4	4	18
Ductile Iron	C1xx series	B&S, RG, R	5	5	4	4	18
Steel	C2xx	B&S, RG, UR	5	5	4	1	15
Ductile iron	C1xx series	B&S, RG, UR	5	5	4	1	15
Concrete with steel cylinder	C300, C303	B&S, R	3	4	4	3	14
PVC	C900, C905	B&S, R	3	3	4	3	13
Concrete with steel cylinder	C300, C303	B&S, UR	3		4	1	12
AC > 8" diameter	C4xx series	Coupled	2	4	5	1	12
Cast Iron > 8" diameter	None	B&S, RG	2	4	4	1	11
PVC	C900, C905	B&S, UR	3	3	4	1	11
Steel	None	Gas welded	3	3	1	2	9
AC ≤ 8" diameter	C4xx series	Coupled	2	1	5	1	9
Cast iron ≤ 8" diameter	None	B&S, RG	2	1	4	1	8
Cast iron	None	B&S, rigid	2	2	1	1	6
B&S = Bell and spigot. RG = rubber gasket R = restrained UR = unrestrained							

Table A.3-18. Relative Earthquake Vulnerability of Water Pipe

By comparing the rankings in Tables A.3-18 against those in Tables A.3-12 and A.3-13, the following trends emerge:

- Both tables rank welded steel pipe as nearly the best pipe. Table A.3-12 provides substantial downgrades for cases where corrosion is likely. Evidence from the Northridge and Loma Prieta earthquakes strongly indicates that corrosion is an important factor.

- Table A.3-18 presents high density polyethylene pipe (HDPE) as being very rugged. To date, there is essentially no empirical evidence of HDPE performance in water systems, but it appears to have performed well in gas distribution systems. Limited tests on pressurized HDPE pipe have shown strain capacities before leak in excess of 25% for tensile and 10% for compression, which suggests very good ruggedness. HDPE pipe is not susceptible to corrosion. There remains some concern about the long-term use and resistance of HDPE pipe to intrusion of certain oil-based compounds; this should first be adequately resolved, then the use of HDPE pipe in areas prone to PGDs may be very effective in reducing pipe damage.

- Table A.3-18 suggests that unrestrained ductile iron pipe is more rugged than AC pipe; this reflects common assumptions about the ductility of DI pipe, but in some cases does not match the empirical evidence, as in Northridge 1994, where AC pipe performed better than DI pipe.

Ballantyne suggests that in high seismic zones (Z • 0.4g), DI pipe, steel pipe and HDPE with fusion welded joints should be used. For purposes of this report, these recommendations appear sound, although the use of these materials might best be considered for any seismically active region (Z • 0.15g) with local soils prone to PGDs. In areas with high PGVs (Z • 0.4g), the use of rubber gasketed AC, DI or PVC pipe might still yield acceptably good performance.

A.3.14 Pipe Damage Statistics – 1995 Kobe Earthquake

The 1995 Hanshin-Awaji earthquake (often called the Hyogo-Ken Nanbu (Kobe) earthquake) was a M 6.7 crustal event that struck directly beneath much of the urbanized city of Kobe, Japan. At the time of the earthquake, the pipeline inventory for the City of Kobe's water system included 3,180 km of ductile iron pipe (push-on joint), 237 km of special ductile iron pipe with special flexible restrained joints, 103 km of high-pressure steel welded pipe, 309 km of cast iron pipe with mechanical joints and 126 km of PVC pipe with push-on gasketed joint [Eidinger et al, 1998].

The City of Kobe's water system suffered 1,757 pipe repairs to mains. The average damage rate to pipe mains was 0.439 repairs per km. The repairs could be classified into one of three types: damage to the main pipe barrel by splitting open; damage to the pipe joint by separating; and damage to air valves and hydrants. The damage rate was divided about 20%-60%-20% for these three types of repairs, respectively. Average pipe repair rates were about 0.2/km for PVC pipe; 1.3/km for CI pipe; 0.25/km for ductile iron pipe with push-on or regular restrained joints; and 0.15/km for welded steel pipe.

Figure A-17 shows the damage rates for pipelines in Kobe, along with the wave propagation damage algorithm, in Tables A.3-4, A.3-14, A.3-15, A.3-16 and Figures A-1 and A-2. The Kobe data is plotted as horizontal lines; meaning the data is not differentiated by level of ground shaking. Also, the Kobe data is not differentiated between damage from PGVs or PGDs. Note that while the ratio of damage between pipeline materials for Kobe is known, to say that one pipe material is that much better than another may be misleading, as the inventory of different pipe materials may have been exposed to differing levels of hazards. The need exists for a GIS evaluation for the Kobe pipe inventory in a manner similar to that done for Loma Prieta 1989 (see Section A.3.11) or Northridge 1994 (see Section A.3.12). Shirozu et al [1996] have performed an analysis of the Kobe data set and their findings are included in the data set used for evaluation of the PGV-based pipeline fragility curves. Table A.3-19 provides a complete breakdown of the pipe damage for this earthquake.

An additional 89,584 service line repairs were made in Kobe [Matsushita]. The service line failure rate was 13.8% of all service lines in the city. The high rate of damage to service line connections reflects the large number of structures and roadways that were damaged or destroyed in the earthquake.

The Cities of Kobe and Ashiya had recently installed a special type of ductile iron pipe, so-called "S and SII Joint Pipe." A total inventory of 270 km of this type of pipeline was installed at the time of the earthquake and no damage was reported to this type of pipeline. The key features were ductile iron body pipe with restrained slip joints at every fitting. Each joint could extend and rotate moderately. This type of pipeline was installed at about a 50% cost premium to regular push-on type joint ductile iron pipeline.

In the neighboring city of Ashiya, the pipeline inventory included 192 km of pipelines. This included 58 km of ductile iron pipe with restrained joints, 96 km of cast iron pipe, 2 km of steel pipe, 23 km of PVC pipe and 14 km of special ductile iron pipe with flexible restrained joints. A total of 303 pipe repairs were made for this water system, an average 1.58 repairs/km = 0.48 repairs/1,000 feet [Eidinger et al, 1998]. The higher damage rate for Ashiya than for Kobe is partially explained in that 100% of Ashiya was exposed to strong ground shaking, whereas perhaps only two-thirds of Kobe was similarly exposed; also, Ashiya had a somewhat higher percentage of cast iron pipe.

A.3.15 Pipe Damage Statistics – Recent Earthquakes

The damage to water system pipelines in recent (1999-2001) earthquakes is briefly summarized in this section. Since sufficiently accurate databases of pipe damage were unavailable at the time of this report, that data is not included in the statistical analyses.

1999 Kocaeli – Izmit (Turkey) Earthquake

The M_w 7.4 Kocaeli (Izmit) earthquake of August 17, 1999 in Turkey led to widespread damage to water transmission and distribution systems that serve a population of about 1.5 million people. Potable water was lost to the bulk of the population immediately after the earthquake, largely due to damage to buried pipelines.

The most common inventories of pipe material were welded steel pipe in large-diameter transmission pipelines and rubber gasketed asbestos cement pipe in most distribution pipelines.

Both transmission and distribution pipelines were heavily damaged by this earthquake. Some of the damage was due to rupture at fault offset, some was due to widespread liquefaction and some was due to strong ground shaking.

Bureau	Type of Pipe														Unknown
		Straight Pipe	Bends	Branches	Other	Subtotal	Slip Out Straight Pipe	Slip Out Fitting	Failure Straight Pipe	Failure Fitting	Intrusion Straight Pipe	Intrusion Fitting	Unknown	Subtotal	Subtotal
Kobe City	DI A K T	9	0	1	0	10	669	23	0	0	5	0	3	700	0
	CI lead, rubber	155	44	36	18	253	118	13	6	3	0	0	1	141	0
	PVC TS	11	0	0	0	11	11	1	1	0	0	0	0	13	0
	Welded Steel SP	9	1	0	0	10	0	0	3	0	0	0	0	3	0
	Steel Threaded SGP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	AC rubber gasket	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Unknown	16	1	3	0	20	99	2	1	1	0	0	0	103	0
	Subtotals	200	46	40	18	304	897	39	11	4	5	0	4	960	0
Ashiya City	DI A K T	0	0	0	0	0	65	18	0	0	0	0	3	86	4
	CI lead, rubber	54	3	9	1	67	3	0	14	0	0	0	0	17	4
	PVC TS	33	2	2	0	37	10	0	61	2	0	0	1	74	5
	Welded Steel SP	1	0	0	0	1	0	0	0	0	0	0	1	1	0
	Steel Threaded SGP	0	0	0	0	0	0	0	1	0	0	0	0	1	0
	AC rubber gasket	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Unknown	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Subtotals	88	5	11	1	105	78	18	76	2	0	0	5	179	13
Nishinomiya City	DI A K T	0	0	0	0	0	234	10	0	0	4	0	8	256	0
	CI lead, rubber	68	8	10	0	86	85	2	2	0	1	0	0	90	0
	PVC TS	52	24	12	0	88	51	15	56	0	3	0	3	128	0
	Welded Steel SP	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Steel Threaded SGP	2	1	0	0	3	1	0	1	0	0	0	0	2	0
	AC rubber gasket	30	0	1	0	31	9	0	2	0	0	0	1	12	0
	Unknown	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Subtotals	153	33	23	0	209	380	27	61	0	8	0	12	488	0

Table A.3-19. Pipe Damage Statistics – 1995 Hanshin Earthquake

Bureau	Type of Pipe														Unknown
		Straight Pipe	Bends	Branches	Other	Subtotal	Slip Out Straight Pipe	Slip Out Fitting	Failure Straight Pipe	Failure Fitting	Intrusion Straight Pipe	Intrusion Fitting	Unknown	Subtotal	Subtotal
Takarazuka City	DI A K T	0	0	0	0	0	97	0	0	0	0	0	1	98	6
	CI lead, rubber	2	6	7	0	15	0	0	2	0	0	0	0	2	3
	PVC TS	29	0	0	0	29	1	0	0	0	0	0	0	1	0
	Welded Steel SP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Steel Threaded SGP	0	0	0	0	0	1	0	0	0	0	0	0	1	0
	AC rubber gasket	44	0	0	0	44	0	0	0	0	0	0	0	0	0
	Unknown	2	0	0	0	2	0	0	0	0	0	0	0	0	2
	Subtotals	77	6	7	0	90	99	0	2	0	0	0	1	102	11
Amagasaki City	DI A K T	0	0	0	0	0	35	4	0	0	0	0	0	39	0
	CI lead, rubber	31	5	8	0	44	8	2	2	1	0	0	0	13	0
	PVC TS	0	0	0	0	0	1	0	3	0	0	0	0	4	0
	Welded Steel SP	2	0	0	0	2	0	0	2	0	0	0	0	2	0
	Steel Threaded SGP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	AC rubber gasket	8	0	0	0	8	0	0	0	0	0	0	0	0	0
	Unknown	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Subtotals	41	5	8	0	54	44	6	7	1	0	0	0	58	0
Osaka City	DI A K T	0	0	0	0	0	17	0	0	0	0	0	2	19	0
	CI lead, rubber	139	2	1	0	142	29	1	6	1	0	0	18	55	0
	PVC TS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Welded Steel SP	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Steel Threaded SGP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	AC rubber gasket	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Unknown	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Subtotals	140	2	1	0	143	46	1	6	1	0	0	20	74	1

Table A.3-19. continued

Bureau	Type of Pipe														Unknown
		Straight Pipe	Bends	Branches	Other	Subtotal	Slip Out Straight Pipe	Slip Out Fitting	Failure Straight Pipe	Failure Fitting	Intrusion Straight Pipe	Intrusion Fitting	Unknown	Subtotal	Subtotal
Hokudan-cho	DI A K T	1	0	0	0	1	9	0	0	0	1	0	1	11	3
	CI lead, rubber	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	PVC TS	22	5	5	0	32	7	0	7	0	0	0	1	15	0
	Welded Steel SP	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Steel Threaded SGP	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	AC rubber gasket	4	0	2	0	6	0	0	0	0	0	0	0	0	3
	Unknown	0	0	1	0	1	0	0	1	0	0	0	0	1	19
	Subtotals	29	5	8	0	42	16	0	8	0	1	0	2	27	25
Total	DI A K T	10	0	1	0	11	1126	55	0	0	10	0	18	1209	13
7 cities	CI lead, rubber	449	68	71	19	607	243	18	32	5	1	0	19	318	7
	PVC TS	147	31	19	0	197	81	16	128	2	3	0	5	235	5
	Welded Steel SP	14	1	0	0	15	0	0	5	0	0	0	1	6	1
	Steel Threaded SGP	3	1	0	0	4	2	0	2	0	0	0	0	4	0
	AC rubber gasket	86	0	3	0	89	9	0	2	0	0	0	1	12	3
	Unknown	19	1	4	0	24	99	2	2	1	0	0	0	104	21
	Subtotals	728	102	98	19	947	1560	91	171	8	14	0	44	1888	50

Table A.3-19. continued

Bureau										
	Total	Length, km	Damage Rate (Repairs/ km)	Air Valves	Gate Valves	Fire Hydrants	Snap taps and others	Unknown	Subtotal	Total Repairs
Kobe City	710	3452.1	0.206							
	394	316.4	1.245							
	24	128.6	0.187							
	13	104.9	0.124							
	0	0								
	0	0								
	123	0								
	1264	4002	0.316	127	281	60	25	0	493	1757
Ashiya City	90	72.1	1.248							
	88	89.4	0.984							
	116	22.9	5.066							
	2	0.35	5.797							
	1	0								
	0	0								
	0	0								
	297	184.745	1.608	2	53	0	10	0	65	362
Nishinomiya City	256	635.1	0.403							
	176	97.7	1.801							
	216	185.9	1.162							
	1	29.1	0.034							
	5	2.3	2.174							
	43	16.2	2.654							
	0	0								
	697	966.3	0.721	12	80	11	24	0	127	824

Table A.3-19. continued

Bureau										
	Total	Length, km	Damage Rate (Repairs/ km)	Air Valves	Gate Valves	Fire Hydrants	Snap taps and others	Unknown	Subtotal	Total Repairs
Takarazuka City	104	732	0.142							
	20	117	0.171							
	30	6.9	4.348							
	0	0								
	1	17	0.059							
	44	1.3	33.846							
	4	0								
	203	874.2	0.232	0	16	1	5	0	22	225
Amagasaki City	39	721.3	0.054							
	57	110.9	0.514							
	4	6.9	0.580							
	4	7.3	0.548							
	0	0								
	8	0.3	26.667							
	0	0								
	112	846.7	0.132	0	12	1	5	0	18	130
Osaka City	19	3508	0.005							
	197	1374	0.143							
	0	0								
	1	110	0.009							
	0	0								
	0	0								
	1	0								
	218	4992	0.044	0	0	0	4	13	17	235

Table A.3-19. continued

Bureau										
	Total	Length, km	Damage Rate (Repairs/ km)	Air Valves	Gate Valves	Fire Hydrants	Snap taps and others	Unknown	Subtotal	Total Repairs
Hokudan-cho	15	40.7	0.369							
	0	1.7	0.000							
	47	80.1	0.587							
	1	8.9	0.112							
	1	0								
	9	22.7	0.396							
	21	0								
	94	154.1	0.612	1	1	0	1	0	3	97
Total 7 cities	1233	9161.3	0.135							
	932	2107.1	0.442							
	437	431.3	1.013							
	22	260.545	0.084							
	8	19.3	0.415							
	104	40.5	2.568							
	149	0								
	2885	12020.1	0.240	142	443	73	74	13	745	3630

Table A.3-19 end

At this time, no precise inventory of pipeline damage is available. However, based on the level of efforts of crews to repair water pipelines and the percentage of water service restored within three weeks after the earthquake, between 1,000 and 3,000 pipe repairs would be required to completely restore water service. An average repair rate, possibly in the range of 0.5 to 1/km, was likely to have occurred in the strongest shaking areas, including the cities of Adapazari and Golcuk and the town of Arifye.

1999 Chi-Chi (Taiwan) Earthquake

The M_w 7.7 Chi-Chi (Ji-Ji) earthquake of September 21, 1999 in Taiwan led to 2,405 deaths and 10,718 injuries. Potable water was lost to 360,000 households immediately after the earthquake, largely due to damage to buried pipelines.

The country had about 32,000 km of water distribution pipelines; perhaps a quarter or more was exposed to strong ground shaking. The largest pipes, with diameters •1.5 meters, are typically concrete cylinder pipe or steel, with ductile iron pipe being the predominant material for moderate diameter pipe and a mix of polyethylene and ductile iron pipe for distribution pipe of •8 inch diameter.

At this time, the analysis of the damaged inventory to pipelines in this earthquake is incomplete. However, the following trends have been observed from preliminary data [Shih et al, 2000]:

- About 48% of all buried water pipe damage is due to ground shaking, a ratio that may change under future analysis. The remaining damage is due to liquefaction (2%), ground collapse (11%), ground cracking and opening (10%), horizontal ground movements (9%), vertical ground movement (16%) and other (4%).
- For the town of Tsautuen, repair rates varied from 0.4/km to 7/km (PGA = 0.2g) to as high as 0.6/km (PGA = 0.6g).

2001 Gujarat Kutch (India) Earthquake

The M_w 7.7 Gujarat (Kutch) earthquake of January 26, 2001 in India led to about 17,000 deaths and about 140,000 injuries. Potable water was lost to over 1,000,000 people immediately after the earthquake, largely due to damage to wells, pump station buildings and buried pipelines.

There was about 3,500 km of water distribution and transmission pipelines in the Kutch District; perhaps 2,500 km was exposed to strong ground shaking. At the time of this report, estimates are that about 700 km of these pipelines will have to be replaced due to earthquake damage. It may take up to four months after the earthquake to complete pipe repairs.

A.4 References

ASCE, 1984, *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*, prepared by the ASCE Technical Council on Lifeline Earthquake Engineering, D. Nyman Principal Investigator, 1984.

Ayala, G. and O'Rourke, M., *Effects of the 1985 Michoacan Earthquake on Water Systems and other Buried Lifelines in Mexico*, National Center for Earthquake Engineering Report No. 89-009, 1989.

Ballantyne, D. B., Berg, E., Kennedy, J., Reneau, R., and Wu, D., *Earthquake Loss Estimation Modeling of the Seattle Water System*, Report to U.S. Geological Survey, Grant 14-08-0001-G1526, Oct. 1990.

Barenberg, M.D., "Correlation of Pipeline Damage with Ground Motion," *Journal of Geotechnical Engineering*, ASCE, Vol. 114, No. 6, June 1988.

Eguchi, R., T., Legg, M.R., Taylor, C. E., Philipson, L. L., Wiggins, J. H., *Earthquake Performance of Water and Natural Gas Supply System*, J. H. Wiggins Company, NSF Grant PFR-8005083, Report 83-1396-5, July 1983.

Eidinger, J., Maison, B. Lee, D., Lau, R, "EBMUD Water Distribution Damage in the 1989 Loma Prieta Earthquake," *4th US Conference on Lifeline Earthquake Engineering*, TCLEE, ASCE, San Francisco, 1995.

Eidinger, J. "Lifelines, Water Distribution System," in *The Loma Prieta, California, Earthquake of October 17, 1989, Performance of the Built Environment-Lifelines*, US Geological Survey Professional Paper 1552-A, pp A63-A80, A. Schiff Ed. Dec. 1998.

Eidinger, J., Lund, LeVal and Ballantyne, Don, "Water and Sewer Systems," in *Hyogo-Ken Nanbu (Kobe) Earthquake of January 17, 1995*, TCLEE Monograph 14, ASCE, 1998.

Eidinger, J., Avila, E., eds., *Guidelines for the Seismic Upgrade of Water Transmission Facilities*, ASCE, TCLEE Monograph No. 15, Jan. 1999.

Grigoriu, M., O'Rourke, T., Khater, M., "Serviceability of San Francisco Auxiliary Water Supply System," *Proceedings of 5th International Conference on Structural Safety and Reliability*, San Francisco, California 1989.

Hovland, H. J., and Daragh, R. D. "Earthquake-Induced Ground Movements in the Mission Bay Area of San Francisco in 1906," *Proceedings of the 2nd Specialty Conference of the Technical Council on Lifeline Earthquake Engineering.* ASCE, Aug. 1981.

Katayama, T., Kubo, K., and Sito, N., "Earthquake Damage to Water and Gas Distribution Systems," *Proceedings—US National Conference on Earthquake Engineering*, EERI, 1975.

Manson, M., *Reports on an Auxiliary Water Supply System for Fire Protection for San Francisco, California*, Report of Board of Public Works, San Francisco, California 1908.

Matsushita, M., “Restoration Process of Kobe Water system from the 1995 Hanshin-Awaji Earthquake,” in *Optimizing Post-Earthquake System Reliability, Proceedings of the 5th US Conference on Lifeline Earthquake Engineering*, TCLEE Monograph 16, ASCE, Aug. 1999.

McCaffery, M. A., and O'Rourke, T. D., "Buried Pipeline Response to Reverse Faulting During the 1971 San Fernando Earthquake," Earthquake Behavior and Safety of Oil and Gas Storage Facilities, Buried Pipelines an Equipment, PVP-Vol.77, New York, ASME, 1983.

Newmark, N.M., and Hall, W. J., "Pipeline Design to Resist Large Fault Displacement," Presented at the US National Conference of Earthquake Engineering, Ann Arbor, Michigan, June 1975.

O’Rourke, M.J., and Ayala, G., 1993, Pipeline Damage to Wave Propagation, *Journal of Geotechnical Engineering*, ASCE, Vol. 119, No. 9, 1993.

O’Rourke, T.D., and Jeon, S-S., “Factors Affecting the Earthquake Damage of Water Distribution Systems,” in *Optimizing Post-Earthquake Lifeline System Reliability*, TCLEE Monograph No. 16, ASCE, 1999.

O’Rourke, T. D., and Tawfik, M.S. “Effects of Lateral Spreading on Buried Pipelines During the 1971 San Fernando Earthquake,” *Earthquake Behavior and Safety of Oil and Gas Storage Facilities, Buried Pipelines and Equipment*, PVC,-Vol.77, New York, ASME, 1983.

Porter, K.A., Scawthorn C., Honegger, D. G., O’Rourke, T.D., and Blackburn, F., “Performance of Water Supply Pipelines in Liquefied Soil,” *Proceedings—4th US-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems*, NIST Special Publication 840, Aug. 1992.

Sato, Ryo and Myurata, Masahiko, *GIS-Based Interactive and Graphic Computer System to Evaluate Seismic Risks on Water Delivery Networks*, Dept. of Civil Engineering and Operations Research, Princeton University, Dec. 1990.

Schussler, H., “The Water Supply System of San Francisco, California,” Spring Valley Water Company, San Francisco, California, July 1906.

Shih, B., Chen, W., Hung, J-H., Chen, C-W., Wang, P-H., Chen, Y-C., and Liu, S-Y., “The Fragility Relations of Buried Water and Gas Pipes,” *International Workshop on Annual Commemoration of Chi-chi Earthquake, Taipei, September 18-20,* 2000.

Shinozuka, M. Takada, S. Ishikawa, H., *Seismic Risk Analysis of Underground Lifeline Systems With the Aid of Damage Probability Matrices*, NSF-PFR-78-15049-CU-2, Columbia University, Sept. 1978.

Shirozu, T., Yune, S., Isoyama, R., and Iwamoto, T., “Report on Damage to Water Distribution Pipes Caused by the 1995 Hyogoken-Nanbu (Kobe) Earthquake,” *Proceedings from the 6th Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction*, National Center for Earthquake Engineering Research Report NCEER-96-0012, Sept. 1996.

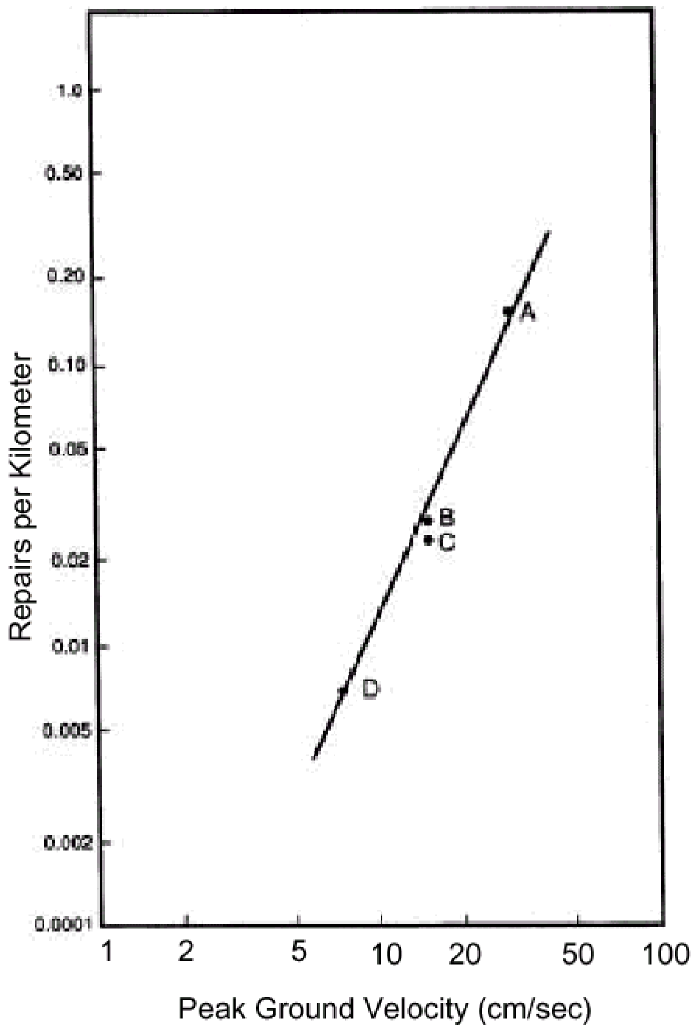
Toprak, Selcuk, *Earthquake effects on buried pipeline systems*, PhD Dissertation, Cornell University, Aug. 1998.

Wang, Leon, Shao-Ping S., and Shijie S., *Seismic Damage Behavior of Buried Pipeline Systems During Recent Severe Earthquakes in US, China and Other Countries*, ODU LEE-02, Old Dominion University, Dec. 1985.

Wang, L., *A New Look Into the Performance of Water Pipeline Systems From 1987 Whittier Narrows, California Earthquake*, Department of Civil Engineering, Old Dominion University, No. ODU LEE-05, Jan. 1990.

Youd, T. L. and Hoose, S. N. "Historic Ground Failures in Northern California Associated with Earthquakes," Geological Survey Professional Paper No. 993, US Geological Survey, Washington DC, GPO 1978.

A.5 Figures



A. 1971 San Fernando. Most common - 3 to 6 inch diameter pipes. PGV = 30 cm/sec.
Observed repair rate = 0.155 repairs / km

B. 1969 Santa Rosa. Most common - 3 to 6 inch diameter pipes. PGV = 15 cm/sec.
Observed repair rate = 0.028 repairs / km

C. 1971 San Fernando. Most common - 3 to 6 inch diameter pipes. PGV = 15 cm/sec.
Observed repair rate = 0.024 repairs / km

D. 1965 Puget Sound. Most common - 8 to 10 inch diameter pipes. PGV = 7.5 cm/sec.
Observed repair rate = 0.007 repairs / km

Note - all data from: O'Rourke, T.D., Factors affecting the performance of cast iron pipelines: A review of U.S. observations and research investigations,
Contractor Report 18, Transport and Road Res. Lab., Crowthorne, U.K.

Figure A-1. Wave Propagation Damage to Cast Iron Pipe [from Barenberg, 1988]

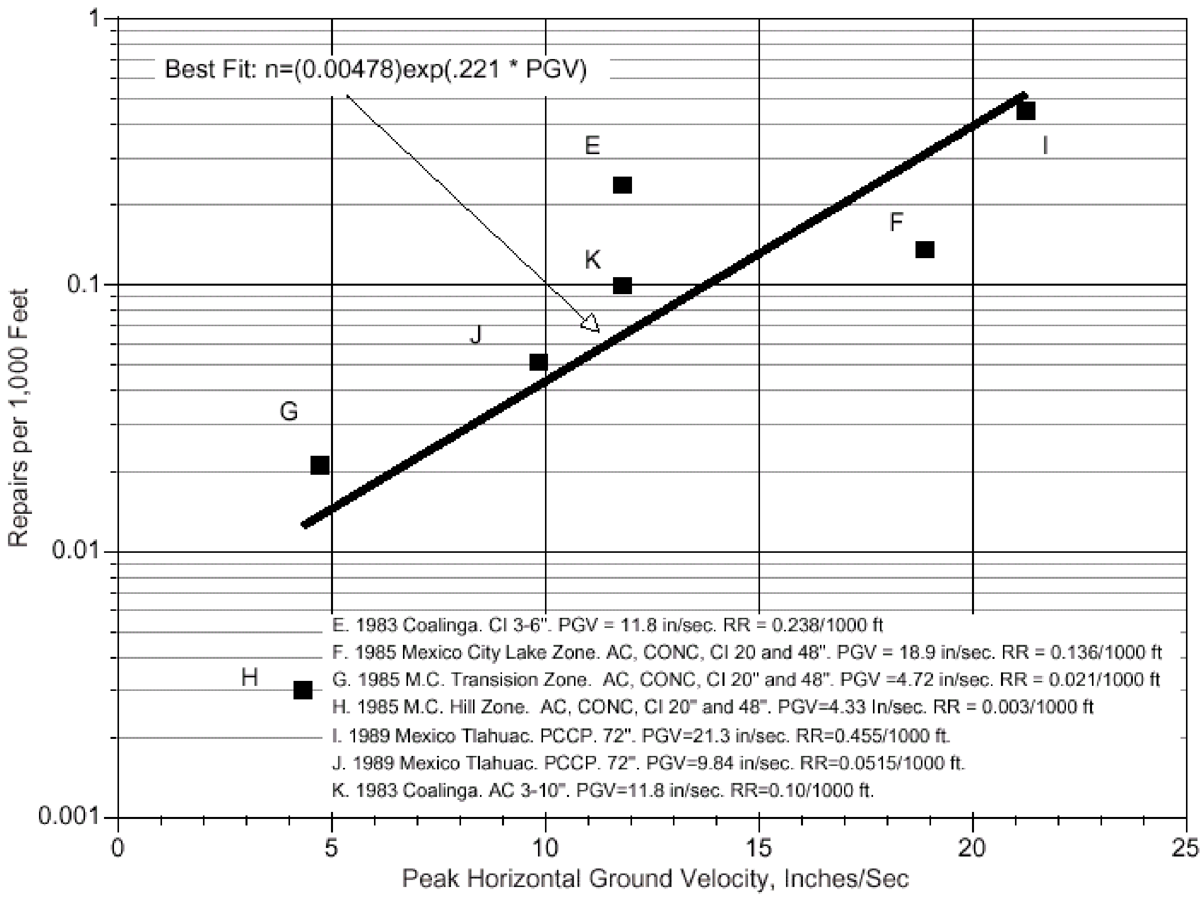


Figure A-2. Pipe Damage – Wave Propagation [from O'Rourke and Ayala, 1994]

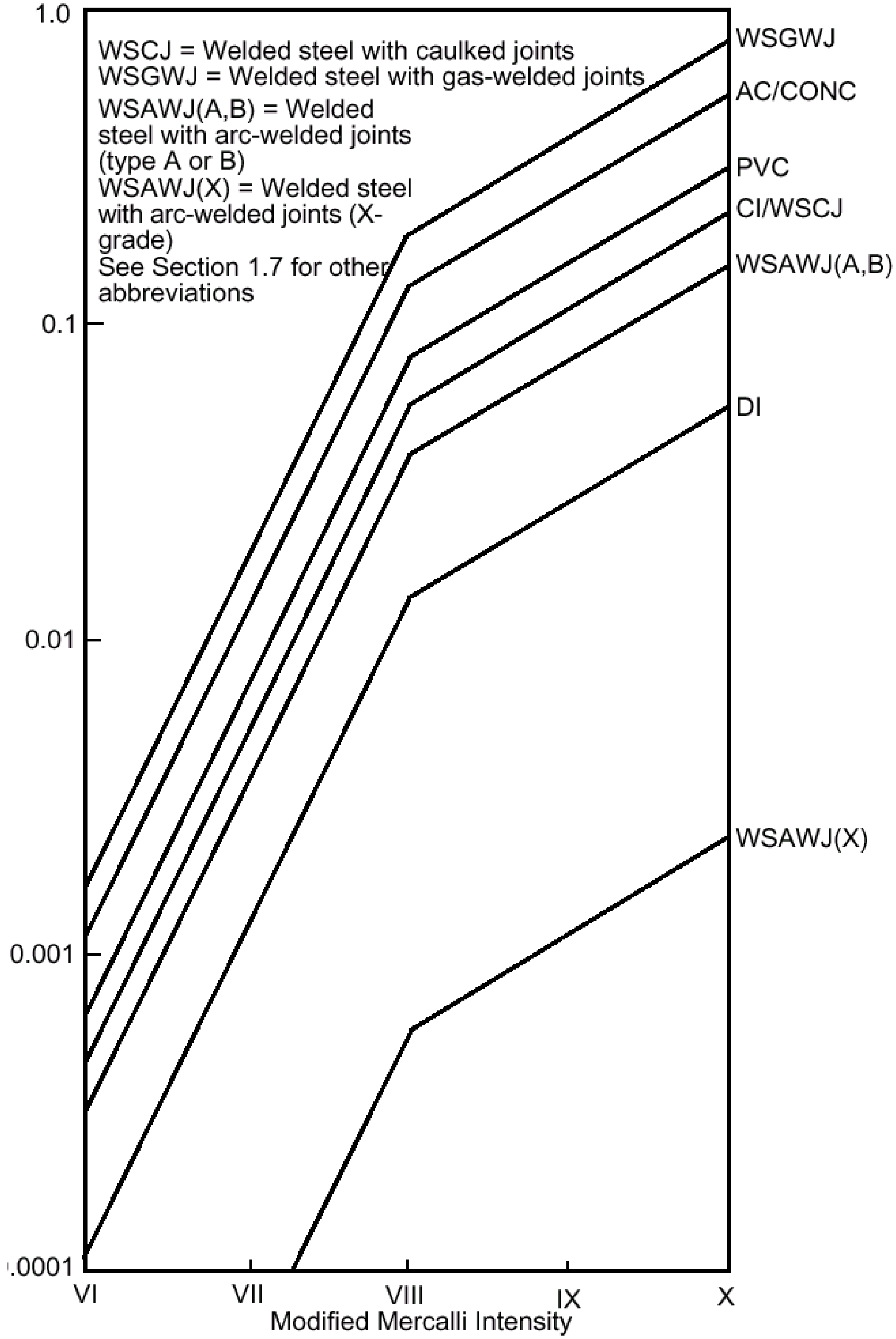


Figure A-3. Pipe Fragility Curves for Ground Shaking Hazard Only [from Ballentyne et al, 1990]

See Section 1.7 for abbreviations

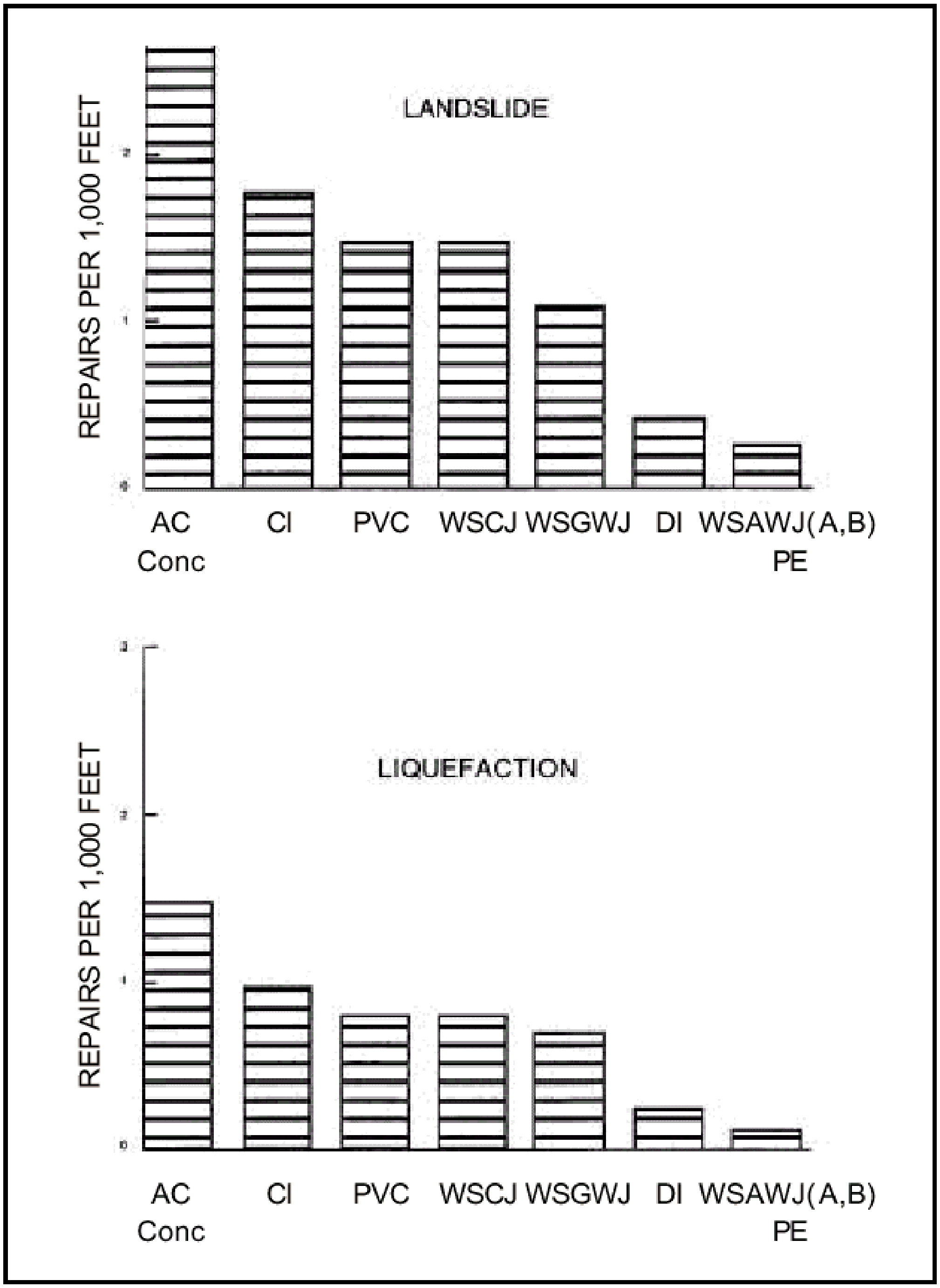


Figure A-4. Earthquake Vulnerability Models for Buried Pipelines for Landslides and Liquefaction

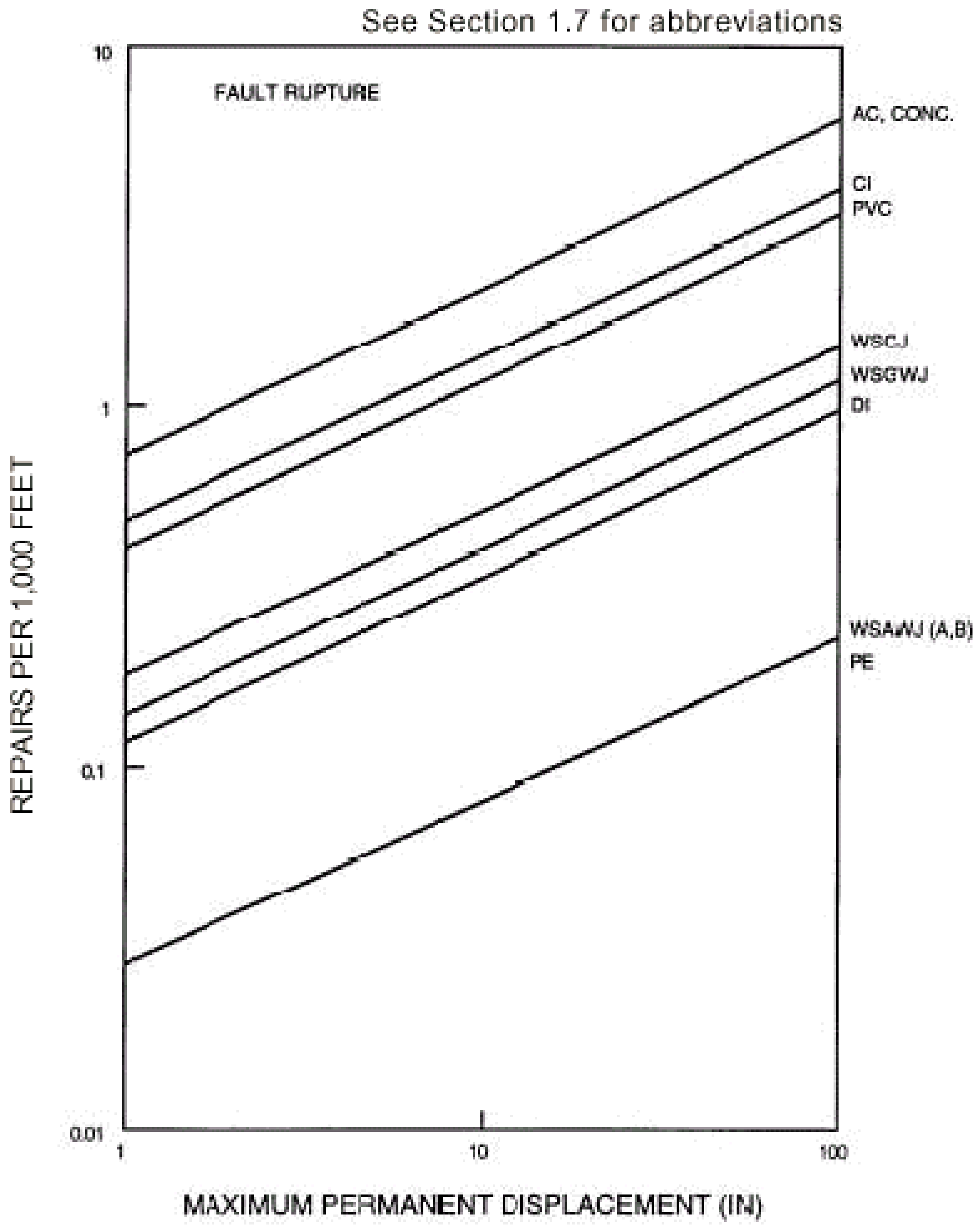


Figure A-5. Earthquake Vulnerability Models for Buried Pipelines for Fault Offset

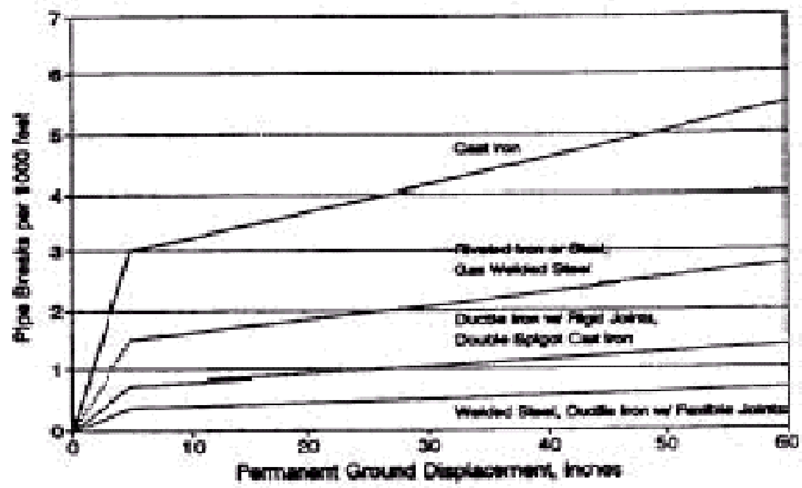


Figure A-6. PGD Damage Algorithm[from Harding and Lawson, 1991]

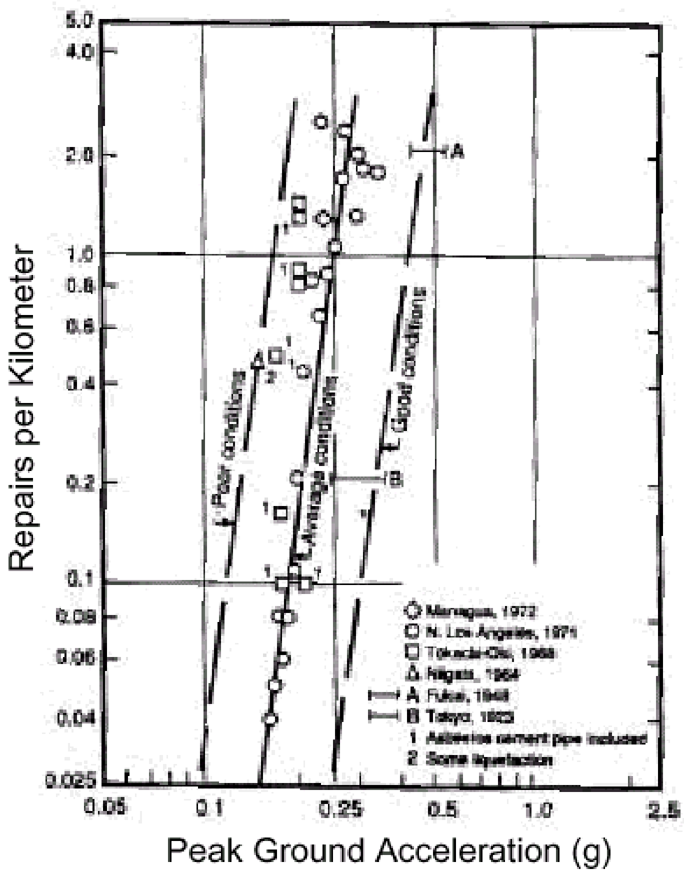


Figure A-7. Pipe Damage [from Katayama et al, 1975]

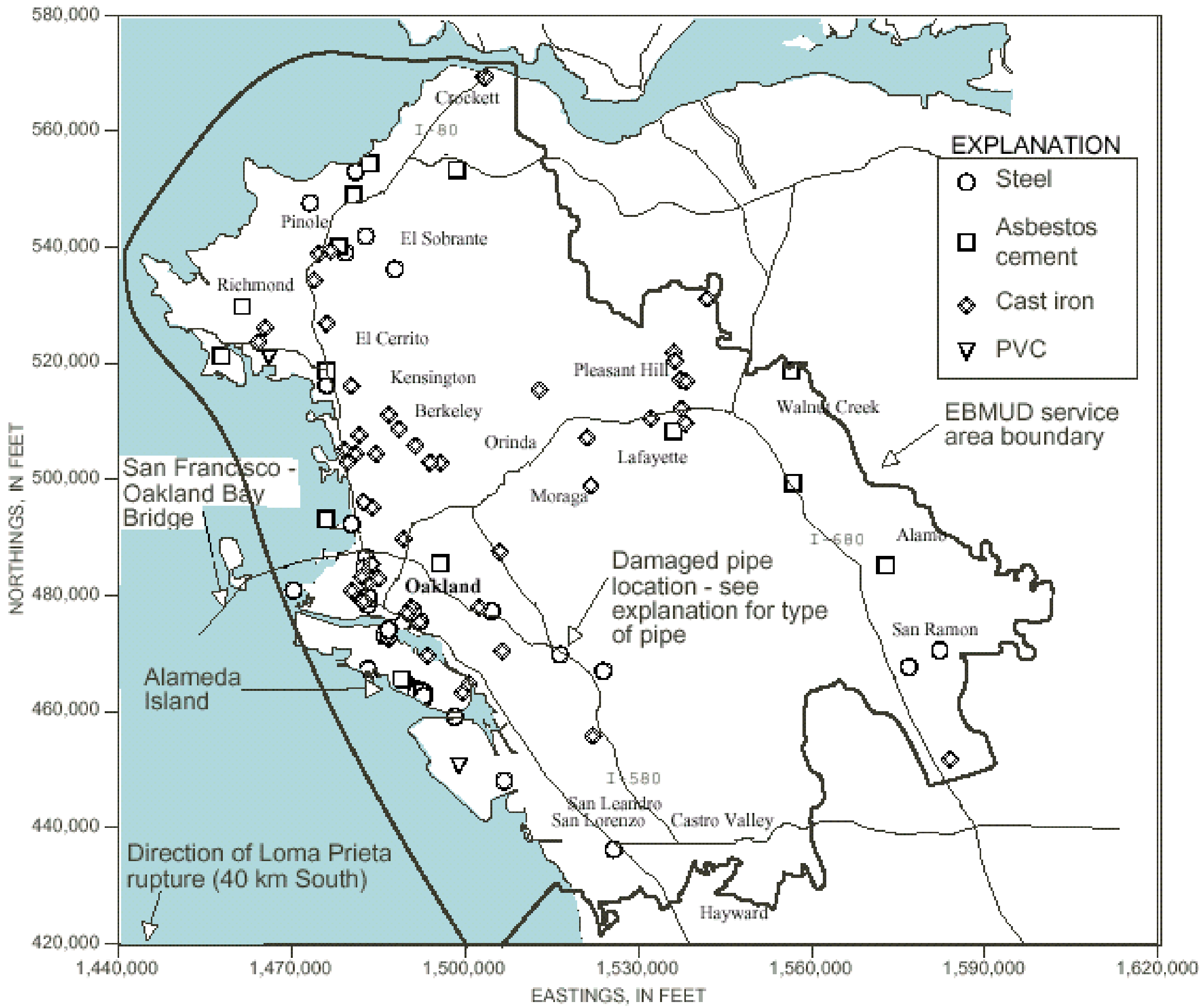


Figure A-8. Location of Pipe Repairs in EBMUD System, 1989 Loma Prieta Earthquake

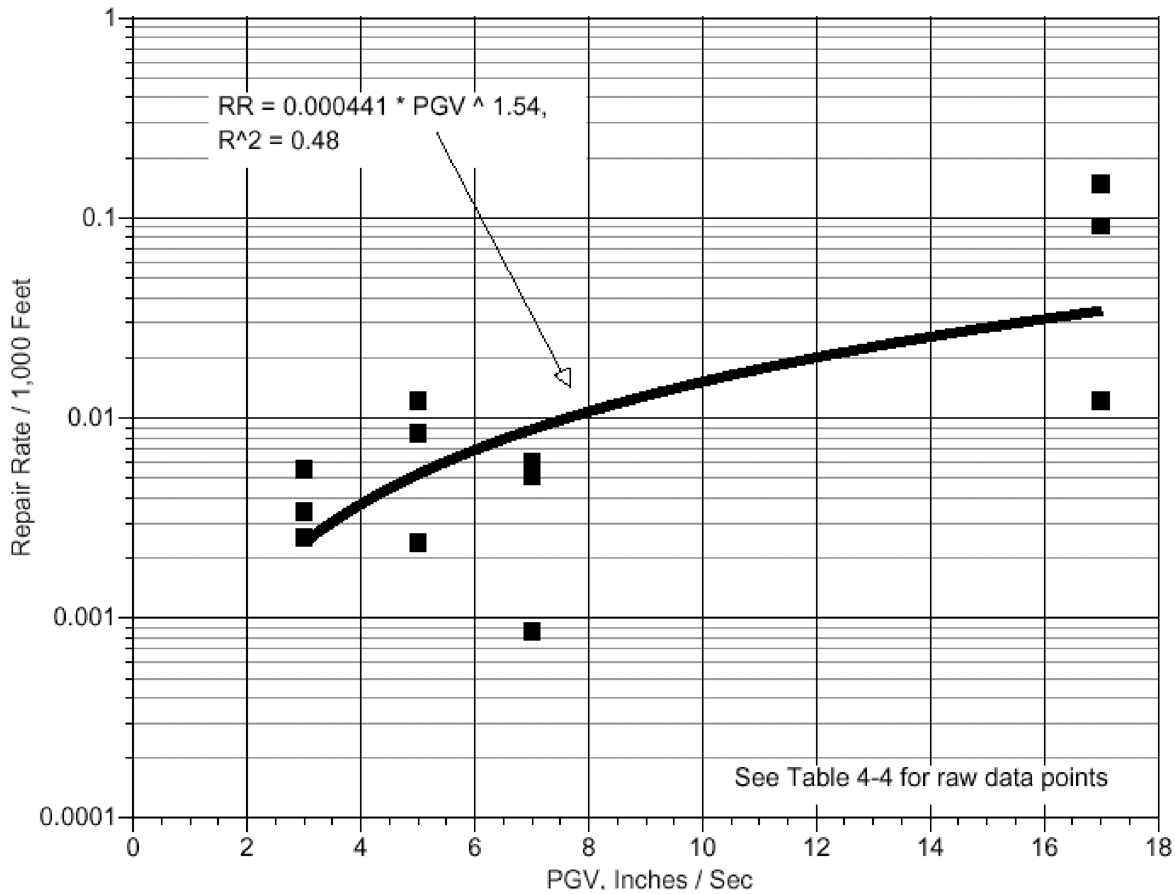


Figure A-9. Repair Rate, Loma Prieta (EBMUD), Ground Shaking, All Materials, CI, AC, WS

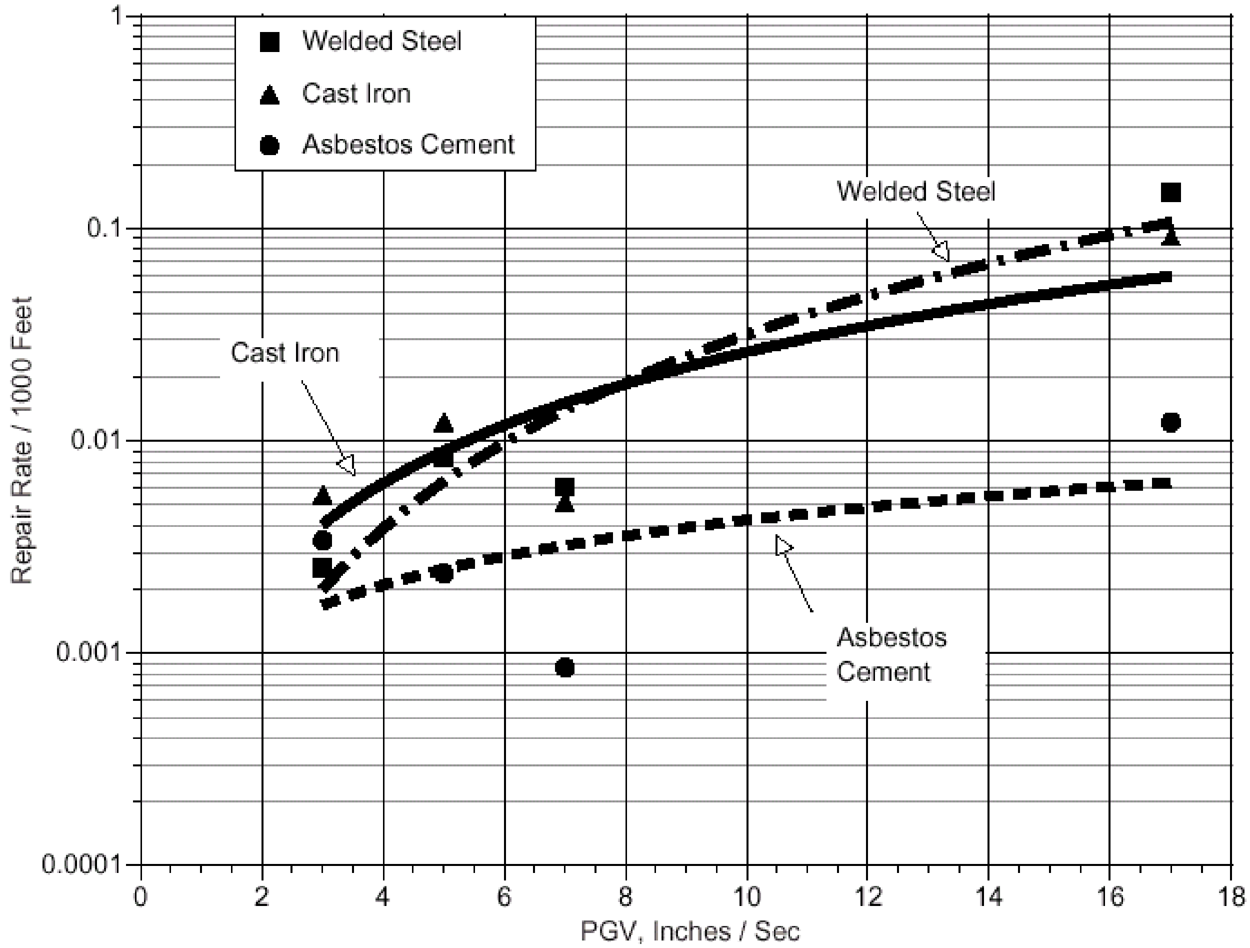


Figure A-10. Repair Rate, Loma Prieta (EBMUD), Ground Shaking, By Material, CI, AC, WS

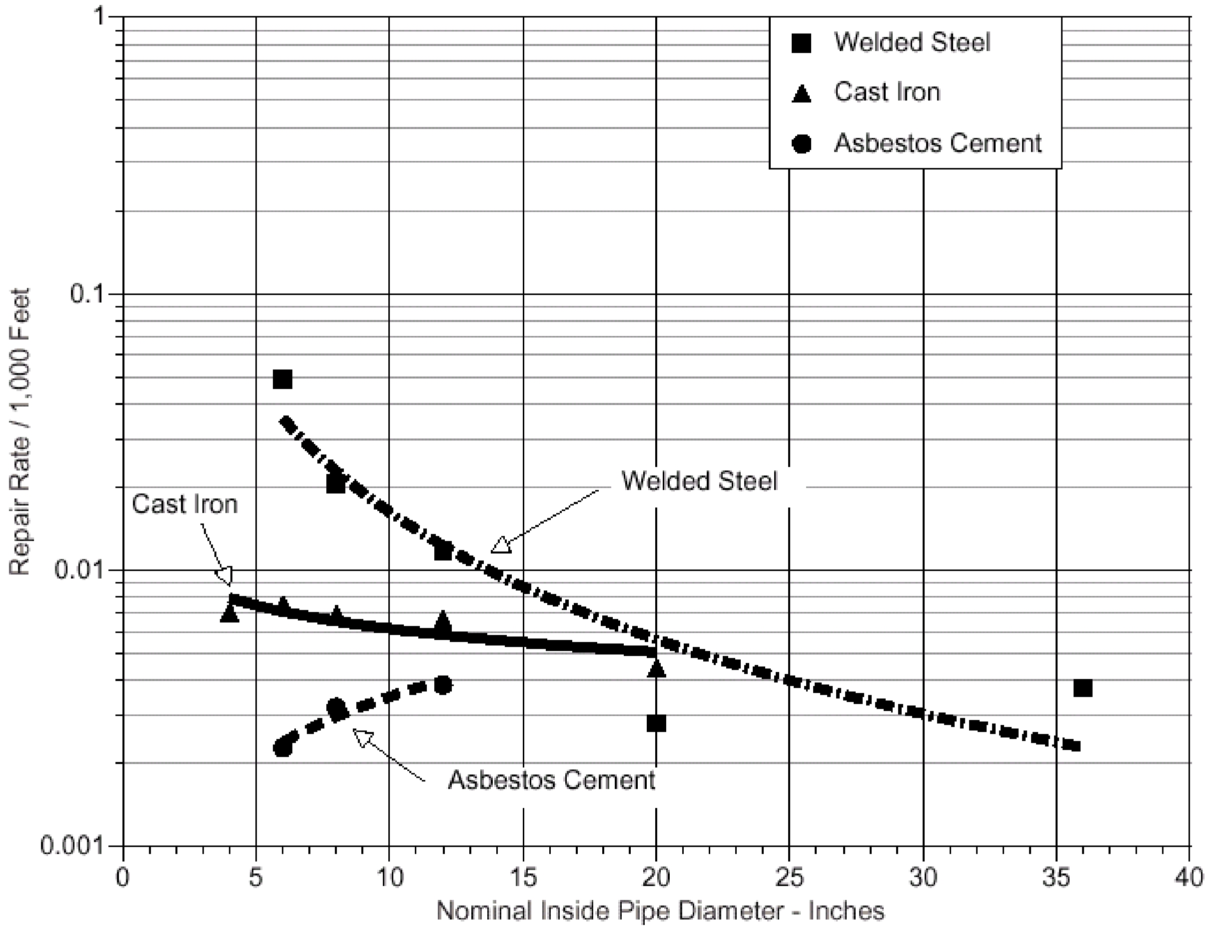


Figure A-11. *Repair Rate, Loma Prieta (EBMUD), Ground Shaking, By Material and Diameter*

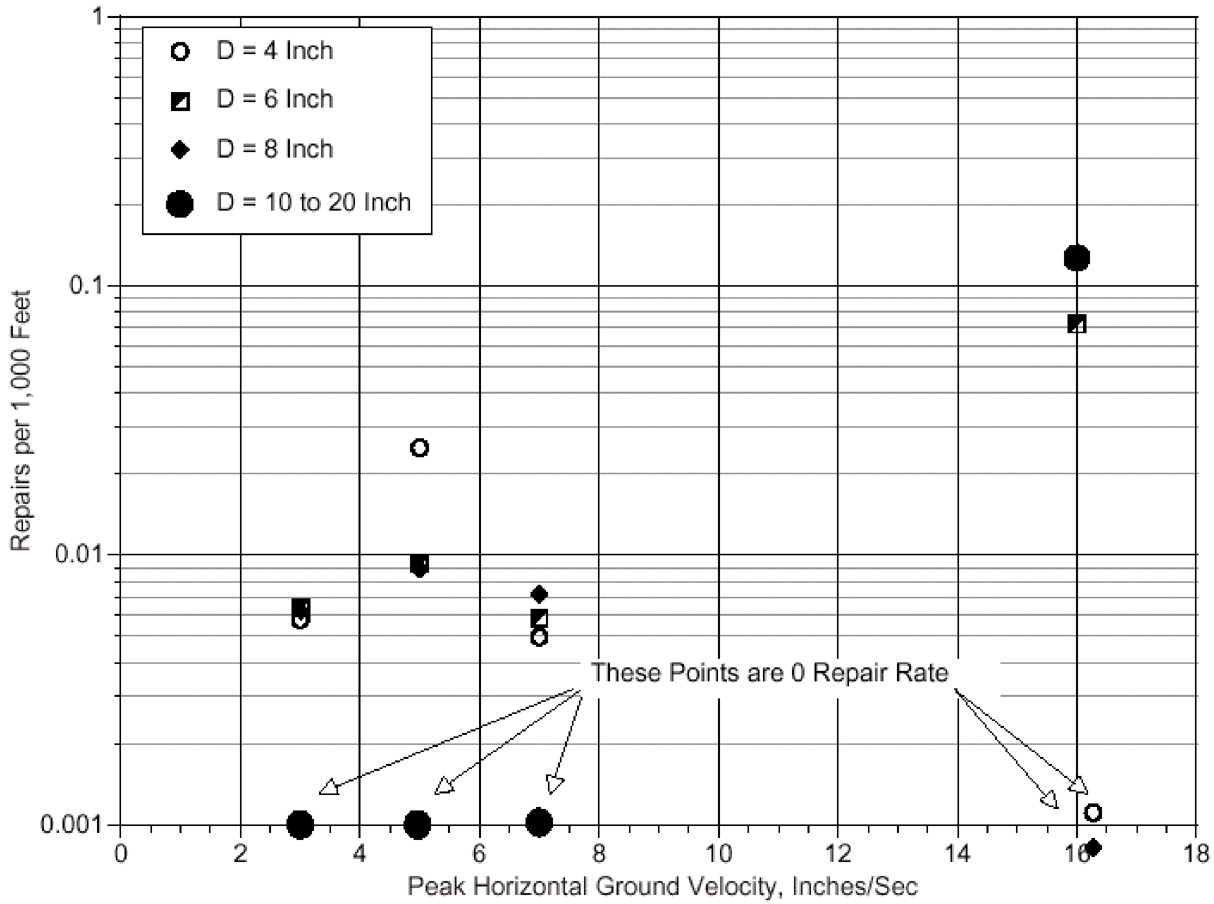


Figure A-12. Repair Rate, Wave Propagation, Cast Iron, Loma Prieta, By Diameter

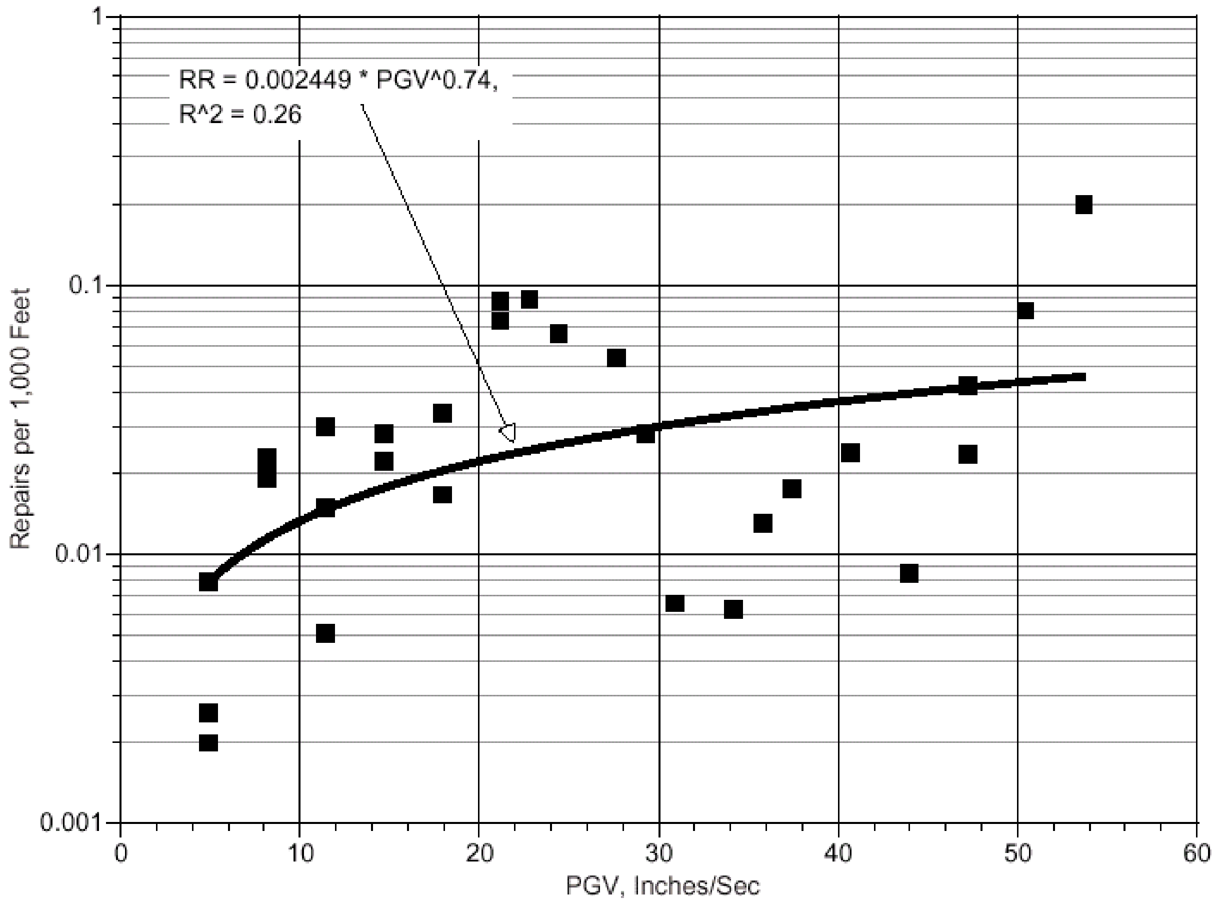


Figure A-13. Repair Rate, Northridge (LADWP), All Materials, Ground Shaking

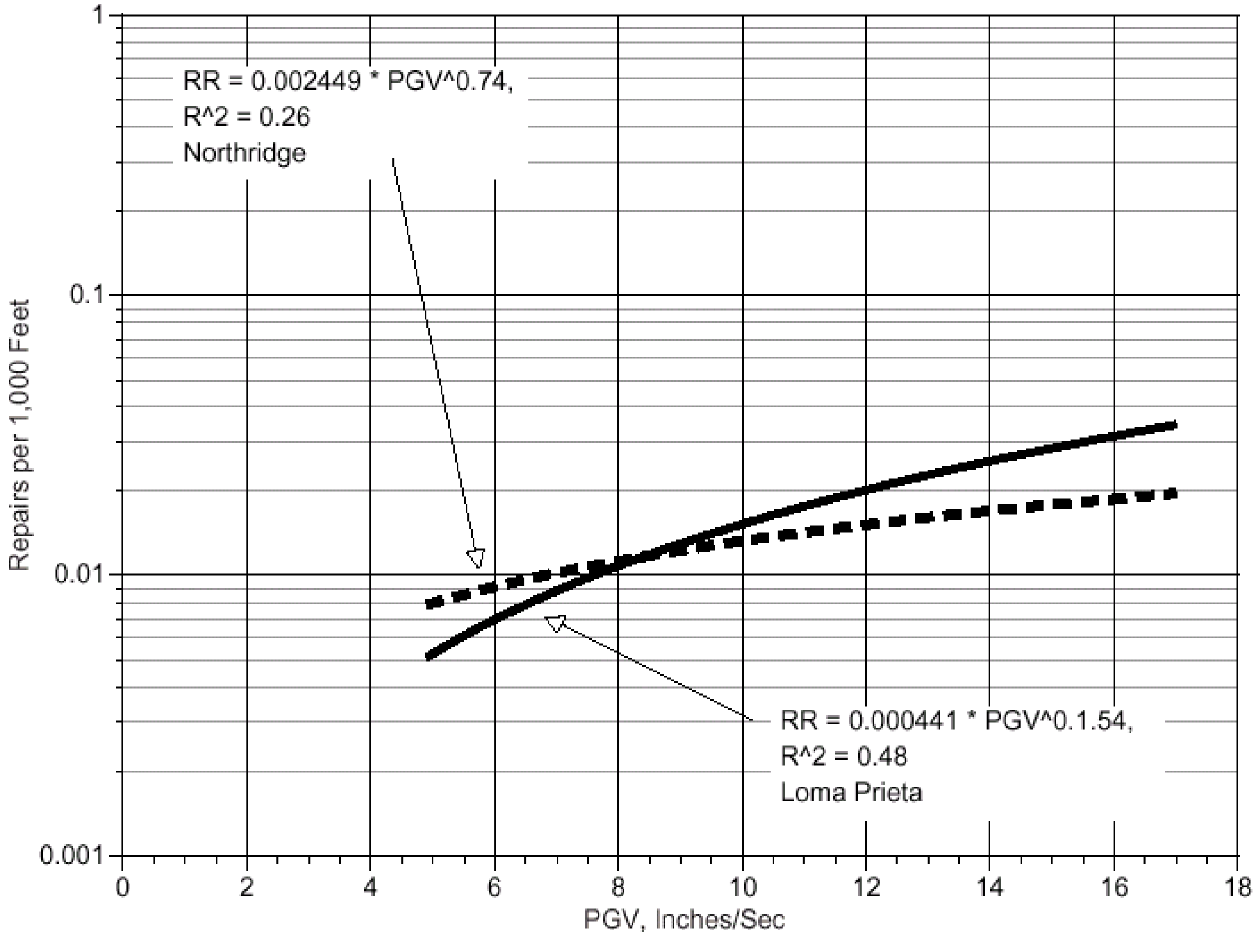


Figure A-14. Repair Rate, Northridge (LADWP) vs. Loma Prieta (EBMUD), All Data

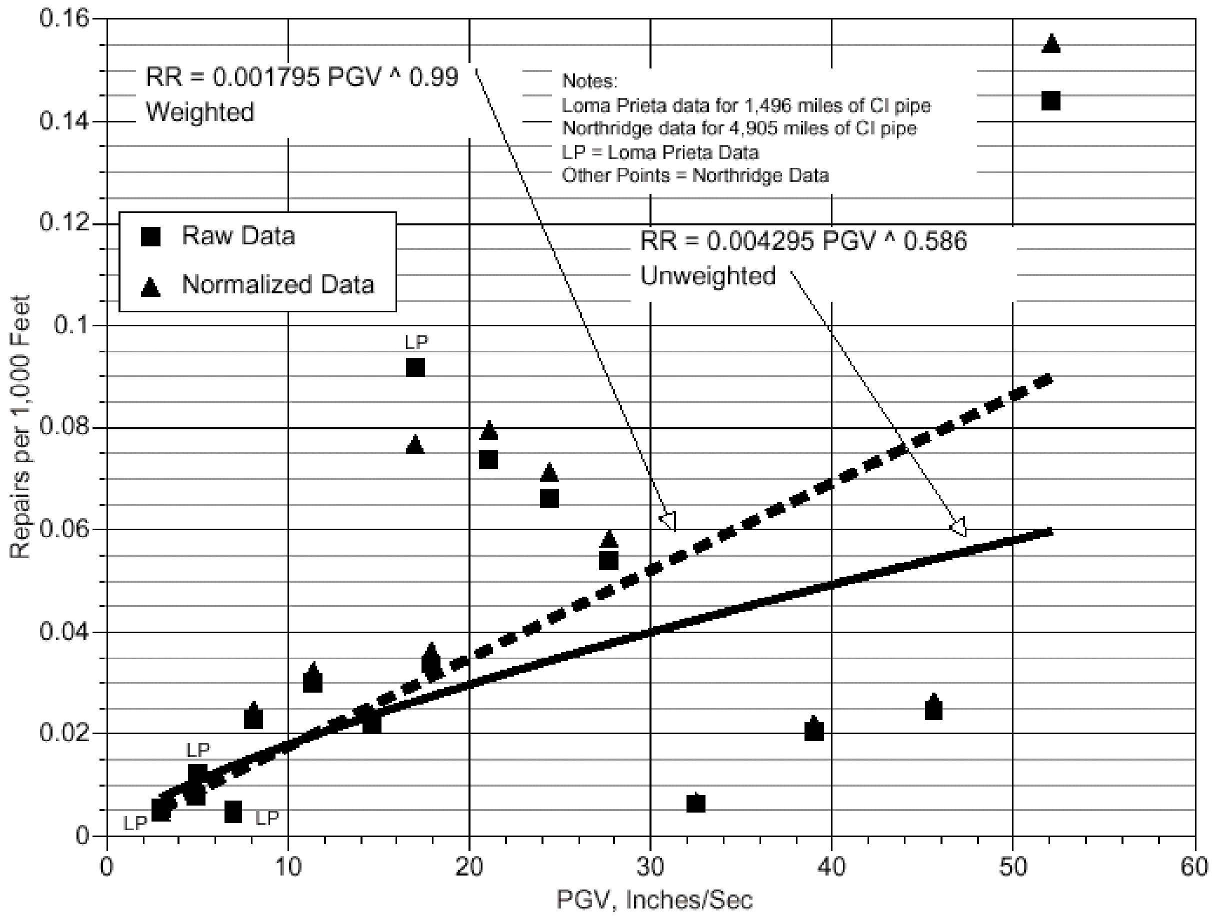


Figure A-15. Repair Rate, Northridge (LADWP) and Loma Prieta (EBMUD), Cast Iron Pipe Only

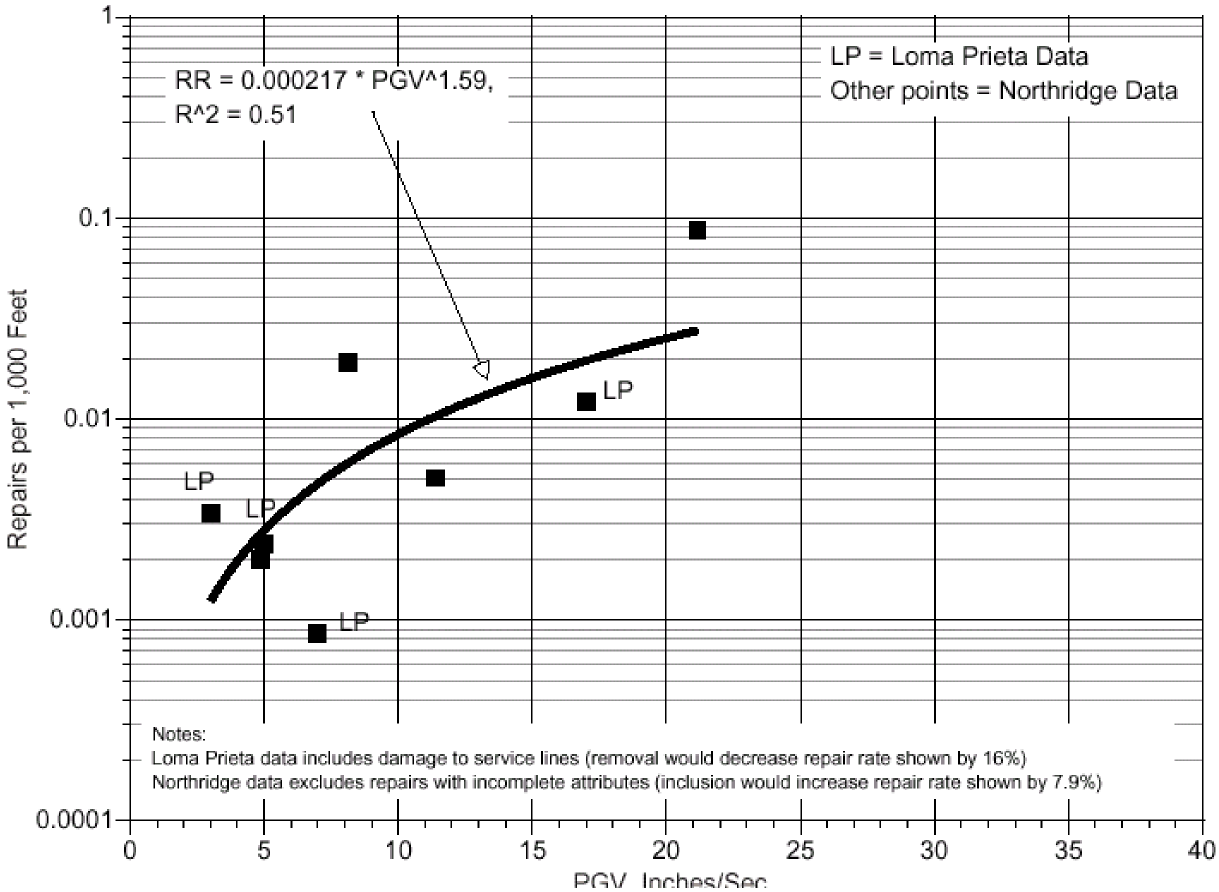


Figure A-16. Repair Rate, Northridge (LADWP) and Loma Prieta (EBMUD), AC Pipe Only

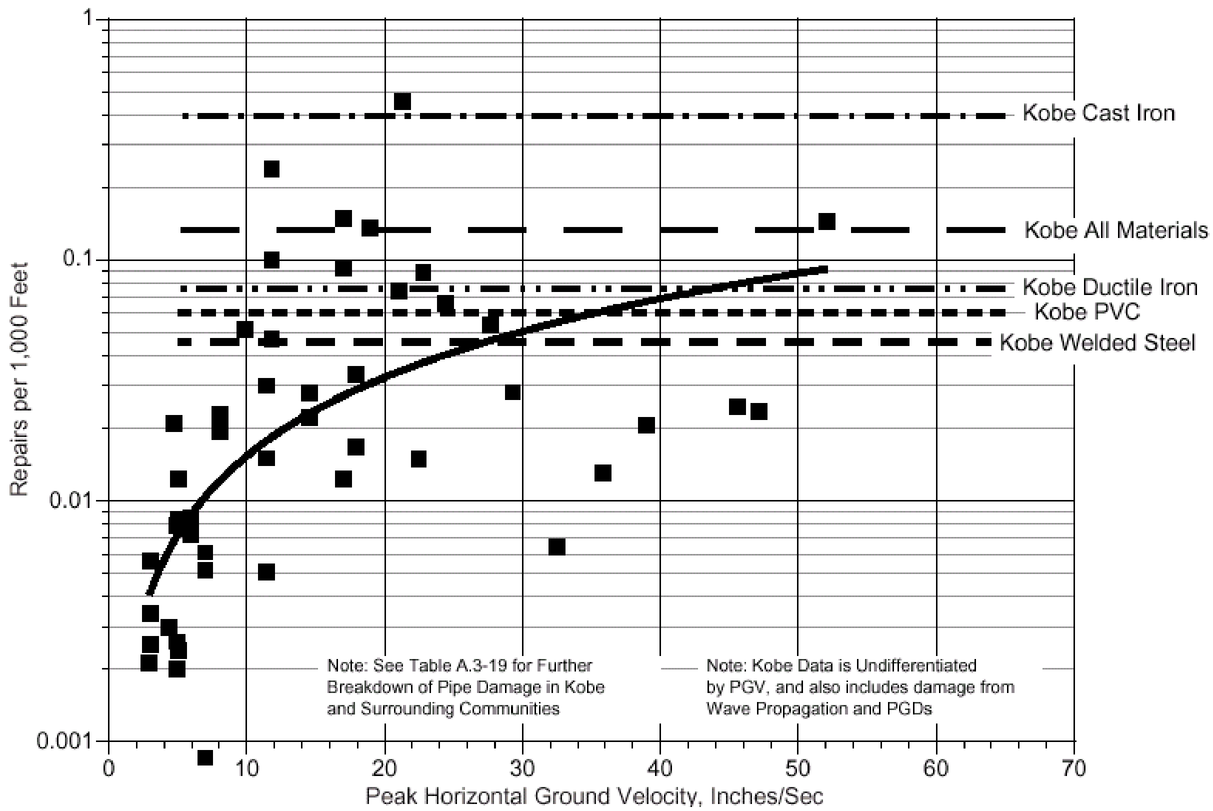


Figure A-17. Pipe Damage – Ground Shaking Data in Tables A.3-4, A.3-14, A.3-15, A.3-16, Figures A-1 and A-2, plus All Data (PGV and PGD) from Kobe, 1995

B. Commentary - Tanks

B.1 Damage States for Fragility Curves

In developing the fragility curves presented in Section 5 of the main report, consideration was made to match the fragility curves as closely as feasible to those used in the HAZUS computer program [HAZUS, 1997]. Essentially, this required the use of five damage states:

- Damage State 1 (DS1): No damage
- DS2: Slight damage
- DS3: Moderate damage
- DS4: Extensive damage
- DS5: Complete (collapse) damage

Section 5.2 of the report provides descriptions of the actual damage states that have been noted or envisioned for on-grade steel tanks. These include:

- Shell buckling (elephant foot buckling)
- Roof damage
- Anchorage failure
- Tank support/column system failure (pertains to elevated tanks)
- Foundation failure (largely a function of soil failures)
- Hydrodynamic pressure failure
- Connecting pipe failure
- Manhole failure

An inherent problem exists in mapping the actual damage states to the HAZUS DS1 through DS5 damage states. The main problem is that the HAZUS damage states developed for use with building-type structures have been adopted for utility systems.

- For buildings, it is reasonable to assume that increasing damage states also relate to increasing direct damage rates and decreased functionality. For example, for DS2, a building is in "slight" damage state, and might suffer a 1% to 5% loss—the cost to repair is 1% to 5% of the replacement cost of the building—and suffers almost no functional loss.
- For tanks, the type of damage that occurs could be inexpensive to repair, but have a high impact on functionality, or vice versa. For example, DS=3 in this report means that the tank has suffered elephant foot buckling but is still leak tight. To repair this type of damage, the owner could replace the buckled lower course of the shell with a new lower course, possibly costing between 20% and 40% of the replacement cost of the entire tank, yet the tank would not have lost any immediate post-earthquake functionality. Another damage state, DS=2,

could pertain to damage to an attached pipe, which would entail repair costs of only 1% to 2% of the replacement value of the tank, but would put the tank completely out of service immediately after the earthquake.

A case can be made that the form of the fragility curves for tanks should be altered from the generic form used in HAZUS. The following improved set of damage states are suggested:

Damage State (Most common damage modes)	**Repair Cost as a Percentage of Replacement Cost**	**Impact on Functionality as a Percentage of Contents Lost Immediately After the Earthquake**
Elephant Foot Buckling with Leak	40% to 100%	100%
Elephant Foot buckling with No Leak	30% to 80%	0%
Upper Shell Buckling	10% to 40%	0% to 20%
Roof System Partial Damage	2% to 20%	0% to 10%
Roof System Collapse	5% to 30%	0% to 20%
Rupture of Overflow Pipe	1% to 2%	0% to 2%
Rupture of Inlet/Outlet Pipe	1% to 5%	100%
Rupture of Drain Pipe	1% to 2%	50% to 100%
Rupture of Bottom Plate from Bottom Course	2% to 20%	100%

Table B.1-1. Water Tank Damage States

As can be seen in this table, no direct correlation exists between repair cost and functionality. As presented in the main report, the damage states are ranked according to increased repair costs for a tank, i.e., DS=2 is for roof damage and pipe damage, generally 1% to 20% loss ratios; DS=3 is for elephant foot buckling with no leak, generally 40% loss ratio; DS=4 for elephant foot buckling with leak, generally 40% to 100% loss ratio; and DS=5 is for complete collapse, generally 100% loss ratio.

Note that the adequate functional performance of a tank that reaches DS=2 is not assured. A review of the empirical tank database in Tables B-8 through B-15 confirms this.

B.2 Replacement Value of Tanks

To estimate the costs to repair a tank, given that it has reached a particular damage state, the following is a rough guideline for the replacement value of water tanks in year 2000 dollars:

- Tanks under 1,000,000 gallons: $1.50 per gallon
- Tanks from 1,000,000 gallons to 5,000,000 gallons: $1.25 per gallon
- Tanks over 5,000,000 gallons: $1.00 per gallon
- Open cut reservoirs can vary in volume from 500,000 gallons to over 100,000,000 gallons. Large open cut reservoirs can cost much less, on a per-gallon basis, than tanks.
- Concrete versus steel tanks. Modern tanks are almost always built from either steel or concrete. There are cost differences between the two styles of materials. Concrete tanks can

have higher initial capital costs than steel tanks, but have lower lifetime operational costs. The economic lifetime of concrete or steel tanks is usually in the range of 40 to 75 years. Industry debate as to which style of tank is "better" is still unresolved.

These cost values are geared to hillside tank sites in urbanized areas of California. The costs can often vary by +50% to –50% for specific locations within high-density urbanized California. The costs will further vary by regional cost factors for different parts of the country. Examples of regional cost factors are provided in the technical manual for HAZUS [HAZUS, 1999].

B.3 Hazard Parameter for Tank Fragility Curves

The fragility curves presented in Section 5 of the main report use PGA as the predictive parameter for damage to tanks. The choice of PGA was based on the best available parameter from the empirical database. However, engineering properties of tanks would suggest that the following improvements could be made if tank-specific fragility curves are to be developed:

- **For damage states associated with tank overturning, elephant foot buckling, etc.** Use the 2% spectral ordinate at the impulsive mode of the tank-liquid system, assuming the tank is at the full fill depth. The 2% damping value is recommended as experimental tests suggest that the 2% value more closely matches actual tank-contents motions than the 5% damping assumed in typical code-based design spectra. The site-specific response spectral shape should reflect the soil conditions for the specific tank. Rock sites will often have less energy than soil sites at the same frequency, even if the sites have the same PGA.

- **For damage states associated with roof damage, etc.** Use the 0.5% spectral ordinate at the convective mode of the tank-liquid system, assuming the tank is at the full-fill depth. The 0.5% damping value is recommended for fluid sloshing modes. For some tanks with low height-to-depth ratios, the fluid convective mode may significantly contribute to overturning moment, and a suitable ratio of the impulsive and convective components to overturning should be considered.

- **For damage states associated with soil failure at the site.** At present time, insufficient empirical data exists to develop fragility curves that relate the performance of tanks to ground settlements, lateral spreads, landslides or surface faulting. These hazards could occur at some sites. Ground failure can impose differential movements for attached pipes, leading to pipe failure. The PGD fragility curves provided in HAZUS are based on engineering judgment and, lacking site specific evaluation, appear reasonable.

B.4 Tank Damage – Past Studies and Experience

Three methods are used to develop damage algorithms: expert opinion, empirical data and analysis. In this section, several previous studies are summarized that discuss tank damage using expert opinion (Section B.4.1) or empirical data (Sections B.4.2, B.4.3, B.4.4).

B.4.1 Earthquake Damage Evaluation Data for California

ATC-13 [ATC, 1985] develops damage algorithms for a number of types of structures, including tanks. The damage algorithms in ATC-13 were based on expert opinion. Since the 1985 publication of ATC-13, the body of knowledge has expanded about the earthquake performance of tanks and some of the findings in ATC-13 are therefore outdated. However, it is useful to examine the ATC-13 information, partly because it serves as a point of comparison with more current information presented in this report.

ATC-13 provided damage algorithms for three categories of liquid storage tanks:

- Underground
- On-Ground
- Elevated

For example, the ATC-13 damage algorithm for an On-Ground Tank is as follows:

CDF	MMI=VI PGA=0.12g	VII 0.21g	VIII 0.35g	IX 0.53g	X 0.70g	XI 0.85g	XII 1.15g
0%	94.0	2.5	0.4				
0.5	6.0	92.9	30.6	2.1			
5		4.6	69.0	94.6	25.7	2.5	0.2
20				3.3	69.3	58.1	27.4
45					5.0	39.1	69.4
80						0.3	3.0
100							

Table B-1. Damage Algorithm – ATC-13 – On Ground Liquid Storage Tank

Explanation of the above table is as follows:

- Central Damage Factor (CDF) represents the percentage damage to the tank or percent of replacement cost.
- Modified Mercalli Scale (MMI) represents the input ground shaking intensity to the tank.
- Peak Ground Acceleration (g) (PGA). ATC-13 does not provide damage algorithms versus input PGA. PGA values in the above table have been added to assist in interpreting ATC-13 damage algorithms versus those used in the present study. The MMI/PGA relationship listed in Table B-1 represents an average of five researchers' MMI/PGA conversion relationships, as described in further detail in [McCann, Sauter and Shah, 1980].
- Damage probabilities. The sum of each column is 100.0%. Table entries with no value have very small probability of occurring, given the input level of shaking (less than 0.1%).

ATC-13 makes no distinction between material types used for construction, whether the tanks are anchored or not, the size or aspect ratio of the tank, or the type of attached appurtenances. The ATC-13 damage algorithms for elevated and buried tanks indicate that elevated tanks are more sensitive to damage than on-grade tanks; and buried tanks are less sensitive to damage than on-grade tanks.

ATC-13 does not provide guidance to relate the cause of damage such as breakage of attached pipes, buckling, weld failures, roof damage, etc. to the CDF. ATC-13 does not provides guidance as to how CDFs relate to tank functionality.

These limitations in the ATC-13 damage algorithm require the use of arbitrary assumptions such as: a CDF of 20% or below means the tank is functional, and a CDF of 45% or above means that the tank is not functional. If this is the rule that is applied, then the ATC-13 damage algorithm above would indicate that no tank would become non-functional at any ground motion up to about MMI IX (PGA = 0.53g). This may not be true, so ATC-13 tank damage functions should not be used without further consideration of tank-specific features.

An applied version of ATC-13 was developed specifically for water systems by Scawthorne and Khater [1992]. This report uses the same damage algorithms in ATC-13 for water tanks located in the highest seismic regions of California, and makes the following suggestions for applying these damage algorithms to water tanks located in lower seismic hazard areas of the US:

- For moderate seismic zones, including the west coast of Oregon, Washington State, the Wasatch front area of Utah, etc., use the damage algorithms in Table 5-1, except shift the MMI scale down by 1. In other words, if the predicted MMI for a particular site was IX, apply the damage algorithm from Table B-1 for MMI X.

- For cases where tanks are to be seismically upgraded, ATC 25-1 suggests using the damage algorithms of Table B-1, except shift the MMI scale up by one or two intensity units. In other words, if the predicted MMI for a particular site with an upgraded tank was IX, apply the damage algorithm from Table B-1 for MMI VII.

B.4.2 Experience Database for Anchored Steel Tanks in Earthquakes Prior to 1988

Section B.4.2 summarizes the actual observed performance for 43 above-ground, anchored liquid storage tanks in 11 earthquakes through 1987 [Hashimoto, and Tiong, 1989]. Tables B-2, B-3 and B-20 provide listings and various attributes of the tanks.

Of these 43 tanks, only one probably lost its entire fluid contents. The likely cause was failure of a stiff attached pipe that experienced larger seismic displacements after anchor failure.

Other tanks were investigated in this effort, including thin-walled stainless steel tanks and elevated storage tanks. These types of tanks had more failures than for above-ground, anchored storage tanks. Thin-walled stainless steel storage tanks are not commonly used in water system lifelines, but are more common to the wine and milk industries. Tanks excluded from this report include those with peak ground accelerations (PGAs) less than 0.15g, fiberglass tanks, tanks with thin course thickness (< 3/16 inch), tanks with fills less than 50% and unanchored tanks.

The earthquakes considered include San Fernando 1971, Managua 1972, Ferndale 1975, Miyagi-ken-oki 1978, Humboldt County, 1980, Greenville, 1980, Coalinga 1983, Chile 1985, Adak 1986, New Zealand 1987 and Whittier 1987. Key results are given in Table B-2.

PGA	Total	No	Anchor	Shell	Minor	Total Loss

		Damage	Damage	Buckling	Leakage at Valve or Pipe	of Contents
0.17g-0.20g	12	12	0	0	0	0
0.25g-0.30g	15	14	1	1	0	0
0.35g-0.40g	5	3	2	0	1	1*
0.50g-0.60g	11	7	4	1	1	0
Total	43	36	7	2	2	1

* Note: Total loss of contents was likely due to increased displacements of attached pipe after anchor failure. The tank shell remained intact.

Table B-2. Earthquake Experience Database (Through 1988) for At Grade Steel Tanks

Thin-walled stainless steel tanks with wall thickness • 0.1 inch have behaved poorly in past earthquakes, even if anchored. Instances of shell buckling, leakage and even total collapse and rupture have been reported. Although damage is much more common than for thicker walled tanks, leakage and total loss of contents is still infrequent. Even for thin-walled tanks, tank shell buckling does not necessarily lead to leakage.

Most of the Table B-2 tanks have diameters between 10 and 30 feet, with heights from between 10 and 50 feet and capacities between 4,400 gallons and 1,750,000 gallons. They were made of steel or aluminum and were at least 50% full at the time of the earthquake. Foundations are believed to be either concrete base mats or concrete ring walls. Known bottom shell course thicknesses range in inches from 3/16 to more than 5/8.

The tanks in Table B-2 are generally smaller than many water agency storage tanks, which often have capacities greater than 2,000,000 gallons.

The actual tanks that comprise the results given in Table B-2 are the 39 tanks given in Table B-3. Four of these tanks have experienced two earthquakes. No tanks in this database are thin-walled stainless steel (shell thickness < 3/16 inch) or fiberglass tanks. The following paragraphs describe the actual damage for the tanks in Table B-3.

- Jensen Filtration Plant washwater tank, San Fernando, 1971. This tank was 100 feet in diameter, 36.5 feet high and filled about half full. This tank had twelve 1-inch diameter anchor bolts that were used as tie-down points during construction and not as restraints against uplift. Anchor bolt pullout ranged from 1.375 inches to 13 inches. The tank shell buckled at the upper courses, particularly in the vicinity of the stairway. No loss of contents was reported.
- Asososca Lake Water Pumping Plant surge tank, Managua, 1972. This tank was 22 meters high, 5 meters in diameter and about two-thirds full at the time of the earthquake. The sixteen 1.5-inch diameter anchor bolts stretched between 0.5 inches to 0.75 inches. No loss of contents was reported.
- Sendai Refinery fire water tank, Miyagi-ken-oki 1978. This tank was about 60 feet high and 40 feet in diameter. Anchor bolts stretched or pulled out from 1 to 6 inches. The tank was leaking at a valve after the earthquake, but buckling or rapid loss of contents did not occur. This leakage was probably due to relative displacement of attached piping.

Earthquake	Facility	PGA (G)	Component	Capacity (Gallons)
Adak 1986	Fuel Pier Yard	0.20	Small Craft Refuel Tank	315000
Adak 1986	Power Plant # 3	0.20	Tank No. 4	50000
Adak 1986	Power Plant #3	0.20	Tank No. 5	50000
Chile 1985	Las Ventanas Power Plant	0.25		70000*
Chile 1985	Las Ventanas Power Plant	0.25		70000*
Chile 1985	Las Ventanas Power Plant	0.25		70000*
Chile 1985	Las Ventanas Power Plant	0.25	Oil Storage Day Tank	250000*
Chile 1985	Las Ventanas Power Plant	0.25	Oil Storage Day Tank	250000*
Coalinga 1983	Coal.Water Filtration Plant	0.60	Wash Water Tank	300000
Coalinga 1983	Kettleman Gas Compressor Stn	0.20	Lube Oil Fuel Tank #2	7200
Coalinga 1983	Kettleman Gas Compressor Stn	0.20	Lube Oil Fuel Tank #3	7200
Coalinga 1983	Kettleman Gas Compressor Stn	0.20	Lube Oil Fuel Tank #6	7200
Coalinga 1983	Pleasant Valley Pumping Station	0.56	Surge Tank	400000
Coalinga 1983	San Lucas Canal Pmp. Stn 17-R	0.35	Surge Tank	10000
Coalinga 1983	Union Oil Butane Plant	0.60	Diesel Fuel Oil Tank	4400
Coalinga 1983	Union Oil Butane Plant	0.60	Diesel Fuel Oil Tank	4400
Ferndale 1975	Humboldt Bay Unit 3	0.30	Condensate Storage Tank	34500
Ferndale 1980	Humboldt Bay Unit 3	0.25	Condensate Storage Tank	34500
Greenville 1980	Sandia	0.25	Fuel Oil Storage Tank	170000
Managua 1972	Asososca Lake	0.50	Surge Tank	105000*
Miyagi-ken-oki 1978	Sendai Refinery	0.28	Fire Water Storage Tank	500000*
New Zealand 1987	Caxton Paper Mill	0.40	Chip Storage Silo	450000*
New Zealand 1987	Caxton Paper Mill	0.40	Hydrogen Peroxide Tank	5700*
New Zealand 1987	Caxton Paper Mill	0.40	Secondary Bleach Tower	50000*
New Zealand 1987	New Zealand Distillery	0.50	Bulk Storage Tank #2	65000*
New Zealand 1987	New Zealand Distillery	0.50	Bulk Storage Tank #5	15000*
New Zealand 1987	New Zealand Distillery	0.50	Bulk Storage Tank #6	15000*
New Zealand 1987	New Zealand Distillery	0.50	Bulk Storage Tank #7	105000*
New Zealand,1987	New Zealand Distillery	0.50	Receiver Tank #9	5700*
New Zealand 1987	Whakatane Board Mills	0.30	Pulp Tank	150000*
New Zealand 1987	Whakatane Board Mills	0.30	Pulp Tank	150000*
New Zealand 1987	Whakatane Board Mills	0.30	Pulp Tank	150000*
San Fernando 1971	Glendale Power Plant	0.28	Distilled Water Tank #1A	14700
San Fernando 1971	Glendale Power Plant	0.28	Distilled Water Tank #1B	14700
San Fernando 1971	Glendale Power Plant	0.28	Distilled Water Tank #2	20000*
San Fernando 1971	Glendale Power Plant	0.28	Fuel Oil Day Tank #1	14700
San Fernando 1971	Jensen Filtration Plant	0.50	Washwater Tank	1750000
San Fernando 1971	Pasadena Power Plant Unit B1	0.20	Distilled Water Tank	120000
San Fernando 1971	Pasadena Power Plant Unit B2	0.20	Distilled Water Tank	120000
San Fernando 1971	Pasadena Power Plant Unit B3	0.20	Distilled Water Tank	86000
Whittier 1987	Pasadena Power Plant Unit B1	0.17	Distilled Water Tank	120000
Whittier 1987	Pasadena Power Plant Unit B2	0.17	Distilled Water Tank	120000
Whittier 1987	Pasadena Power Plant Unit B3	0.17	Distilled Water Tank	86000

* Estimated capacity

Table B-3. Database Tanks (Through 1988)

- Sandia National Laboratory fuel oil storage tank, Greenville, 1980. This tank was 50 feet tall, 25 feet in diameter and full at the time of the earthquake. All of the twenty 0.625-inch diameter Wej-it expansion anchors failed. The shell suffered elephant foot buckling, but did not rupture.

- San Lucas Canal pumping stations surge tanks, Coalinga, 1983. A series of pumping station are distributed along the San Lucas Canal have surge tanks of different designs. Tank diameters typically range from 10 feet to 15 feet, and shell heights vary from 22 feet to 30 feet. The surge tanks are skirt supported with anchorage bolted through the skirt bottom flange. Various tanks had anchors pulled or broken. At Station 17-R, rocking motion of one surge tank was sufficient to stretch or break most of its anchors. The 24-inch diameter supply/discharge line routed out of the ground into the bottom of this tank reportedly failed. While actual details of this pipe failure are not available, a loss of tank contents probably resulted. An average horizontal PGA of 0.35g has been estimated for the San Lucas Canal pumping stations. This is an average value for all the pumping stations distributed along the canal. Since Station 17-R suffered greater damage than other stations, including ground failures, the ground motion experienced was probably greater than the average value of 0.35g.

- Pleasant Valley Pumping Station surge tower, Coalinga, 1983. This tower is 100 feet high and anchored by 1.5 inch diameter J-bolts. An average horizontal PGA of 0.56g was recorded near this station. Because the anchor bolts were equally stretched about 1.5 inches, there is speculation that water hammer in the pipeline feeding this tower caused water to impact the roof with resulting uplift. No loss of contents was reported.

- Coalinga Water Filtration Plant washwater tank, Coalinga 1983. This tank is 60 feet high and 30 feet in diameter, made of A36 steel. The bottom plate is 0.25 inch thick and the fluid height is 45 feet. Anchorage is 24 1.5-inch diameter bolts, A325 steel, attached by lugs. Shell thickness ranges from 0.375-inch at the lowest course to 0.25-inch at the upper course). The foundation is a concrete ring wall. Foundation motion pushed soil away and caused a gap of about 0.5 inches between the southwest and northeast sides of the concrete ring wall and adjacent soil. Some minor leakage, which was not enough to take the tank out of service, was noted at a pipe joint after the earthquake, but was easily stopped by tightening the dresser coupling. Water leakage was observed at the base of the tank. After the earthquake, the tank was drained, the shell to bottom plate welds were sandblasted, and the tank was vacuum tested with no apparent leakage. The water has since been attributed to sources other than tank leakage. The anchor bolts were stretched and were torqued down after the earthquake. The tank remains functional.

B.4.3 Tank Damage Description in the 1989 Loma Prieta Earthquake

Numerous reports of damage to liquid storage tanks were due to the Loma Prieta 1989 earthquake [EERI, 1990]. Most of the damage was to unanchored storage tanks at refineries and wineries, with most of the tanks having lost their contents. Content loss was most often due to failures in attached piping, caused by excessive displacements at the tank-pipe connections from tank uplifting motions. The following paragraphs describe some tanks that had water content loss, which are similar to water system tanks, and are either anchored concrete or steel tanks, or unanchored redwood tanks. Thin-walled stainless steel tanks are excluded. Typical damage to some unanchored tanks is described.

Concrete Tanks. In the Los Altos hills, a 1,100,000 gallon, prestressed concrete tank failed. The tank was built of precast concrete panels and was post-tensioned with wire. The outermost surface was gunnite. The earthquake caused a 4-inch vertical crack in the tank wall, which released the water contents. Corrosion in the wires may have contributed to the failure. Estimated ground accelerations were in the 0.25g to 0.35g range.

Wood Tanks. In the San Lorenzo valley, near Santa Cruz, five unanchored redwood tanks (10,000 gallons to 150,000 gallons) were lost. Estimated ground motions were in the 0.20g to 0.40g range.

In the Los Gatos region, a 10,000-gallon redwood tank collapsed. Estimated ground motions were in the 0.10g to 0.30g range.

Near Santa Cruz, 20 unanchored 8,000 gallon oak tanks at a winery rocked on unanchored foundations. One tank was damaged after it rocked off its foundation support beams and hit a nearby brick wall. Estimated ground accelerations were in the 0.2g to 0.4g range for about 10 seconds.

Steel Tanks. At the Moss Landing power plant, a 750,000-gallon raw water storage tank experienced a rapid loss of contents. Rupture occurred at the welded seam of the baseplate and shell wall that had been thinned by corrosion. Several dozen other tanks at the Moss Landing plant, ranging from very small up to 2,000,000 gallons, did not lose their contents. Estimated peak ground acceleration was 0.39g.

At the Hunters Point power plant, there was a small leak at a flange connection to a distilled water tank. Estimated ground acceleration was 0.10g.

In Watsonville, a 1,000,000-gallon welded steel tank built in 1971 buckled at the roof-shell connection. Electronic water-level-transmitting devices were damaged from wave action. A pilot line-to-altitude valve broke, causing a small leak, but otherwise, did not leak. Nine other tanks at this site that did not leak.

At Sunny Mesa, a 200,000-gallon unanchored welded steel tank tilted, with 2-inch settlement on one side and base lift-off on the other side. The tank did not leak, but the attached 8-inch diameter line broke, causing release of the tank's entire contents above the tank outlet.

In Hollister, a 2,000,000-gallon welded steel tank performed well, except that a pulled pipe coupling in a 6-inch diameter line almost drained the tank.

B.4.4 Tank Damage Description in the 1994 Northridge Earthquake

Observations based on a the Los Angeles Department of Water and Power inspection reports of January 21, 1994 are described below. The inventory of tanks and reservoirs in the entire water system is: 13 riveted steel, 38 welded steel, 8 concrete, 9 prestressed concrete and 29 open cut. Note that most of these tanks and reservoirs are located at substantial distances from the zone of highest shaking.

- Tank A (Steel tank). Top panel slightly buckled, as was the roof. It was uncertain whether the tank leaked its contents, as it was empty at time of inspection.
- Tank B (Steel tank). Apparent that some seepage occurred at the bottom of the tank. Some tank shell and roof steel plates were slightly buckled.
- Open Cut Reservoir C. Significant damage occurred to the connections of the roof beams to the walls.

- Tank D (Steel tank with wooden roof). Tank roof almost completely collapsed. Top course was severely bent, and the second to top course was warped and buckled. Settlement of 6 inches on one side. Inlet and outlet pipes broken. Some soil erosion around the inlet and outlet pipes, undermining a small portion of the tank. Overflow pipe broken completely free of the outside of the tank shell. Roof debris at the bottom of the tank. Roof debris may include hazardous materials, requiring special disposal.
- Tank E (Steel tank with wooden roof). Tank roof shifted about 10 feet to one side, had partial collapse, but was otherwise largely intact. Shell was structurally sound, but top course buckled in one area. Suspected crack in tank shell to inlet/outlet pipe connection. Possible rupture at the bottom of the tank. Inlet outlet pipe pulled out of its mechanical couplings. A 12-inch gate valve failed. Overflow pipe separated from the tank wall. Severe soil erosion due to loss of water contents.
- Tank F (Steel tank). All anchor bolts were stretched and hold-down plates were bent. Shell was slightly buckled.
- Tank G. No major structural damage, but the tank was empty at time of inspection. Minor damage at roof joints. No sign of leakage.
- Tank H. A 8-inch gate valve failed and the tank was empty at time of inspection.
- Tank I. A 12-inch gate valve failed. The roof was dislocated from the tank. Roof trusses failed at the center of the tank. The top of the tank buckled at every roof-connection point. The tank was empty at time of inspection.
- Tank J (Riveted steel tank). Tank deflection and settlement severed piping. The slope adjacent to the tank either slid or shows signs of impending slide. All piping, including inlet/outlet lines and overflow line severed. This tank apparently suffered a non-leaking elephant foot buckle in the 1971 San Fernando earthquake, and had been kept in service.

B.4.5 Performance of Petroleum Storage Tanks

In a report for the National Institute of Standards and Technology (NIST), Cooper [1997] examined the performance of steel tanks in ten earthquakes: 1933 Long Beach, 1952 Kern County, 1964 Alaska, 1971 San Fernando, 1979 Imperial Valley, 1983 Coalinga, 1989 Loma Prieta, 1992 Landers, 1994 Northridge and 1995 Kobe. Most of the tanks were on-grade steel and contained petroleum; a few contained water.

For each of the ten earthquakes, Cooper describes the location of each tank; the diameter and height of each tank, and the level of damage observed. Many pictures of damaged tanks are provided and, where available, instrumented recordings of ground motion.

A numerical analysis of the results from Cooper's data collection is provided in Section B.4.6 below. The more qualitative conclusions of this study are as follows:

- The extent of damage is strongly correlated with the level of fill of the contents. Many oil tanks are only partially filled at any given time. Tanks with low levels of fill appear to suffer less damage than full tanks with all other factors being equal.

- All of the damage modes described in Section B.2 have been observed in these earthquakes.
- As the ratio of the tank height-to-tank diameter (H/D) increases, the propensity for elephant foot buckling increases. Unanchored tanks with H/D less than 0.5 were not observed to have elephant foot buckling.
- Oil tanks with frangible roof or shell joints often suffered damage, especially those with low H/D ratios. Roof damage is a common damage mode in water tanks as well.
- Small bolted steel tanks with high H/D ratios have not performed well in earthquakes. This may be due to high H/D ratios, thinner wall construction, lack of anchorage or lack of seismic design in older tanks.
- Unanchored tanks with low H/D ratios have uplifted in past earthquakes, but have not been damaged. The need to anchor these tanks is questioned.
- Increased thickness annulus rings near the outside of the bottom plate appear to be a good design measure.
- More flexibility is needed to accommodate relative tank and foundation movements for attached pipes.

B.4.6 Statistical Analysis of Tank Performance, 1933-1994

A statistical analysis of on-grade steel tanks was reported by O'Rourke and So [1999], which is based on a thesis by So [1999]. The seismic performance for 424 tanks were considered from the following earthquakes: 1933 Long Beach, 1952 Kern County, 1964 Alaska, 1971 San Fernando, 1979 Imperial Valley, 1983 Coalinga, 1989 Loma Prieta, 1992 Landers and 1994 Northridge. The damage descriptions from Cooper [1997] were used to establish most of the empirical database, with some supplemental material from other sources.

Quantitative attributes were assigned to each database tank, summarized in Table B-4.

Parameter	Range	Median	No. of Tanks
Diameter D, (feet)	10 to 275	62	343
Height H, (feet)	16 to 63	40	343
Percent Full, % Full	0% to 100%	50%	247

Table B-4. Physical Characteristics of Database Tanks [after O'Rourke and So]

Of the 424 tanks in the database, some were missing attributes. Table B-5 lists the tanks from each earthquake.

Event	No. of Tanks Affected	PGA Range (g)	Median PGA (g)	PGA Source
1933 Long Beach	49		0.17	Cooper 1997
1952 Kern County	24		0.19	Cooper 1997
1964 Alaska	26			Not available
1971 San Fernando	20	0.30 to 1.20	0.60	Wald et al 1998
1979 Imperial Valley	24	0.24 to 0.49	0.24	Haroun 1983
1983 Coalinga	38	0.71	0.71	Cooper 1997
1989 Loma Prieta	140	0.11 to 0.54	0.13	Cooper 1997
1992 Landers	33	0.10 to 0.56	0.20	Cooper 1997, Ballantyne and Crouse 1997, Wald et al 1998
1994 Northridge	70	0.30 to 1.00	0.63	Brown et al 1995, Wald et al 1998

Table B-5. Earthquake Characteristics for Tank Database [after O'Rourke and So]

Table B-5 lists the assumed PGA values or range of values for the 424 tanks in the database of O'Rourke and So. The PGA values used in Table B-5 do not always match the PGA values in Table B-3. For example, for the eight anchored steel tanks in Table B-3 for the 1983 Coalinga earthquake, tank-specific PGAs ranged from 0.20g to 0.60g. For the 38 tanks in Table B-5 for the same earthquake, all tanks are assigned a PGA of 0.71g.

Using the data in Table B-5, O'Rourke and So prepared fragility curves using the following procedure:

Each tank was assigned one of five damage states from 1 to 5. If a tank had multiple types of damage, the most severe damage state (5) was assigned to the tank. The damage states are as follows:

- Damage state 1: No damage
- Damage state 2: Damage to roof, minor loss of content, minor shell damage, damage to attached pipes, no elephant foot failure
- Damage state 3: Elephant foot buckling with no leak or minor loss of contents
- Damage state 4: Elephant foot buckling with major loss of content, severe damage
- Damage state 5: Total failure, tank collapse

Each tank was then assigned one of eight PGA bins ranging from 0.1g to 1.3g.

Using a logistic regression model, a cumulative density function was fitted through the data, which relates PGA to the probability of reaching or exceeding a particular damage state.

O’Rourke and So found that the upward trend of damage is relevant (i.e., increasing PGA leads to a higher chance of reaching a higher damage state), but there is considerable scatter of data.

The most relevant data set for tanks in water distribution systems are for steel tanks that had fill levels between 50% and 100% of capacity at the time of the earthquake. Table B-6 shows this data set.

PGA (g)	All Tanks	DS ≥ 1	DS ≥ 2	DS ≥ 3	DS ≥ 4	DS = 5
0.15	28	28	26	8	0	0
0.30	29	29	22	6	1	0
0.45	4	4	2	0	0	0
0.60	37	37	21	8	5	2
0.75	26	26	17	10	4	2
0.90	8	8	3	3	3	0
1.05	1	1	1	1	1	1
Total	**133**	**133**	**92**	**36**	**14**	**5**

Table B-6. Damage Matrix for Steel Tanks with 50% ≤ Full ≤ 100%

Fragility curves were then fitted into this dataset. The fragility curve form is the two-parameter fragility model, with the two parameters being the median and a lognormal standard deviation. To fit the two parameters, the median was selected as the 50^{th} percentile PGA value to reach a particular damage state. The lognormal standard deviation was computed by assuming that the cumulative density function value at the 80^{th} percentile fitted the lognormal function. So [1999] found that the goodness of fit (R^2) term of the lognormal distribution function ranged from 0.31 (damage state 2) to 0.83 (damage state 4), indicating a lot of scatter in the data and that the indicator of damage, PGA, may not be an ideal predictor. Given the difficulty in establishing the data set, the uncertainty involved in selecting the PGA for each tank and the omission of key tank design variables (e.g., tank wall thickness), is it not surprising that the lognormal fragility curve would not be a “tight” fit to the observed tank performance. However, the form of the fragility curve is the same as that used in the HAZUS program, which allows comparisons. The results are shown in Table B-7.

Damage State	**Empirical Median (Fill ≥50%)** (g)	**Empirical Standard Deviation** (β)	**HAZUS Unanchored, Near Full Median (g)**	**HAZUS Unanchored, Near Full Beta** (β)	**HAZUS Anchored, Near Full Median (g)**	**HAZUS Anchored, Near Full Beta** (β)
DS ≥ 2	0.49	0.55	0.15	0.70	0.30	0.60
DS ≥ 3	0.86	0.39	0.35	0.75	0.70	0.60
DS ≥ 4	0.99	0.27	0.68	0.75	1.25	0.65
DS = 5	1.17	0.21	0.95	0.70	1.60	0.60

Table B-7. Fragility Curves – O’Rourke Empirical versus HAZUS

It should be noted that the HAZUS fragility curves for DS=2 cover the case with only slight leaks in attached pipes, while the empirical dataset by O’Rourke and So assumes that any pipe damage is in DS2, a minor leak or gross pipe break. Also, the HAZUS curves are applicable only for water tanks that are at least 80% full at the time of the earthquake.

The empirical work of O’Rourke and So suggests the following limitations:

- The empirical fragility curves are based on the PGA. The PGA in the empirical dataset is sometimes the maximum PGA of two horizontal motions for sites near instrumental recordings, and are sometimes based on attenuation models (average PGA of two horizontal motions).
- The empirical dataset includes tanks from 50% full to 100% full that were mostly unanchored oil tanks. (It is common for oil tanks to be less than completely full. It is uncommon for water tanks to be less than 80% full; most water tanks are kept between 80% and 100% full, depending on time of day.) The higher the fill level, the higher the forces and movements in a tank.
- The empirical data set includes a lot of oil tanks located on soil sites. Many water tanks are located in hillside areas, which are better characterized as rock sites. The difference in spectral shapes for the impulsive and convective mode periods is considerable between rock and soil sites, suggesting that tanks located on rock sites should perform better than tanks located on soil sites, if both sites are predicted to have the same PGA and all other factors are equal.

B.5 Tank Database

Tables B-8 through B-19 provide the tank database used in the development of the tank fragility data in the main report. The references quoted in these tables can be found in the reference portion of Section 5 of the main report.

Table B-20 provides a summary of the various abbreviations used in these tables.

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
1	A	0.17	28.90	8.80	0.30	8.62	0.98	4	Failed, also oil splashed from top	Riveted. Used same PGA for all Long Beach Tanks. The 0.17g value is from an instrument 29 km from epicenter.	U	Cooper, 1997
2	1 of 3	0.17	28.90	8.80	0.30	4.40	0.50	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
3	2 of 3	0.17	28.90	8.80	0.30	4.40	0.50	1	NoDamage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
4	3 of 3	0.17	28.90	8.80	0.30	4.40	0.50	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
5	B	0.17	U	U	U	U	U	5	Total failure	Riveted. Used same PGA for all Long Beach Tanks	U	Cooper, 1997
6	1 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
7	2 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
8	3 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
9	4 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
10	5 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
11	6 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
12	7 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
13	8 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
14	9 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
15	10 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
16	11 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
17	12 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
18	13 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
19	14 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
20	15 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach	U	Cooper, 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
										Tanks		
21	16 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
22	17 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
23	18 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
24	19 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
25	20 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
26	21 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
27	22 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
28	23 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
29	24 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
30	25 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
31	26 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
32	27 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
33	28 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
34	29 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
35	30 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
36	31 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
37	32 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
38	33 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
39	34 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
40	35 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
41	36 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
42	37 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
43	38 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
44	39 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
45	40 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
46	41 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
47	42 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
48	43 of 43	0.17	U	U	U	U	U	1	No Damage	Used same PGA for all Long Beach Tanks	U	Cooper, 1997
49	C	0.17	45.50	19	0.42	14.5	0.76	4	Damage to upper shell course but no elephant foot buckle. Portions of shell 200 ft from tank after failure	Riveted. Used same PGA for all Long Beach Tanks	U	Cooper, 1997

Comments.

There is shell / roof damage mentioned in Cooper 1997 but not reflected in the database

The 0.17g ground motion is from an instrument in Long Beach (location unknown), with 0.2g vertical and only 0.17g known in one horizontal direction

The damage mode for Tank 49 was listed as "2" by So, but the shell ended up 200 feet from the tank. Changed to 4 (extensive damage, possibly partially salvagable)

The 0.17g motion might be low for these tanks.

Table B-8. Long Beach 1933 M6.4

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
1	550x81	0.19	34.90	9.14	0.26	1.22	0.13	3	Bottom ring bulged 1/4"	Used same PGA for all Kern County Tanks	U	Cooper, 1997
2	550x82	0.19	34.90	9.14	0.26	5.79	0.63	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
3	550x83	0.19	34.90	9.11	0.26	0.79	0.09	2	Earth impronts on bottom edge	Used same PGA for all Kern County Tanks	U	Cooper, 1997
4	550x84	0.19	34.90	9.14	0.26	5.52	0.60	2	Some oil splashed onto top	Used same PGA for all Kern County Tanks	U	Cooper, 1997
5	550x85	0.19	34.90	9.05	0.26	2.87	0.32	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
6	550x86	0.19	34.90	9.08	0.26	8.29	0.91	2	Approx. 15 seals damaged, oil splashed over side, earth imprints by bottom edge	Used same PGA for all Kern County Tanks	U	Cooper, 1997
7	37003	0.19	28.71	9.2	0.32	2.68	0.29	2	Oil splashed onto roof	Used same PGA for all Kern County Tanks	U	Cooper, 1997
8	37014	0.19	28.71	9.14	0.32	5.73	0.63	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
9	550x79	0.19	34.99	9.11	0.26	1.4	0.15	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
10	800x11	0.19	35.72	12.74	0.36	3.08	0.24	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
11	37004	0.19	28.71	9.17	0.32	6.04	0.66	3	Tank settled, lower course budlged, oil splashed on shell	Used same PGA for all Kern County Tanks	U	Cooper, 1997
12	37015	0.19	28.71	9.17	0.32	2.26	0.25	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
13	37005	0.19	28.71	9.17	0.32	6.49	0.71	2	Bottom leaked, oil splaashed over wind girder	Used same PGA for all Kern County Tanks	U	Cooper, 1997
14	37016	0.19	28.71	9.17	0.32	0.73	0.08	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
15	37006	0.19	28.65	9.2	0.32	4.82	0.52	2	Oil splahed onto roof	Used same PGA for all Kern County Tanks	U	Cooper, 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
16	370x13	0.19	28.93	9.08	0.31	4.82	0.53	2	Earth imprints by bottom edge	Used same PGA for all Kern County Tanks	U	Cooper, 1997
17	55021	0.19	34.93	9.11	0.26	3.78	0.41	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
18	55022	0.19	34.93	9.11	0.26	1.68	0.18	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
19	55047	0.19	34.93	9.14	0.26	0.98	0.11	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
20	80105	0.19	35.69	12.74	0.36	0	0.00	1	No Damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
21	PG&E 1	0.19	36.60	6.25	0.17	U	U	2	Damage to roof truss	Used same PGA for all Kern County Tanks	U	Cooper, 1997
22	PG&E 2	0.19	23.80	8.93	0.38	U	U	2	Damage to roof truss	Used same PGA for all Kern County Tanks	U	Cooper, 1997
23	PG&E 3	0.19	23.80	13.5	0.57	U	U	2	Seal damage	Used same PGA for all Kern County Tanks	U	Cooper, 1997
24	PG&E 4	0.19	36.60	8.9	0.24	U	U	2	Damage to roof truss	Used same PGA for all Kern County Tanks	U	Cooper, 1997

Comments.

Most tanks bolted steel or riveted steel (tanks 1 through 20)

A number of smaller diameter bolted steel tanks either failed in elephant foot buckling, or at least in one case, collapsed and fell over; the collapsed tank was nearly full

Corrections made for tanks 21, 22, 23,24 for D and H information

The 0.19g PGA value by So is based on the Taft instrument, located 41 km NW of epicenter

The Cooper report talks about a lot of other tanks that were damaged in this event, but these are not included in the table

Table B-9. Kern County 1952 M7.5

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
1	B	0.20	30.50	9.60	0.31	9.12	1.00	2	Damage to roof, top wall, roof columns		U	Hanson 1973
2	C, Shell Oil at Anchorage airport	0.20	13.70	9.60	0.70	9.12	1.00	4	Damage to roof, top wall, roof rafters, bottom wall buckled EFB		U	Hanson 1973
3	D, Shell Oil at Anchorage Port Area	0.20	36.60	9.60	0.26	9.12	1.00	2	Damage to roof and top shell and columns		U	Hanson 1973
4	E	0.20	36.58	9.75	0.27		0.10	1	No damage		U	Hanson 1973
5	F	0.20	36.60	9.75	0.27		0.10	1	No damage		U	Hanson 1973
6	G-1	0.20	33.50	9.75	0.29		0.10	1	No damage		U	Hanson 1973
7	G-2	0.20	33.50	9.75	0.29		0.10	1	No damage	Assumed almost empty	U	Photo
8	H	0.20	27.40	9.75	0.36	9.12	0.66	1	No damage except to swing joint in floating section		U	Hanson 1973
9	I	0.20	16.70	7	0.42	6.65	1.00	2	Damage to roof rafters and top wall		U	Hanson 1973
10	J	0.20	9.10	12.2	1.34	12.2	1.00	4	Extensive bottom shell buckling, loss of contents		U	Hanson 1973
11	K	0.20	9.10	12.2	1.34	12.2	1.00	4	Extensive bottom shell buckling, loss of contents		U	Hanson 1973
12	L	0.20	9.10	12.2	1.34	12.2	1.00	4	Extensive bottom shell buckling, loss of contents		U	Hanson 1973
13	M, Chevron	0.20	8.50	12.2	1.44	12.2	1.00	5	Collapsed, failed		U	Hanson 1973
14	N	0.20	12.80	12.2	0.95	11.59	0.95	3	Bottom shell buckling		U	Hanson 1973
15	O	0.20	6.10	12.2	2.00	11.59	0.95	4	Bottom shell buckling, broken shell/ bottom weld		U	Hanson 1973
16	P	0.20	43.90	17.1	0.39	16.25	0.95	2	Floating roof buckled, large waves		U	Hanson 1973
17	Q	0.20	34.10	17.1	0.50	16.25	0.95	2	Floating roof pontoon damaged		U	Hanson 1973
18	R	0.20	14.90	14.6	0.98	13.87	0.95	3	Bottom buckled, 12-inch uplift		U	Hanson 1973
19	S	0.20	27.40	14.6	0.53	10.95	0.75	2	3/4 full, roof and roof/shell damage	Over 3/4 full	U	Hanson 1973
20	T	0.20	48.80	17.1	0.35		0.50	2	Support columns twisted and rafters damaged	Assumed 50% full based on damage		Hanson 1973
21	U	0.20	48.80	17.1	0.35		0.50	1	No damage	Assumed 50% full		Hanson 1973
22	R200	0.20	9.10	14.6	1.60	14.6	1.00	5	Water, full, failed	Tank fell over. EFB, bottom plate tore from wall, cone roof ripped off completely	U	Cooper 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
23	R162	0.20	27.40	14.6	0.53	14.6	1.00	2	Full, cone roof damage no elephant foot		U	Cooper 1997
24	R163	0.20	27.40	14.6	0.53	14.6	1.00	2	Full, cone roof damage no elephant foot		U	Cooper 1997
25	R100	0.20	34.10	17.1	0.50	2.85	0.17	2	Floating roof, 1/6 full, roof damage		U	Cooper 1997
26	R120	0.20	21.30	14.6	0.69	4.87	0.33	2	Floating roof, 1/3 full, roof damage		U	Cooper 1997
27	R110	0.20	43.90	17.1	0.39	11.97	0.50	2	Floating roof, roof damage, 39 feet	Assumed 50% full	U	Cooper 1997
28	R140	0.20	14.90	14.6	0.98	U	0.50	3	Elephant foot buckling, no leak	Assumed 50% full	U	Cooper 1997
29	AA4	0.20	3.20	9.1	2.84	3.03	0.33	1	1/3 full, walked, no damage		U	Cooper 1997
30	AA7	0.20	12.1	13	1.07	U	0.75	4	Severe elephant foot buckling	Assumed .75 full based on damage	U	Cooper 1997
31	AA5	0.20	8.5	12.2	1.44	U	0.75	5	Failed, collapsed	Assumed .75 full based on damage	U	Cooper 1997
32	Army 1	0.30	93	28	0.30		0.7	3	Slight EFB, remained in service. EFB occurred only to non-full tanks	Designed to Z=0.3g. PGA inferred from MMI VII-VIII	UA	Belanger 1973
33	Army 2	0.30	93	28	0.30		0.7	3	Slight EFB, remained in service. EFB occurred only to non-full tanks	Designed to Z=0.3g. PGA inferred from MMI VII-VIII	UA	Belanger 1973
34	Army 3	0.30	93	28	0.30		0.7	3	Slight EFB, remained in service. EFB occurred only to non-full tanks	Designed to Z=0.3g. PGA inferred from MMI VII-VIII	UA	Belanger 1973
35	Army 4	0.30	93	28	0.30		0.7	3	Slight EFB, remained in service. EFB occurred only to non-full tanks	Designed to Z=0.3g. PGA inferred from MMI VII-VIII	UA	Belanger 1973
36	Army 5	0.30	93	28	0.30		0.95	2	Damage to side pipes, sloshing	Designed to Z=0.3g. PGA inferred from MMI VII-VIII	UA	Belanger 1973
37	Army 6	0.30	93	28	0.30		0.95	2	Damage to side pipes	Designed to Z=0.3g. PGA inferred from MMI VII-VIII	UA	Belanger 1973
38	Army 7	0.30	93	28	0.30		0.95	2	Damage to side pipes	Designed to Z=0.3g. PGA inferred from MMI VII-VIII	UA	Belanger 1973
39	Army 8	0.30	93	28	0.30		0.95	2	Damage to side pipes	Designed to Z=0.3g. PGA inferred from MMI VII-VIII	UA	Belanger 1973

Comments
Tanks B - T are in Anchorage area, 130 km from epicenter
Tanks R200 - R140 believed to be Nikiska Refinery. 210 km from epicenter.
Tanks AA are at Anchorage airport
Tanks D, E, F, G are at Anchorage port area, 150 yards from waterfront. 1 in 5 was damaged (Tank G2 based on observation from photo)
Tanks M, N, O are at Anchorage airport area.
PGA ground motion = 0.2g is taken to be the estimated maximum ground acceleration in Anchorage (ref. Hanson, 1973)

Table B-10. Alaska 1964 M8.4

No.	Tank ID	PGA (g)	Diameter , D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
1	MWD Jensen FP Washwater	0.60	31.00	11.00	0.35	5.50	0.58	3	Roof, upper shell damaged due to wrinkling, uplifted 13 inches max based on observed anchor bolt stretch. No efb (Cooper),	Welded steel. Assumed 1/2 to 2/3 full - 50%. PGA from Wald. Anchor bolts were for installation, not for seismic design	A	Cooper 1997, Wald 1998, CDMG 1975
2	OV Hospital	0.60	17.00	12.00	0.71	10.80	0.90	4	Elephant foot buckle, 3 m long floor / shell tear; inlet / outlet piping damage; loss of contents. Roof rafters buckled	Welded steel tank	U	Cooper, Wald
3	Vet Hosp 1	1.20					0.90	2	I/O pipe damage, anchor bolt stretch . Buckled anchorage system	Small Riveted steel tank. Assumed near full	A	Cooper, Wald
4	Vet Hosp 2	1.20					0.90	1	No significant damage	Small Welded steel tank. Assumed near full	U	Cooper, Wald
5	Alta Vista 1, LADWP	1.20	16.60	8.6	0.52	7.74	0.90	2	Damage to inlet / outlet fittings	Riveted steel tank, built 1931	U	Cooper, Wald
6	Alta Vista 2, LADWP	1.20	29.20	11.2	0.38	10.08	0.90	2	Damage to inlet / outlet fittings	Welded Steel Tank, built 1954	U	Cooper, Wald
7	Newhall CWD 1	0.60					0.90	3	Floor plate ruptures and shell buckling	Assumed near full	U	Cooper, Wald
8	Newhall CWD 2	0.60					0.90	3	Floor plate ruptures and shell buckling	Assumed near full	U	Cooper, Wald
9	Mutual Water Co 1	1.20	6.20	6.2	1.00	5.58	0.90	5	Failed	Small bolted tank	U	Cooper, Wald
10	Mutual Water Co 2	1.20	6.20	6.2	1.00	5.58	0.90	5	Failed	Small bolted tank	U	Cooper, Wald
11	Mutual Water Co 3	1.20	6.20	6.2	1.00	5.58	0.90	5	Failed	Small bolted tank	U	Cooper, Wald
12	Mutual Water Co 4	1.20	6.20	6.2	1.00	5.58	0.90	5	Failed	Small bolted tank	U	Cooper, Wald
13	Mutual Water Co 5	1.20	6.20	6.2	1.00	5.58	0.90	5	Failed	Small bolted tank	U	Cooper, Wald

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
14	Sesnon, LADWP	0.30	28.04	12.8	0.46	12.35	0.96	3	Developed a buckle 7.4 m above the bottom on a 150 degree arc. Uplifted. Damage to wood roof	1" thick bottom course, built 1956	UA	Cooper 1997, Wald 1998, CDMG 1975
15	Granada High, LADWP	0.40	16.77	13.8	0.82	12.42	0.90	2	Roof collapse and shifting of wood roof	Riveted steel, 1929 construction, wood roof	U	Cooper, Wald
16	Newhall 1	0.60	18.50	12.2	0.66	12.2	1.00	3	Elephant foot buckle on one side		U	Cooper, Wald
17	Newhall 2	0.60	18.50	12.2	0.66	12.2	1.00	3	Elephant foot buckle on one side		U	Cooper, Wald
18	Newhall 3	0.60	18.50	12.2	0.66	12.2	1.00	3	Elephant foot buckle on one side		U	Cooper, Wald
19	Newhall 4	0.60	37.00	12.2	0.33		0.90	2	Minor pipe damage	Assumed near full	U	Cooper, Wald
20	Newhall 5	0.60	37.00	12.2	0.33		0.90	2	Minor pipe damage	Assumed near full	U	Cooper, Wald

Comments

MWDJP. Water tank at Jensen Filter plant (MWD). Fill data corrected from So

Location of Mutual Water Co is unknown. Why PGA = 1.2g not verified

Fill Levels for tanks 2, 3, 4, 5, 6, 7, 8, 9, 10,11,12,13, 15 set to 90%, based on normal water system operations procedures (je)

Table B-11. San Fernando 1971 M6.7

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
1	IID El Centro 1 of 6	0.49	41.20	13.70	0.33	13.56	0.99	2	Roof damage and spill due to sloshing. Tank may have uplifted	PGA from Haroun	UA	Cooper 1997, Haroun 1983, EERI 1980
2	IID El Centro 2 of 6	0.49	22.30	6.10	0.27	6.04	0.99	1	No damage per EERI 1980	PGA from Haroun	UA	Cooper 1997, Haroun 1983, EERI 1980
3	IID El Centro 3 of 6	0.49	U	U		U		1	No apparent damage. "some" damage reported in EERI, 1980	PGA from Haroun	UA	Cooper 1997, Haroun 1983, EERI 1980
4	IID El Centro 4 of 6	0.49	U	U		U		2	A cracked weld at roof / wall allowed some oil sloshing to leak out	PGA from Haroun	UA	Cooper 1997, Haroun 1983, EERI 1980
5	IID El Centro 5 of 6	0.49	U	U		U		1	No apparent damage. "some" damage reported in EERI, 1980	PGA from Haroun	UA	Cooper 1997, Haroun 1983, EERI 1980
6	IID El Centro 6 of 6	0.49	U	U		U		1	No apparent damage	PGA from Haroun	UA	Cooper 1997, Haroun 1983, EERI 1980
7	IP 1	0.24	24.40	14.6	0.60	6.28	0.43	2	Roof seal damage, broken anti-rotation devi ces, relief piping damage, settlement	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983
8	IP 2	0.24	24.40	14.6	0.60	7.15	0.49	2	Roof seal damage, broken anti-rotation devi ces, relief piping damage, settlement	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
9	IP 3	0.24	20.40	12.3	0.60	4.8	0.39	1	No apparent damage	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
10	IP 4	0.24	14.60	14.6	1.00	7.74	0.53	3	Roof seal damage, broken anti-rotation devi ces, relief piping damage, settlement. Small EFB with no leak	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
11	IP 5	0.24	14.60	14.6	1.00	10.6	0.73	3	Anito rotation devices disconnected; EFB no leak, roof drains leaks, settlement of tank 1 inch	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
12	IP 6	0.24	13.00	12.2	0.94	4.64	0.38	2	Primary seal on floating roof damaged	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
13	IP 7	0.24	13.00	12.2	0.94	4.88	0.40	1	No apparent damage	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
14	IP 8	0.24	24.70	14.6	0.59	11.97	0.82	3	Prinary seal on floating roof damaged. Stair platform damaged. Settlement of tank 1 inch, roof drain leaks, leak in tank where floor plates overlap and join shell	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
15	IP 9	0.24	13.00	12.2	0.94	7.93	0.65	2	Roof drain leaks, swingline cable broke	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
16	IP 10	0.24	13.00	12.2	0.94	9.27	0.76	2	Roof drain leaks	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
17	IP 11	0.24	14.20	12.2	0.86	10.49	0.86	2	Relief piping damaged, grounding cable disconnected, settlement of tank 1 to 2 inches, swingline leaking	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
18	IP 12	0.24	13.00	12.2	0.94	10.49	0.86	2	Swingline cable broke, swingline jumped track can caused floating roof to hang, gauge-antirotation pipe broke from floor and bent severely, roof drain leaks	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
19	IP 13	0.24	12.60	14.9	1.18	10.43	0.70	4	Elephant foot buckling 6 to 8 inches outwards over 90 degree arc, shell / bottom separation, relief piping damaged, cracks in epoxy coating on floor, gauge-antirotation pipe broke from floor, floating roof level indicator cable broke	PGA from Haroun. Tank built to API 650. Possibly nearly full per EERI 1980	UA	Cooper 1997, Haroun 1983, EERI 1980
20	IP 14	0.24	14.70	14.9	1.01	9.09	0.61	2	Cracks in concrete ringwall	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
21	IP 15	0.24	15.20	14.9	0.98	9.09	0.61	2	Cracks in concrete ringwall	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
22	IP 16	0.24	14.60	14.6	1.00	12.12	0.83	3	Elephant foot buckling 6 inches outward, no tearing of the bottom plate to bottom course, swingline moutings broke, grounding cable pulled out of ground, relief pipng broke, cracks in concrete ringwall foundation	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
23	IPC-1	0.24	6.50	7.3	1.12	2.19	0.30	1	No apparent damage	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980
24	IPC-2	0.24	6.50	7.3	1.12	2.85	0.39	1	No apparent damage	PGA from Haroun. Tank built to API 650	UA	Cooper 1997, Haroun 1983, EERI 1980

Comments

IP 1 to IP 16 are at the SPPL terminal (now SFPPL - Santa Fe Pacific Pipelines). Built 1958 to 1965 with EQ design considerations

IP 13. DS changed from 3 (So) to 4, as the weld separation led to loss of contents

Valley Nitrogen, 20 km from epicenter and 12 km from fault and no significant damage to 4 or 5 tanks at that site (these tanks are not in the above table)

City of El Centro had 2 elevated water steel tanks (150,000 gal and 250,000 gal).

The smaller tank (built 1940) suffered moderate structural damage to support members and was subsequently emptied, eventually repaired and put back in service.

The larger tank (250,000 gal, built 1970s) was not damaged, and was 40% full at the time of the earthquake (ref. EERI, Feb 1980 D. Leeds, Ed.)

The Calcot Industries elevated water tank suffered minor damage to diagonal bracing (100,000 gallons, full at time of earthquake), designed 1962.

South of Brawley, a 100,000 gallon elevated steel tank collapsed. The tank was designed and built in 1961 using V = 0.1W.

Table B-12. Imperial Valley 1979 M6.5

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
1	Site A 1	0.47	U	U		U	0.95	2	Roof damage	Large tank	U	Cooper 1997
2	Site A 2	0.47	U	U		U	0.95	2	Roof damage	Large tank	U	Cooper 1997
3	Site A 3	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
4	Site A 4	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
5	Site A 5	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
6	Site A 6	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
7	Site A 7	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
8	Site A 8	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
9	Site A 9	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
10	Site A 10	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
11	Site A 11	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
12	Site A 12	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
13	Site A 13	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
14	Site A 14	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
15	Site A 15	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
16	Site A 16	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
17	Site A 17	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
18	Site A 18	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
19	Site A 19	0.47	U	U		U	U	1	No apparent damage	Not full	U	Cooper 1997
20	Site B 1 of 6	0.57	43.00	14.8	0.34	14.8	1.00	2	Splashing, some roof secondary seal damage	Constructed per API 650, 1956	UA	Cooper 1997
21	Site B 2 of 6	0.57	43.00	14.8	0.34	14.8	1.00	2	Splashing, some roof secondary seal damage	Constructed per API 650, 1956	UA	Cooper 1997
22	Site B 3 of 6	0.57	43.00	14.8	0.34	7.4	0.50	1	No apparent damage	Constructed per API 650, 1956	UA	Cooper 1997
23	Site B 4 of 6	0.57	43.00	14.8	0.34	7.4	0.50	1	No apparent damage	Constructed per API 650, 1956	UA	Cooper 1997
24	Site B 5 of 6	0.57	43.00	14.8	0.34	7.4	0.50	1	No apparent damage	Constructed per API 650, 1956	UA	Cooper 1997
25	Site B 6 of 6	0.57	43	14.8	0.34	0.74	0.05	2	Roof seal damage	Constructed per API 650, 1956	UA	Cooper 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
26	Site B	0.57	18.5	12	0.65	12	1.00	1	Settled uniformly about 2 inches, but no visible damage	Firewater tank	U	Cooper 1997
27	Site C Tank 7	0.39	61.5	14.8	0.24	10.7	0.72	4	Roof seal damage, oil splashed over top. Tank pounded into foundation 4 inches, uplifted and with steel tear and significant leak of contents where pipe entered through bottom plate. Pipe support moved 4 inches	Built to API 650	UA	Cooper 1997
28	Site C Tank 8	0.39	61.5	14.8	0.24	3	0.20	2	Roof seal damage, wind girder buckled on south side	Built to API 650	UA	Cooper 1997
29	Site C Tank 13	0.39	61.5	14.8	0.24	3	0.20	2	Roof seal damage	Built to API 650	UA	Cooper 1997
30	Site C Tank 13	0.39	61.5	14.8	0.24	3	0.20	2	Roof seal damage	Built to API 650	UA	Cooper 1997
31	Site C	0.39	37	12	0.32	U		3	Slight bulge in bottom course but not elephant foot buckling	Riveted shell, open top, firewater	UA	Cooper 1997
32	Site D 1 of 2	0.70	U	U		U		3	Buckling of top bolted ring	Riveted shell, old	U	Cooper 1997
33	Site D 2 of 2	0.70	U	U		U		2	Broken valves / fittings	Riveted shell, old	U	Cooper 1997
34	Site E 1 of 2	0.62	U	U		U		2	Broken cast iron valves / fittings, pulled Dresser couplings, minor tank settlement	Small Bolted tank	U	Cooper 1997
35	Site E 2 of 2	0.62	U	U		U		2	Broken cast iron valves / fittings, pulled Dresser couplings, minor tank settlement	Small Bolted tank	U	Cooper 1997
36	Site F 1	0.57	34	12	0.35	7.9	0.66	1	No apparent damage	AWWA D100, Built 1971	U	Cooper 1997
37	Site G 1 of 2	0.43	17	10	0.59	7.5	0.75	3	Elephant foot buckling	Bolted steel	U	Cooper 1997
38	Site G 2 of 2	0.43	17	10	0.59	7.5	0.75	3	Elephant foot buckling	Bolted steel	U	Cooper 1997
39	Filter Plant Backwash	0.39	9.14	18.3	2.00	13.71	0.75	2	Minor leaks at outlet pipe due to rocking of tank (possibly not from EQ). Stretched anchor bolts	A36 steel, 0.25" bottom plate, .375" bottom course	A	Hashimoto 1989, EERI 1984
40	Main Tank	0.23					0.50	1	Slight	Southwest of epicenter		EERI 1984

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
41	East Tank	0.45					0.50	2	Broken CI inlet/outlet pipe	South of epicenter		EERI 1984

Comments
O'Rourke and So [1999] use PGA = 0.71g, which is average of the peak accelerations given in Cooper (0.6g to 0.82g). PGAs in this table based on attenuation, and to be consistent with Hashimoto [1989]
Site A had 19 tanks, mostly riveted steel tanks. Site C is mainline pumping station
Tank 27. DS set to 4 to reflect tear of bottom plate and loss of contents
Tank 31. DS (2) per So changed to 3 to relfect initiation of elephant foot buckling without leak
Site G had other bolted steel tanks with leakage at bolt holes and other minor damage
Sites H and I located 16 km from epicenter (not in table). Damge not extensive at these sites, including sloshing losses and some damage to piping

Table B-13. Coalinga 1983 M6.7

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
1	Jackson Oaks	0.50	14.00	8.54	1.00	U	0.95	3	Broken pipe coupling, slight EFB	H/D ratio based on photo	UA	EERI 1985
2	United Technology 1	0.40						2	Tank slid 2-3 inches, rupturing pipes		UA	EERI 1985
3	United Technology 2	0.40						2	Tank slid 2-3 inches, rupturing pipes		UA	EERI 1985
4	Tank 2	0.25						1	No damage	PGA estimated - opposite side of valley	U	EERI 1985
5	Tank 3	0.25						1	No damage	PGA estimated - opposite side of valley	U	EERI 1985
6	Tank 4	0.25						1	No damage	PGA estimated - opposite side of valley	U	EERI 1985
7	Tank 5	0.25						1	No damage	PGA estimated - opposite side of valley	U	EERI 1985
8	Tank 6	0.25						1	No damage	PGA estimated - opposite side of valley	U	EERI 1985
9	Tank 7	0.25						1	No damage	PGA estimated - opposite side of valley	U	EERI 1985
10	Tank 8	0.25						1	No damage	PGA estimated - opposite side of valley	U	EERI 1985
11	Tank 9	0.25						1	No damage	PGA estimated - opposite side of valley	U	EERI 1985
12	Tank 10	0.25						1	No damage	PGA estimated - opposite side of valley	U	EERI 1985

Comments

The Jackson Oaks tank is one of 10 tanks in the Morgan Hill water system

Damage to the water system was confined to an area near Jackson Oaks, with the most intense shaking

Damage to the pipe at the Jackson Tank is assumed to have occurred due to rocking of the tank (likely unanchored)

The location of the other 9 tanks is presumed more distant from the Calaveras fault, with no reported damage

United Technologies. PGA estimated from nearby instruments. Tanks located on hillside.

2 Redwood tanks fell at San Martin winery (PGA about 0.3 - 0.4 g)

40 of 100 small stainless steel tanks at San Martin wintery were buckled; 13 of 40 leaked

Table B-14. Morgan Hill 1984 M6.2

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
1	Richmond 1	0.13	18.85	15.10	0.80	7.55	0.50	3	Elephant foot buckling, pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
2	Richmond 2	0.13	18.85	15.10	0.80	7.55	0.50	3	Elephant foot buckling, pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
3	Richmond 3	0.13	18.85	15.10	0.80	7.55	0.50	3	Elephant foot buckling, pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
4	Richmond 4	0.13	18.85	15.10	0.80	7.55	0.50	3	Elephant foot buckling, pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
5	Richmond 5	0.13	18.85	15.10	0.80	7.55	0.50	3	Elephant foot buckling, pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
6	Richmond 6	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
7	Richmond 7	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
8	Richmond 8	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
9	Richmond 9	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
10	Richmond 10	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
11	Richmond 11	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
12	Richmond 12	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
13	Richmond 13	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
14	Richmond 14	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
15	Richmond 15	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
16	Richmond 16	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
17	Richmond 17	0.13	18.85	15.10	0.80	7.55	0.50	2	Pipe supports pulled from tank shell	Tanks assumed 50% full, average dimensions	U	Cooper 1997
18	Richmond 18	0.13	13.00	12.00	0.92	6.00	0.50	3	Elephant foot buckling	Tanks assumed 50% full, average dimensions	U	Cooper 1997
19	Richmond 19	0.13	13.00	12.00	0.92	6.00	0.50	3	Elephant foot buckling (incipient)	Tanks assumed 50% full, average dimensions	U	Cooper 1997
20	Richmond 20	0.13	13.00	12.00	0.92	6.00	0.50	1	No apparent damage	Tanks assumed 50% full, average dimensions	U	Cooper 1997
21	Lube 1 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
22	Lube 2 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
23	Lube 3 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
24	Lube 4 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
25	Lube 5 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
26	Lube 6 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
27	Lube 7 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
28	Lube 8 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
29	Lube 9 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
30	Lube 10 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
31	Lube 11 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
32	Lube 12 of 60	0.13	3.70	7.4	2.00	1.85	0.25	1	No apparent damage		UA	Cooper 1997
33	Lube 13 of 60	0.13	3.70	15.4	4.16	3.85	0.25	2	Anchor bolts restraining and bending bottom plate		A	Cooper 1997
34	Lube 14 of 60	0.13	3.70	15.4	4.16	3.85	0.25	2	Anchor bolts restraining and bending bottom plate		A	Cooper 1997
35	Lube 15 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997
36	Lube 16 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997
37	Lube 17 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997
38	Lube 18 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
39	Lube 19 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997
40	Lube 20 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997
41	Lube 21 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997
42	Lube 22 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997
43	Lube 23 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997
44	Lube 24 of 60	0.13	3.70	15.4	4.16	3.85	0.25	1	No apparent damage		UA	Cooper 1997
45	Lube 25 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
46	Lube 26 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
47	Lube 27 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
48	Lube 28 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
49	Lube 29 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
50	Lube 30 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
51	Lube 31 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
52	Lube 32 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
53	Lube 33 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
54	Lube 34 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
55	Lube 35 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
56	Lube 36 of 60	0.13	3.70	11	2.97	2.75	0.25	1	No apparent damage		UA	Cooper 1997
57	Lube 37 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
58	Lube 38 of	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
	60											
59	Lube 39 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
60	Lube 40 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
61	Lube 41 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
62	Lube 42 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
63	Lube 43 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
64	Lube 44 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
65	Lube 45 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
66	Lube 46 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
67	Lube 47 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
68	Lube 48 of 60	0.13	6.50	12.3	1.89	3.08	0.25	1	No apparent damage		UA	Cooper 1997
69	Lube 49 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
70	Lube 50 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
71	Lube 51 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
72	Lube 52 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
73	Lube 53 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
74	Lube 54 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
75	Lube 55 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
76	Lube 56 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
77	Lube 57 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
78	Lube 58 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
79	Lube 59 of 60	0.13	9.20	12.3	1.34	3.08	0.25	1	No apparent damage		UA	Cooper 1997
80	Lube 60 of 60	0.13	9.20	12.3	1.34	12.3	1.00	3	Elephant foot buckling. Walkway between this tank and another pulled loose and fell to ground		UA	Cooper 1997
81	San Jose 1 of 32	0.17	23.7	14.8	0.62	14.1	0.95	2	Severe bending and buckling of internal pan	Assumed nearly full	U	Cooper 1997
82	San Jose 2 of 32	0.17	27	14.6	0.54	14.1	0.96	2	Severe bending and buckling of internal pan	Assumed nearly full	U	Cooper 1997
83	San Jose 3 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
84	San Jose 4 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
85	San Jose 5 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
86	San Jose 6 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
87	San Jose 7 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
88	San Jose 8 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
89	San Jose 9 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
90	San Jose 10 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
91	San Jose 11 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
92	San Jose 12 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
93	San Jose 13 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
94	San Jose 14 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
95	San Jose 15 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
96	San Jose 16	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
	of 32											
97	San Jose 17 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
98	San Jose 18 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
99	San Jose 19 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
100	San Jose 20 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
101	San Jose 21 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
102	San Jose 22 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
103	San Jose 23 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
104	San Jose 24 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
105	San Jose 25 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
106	San Jose 26 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
107	San Jose 27 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
108	San Jose 28 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
109	San Jose 29 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
110	San Jose 30 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
111	San Jose 31 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
112	San Jose 32 of 32	0.17	19.8	14.6	0.74	U		1	No apparent damage		U	Cooper 1997
113	Brisbane 1 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
114	Brisbane 2 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
115	Brisbane 3 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
116	Brisbane 4 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
117	Brisbane 5 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
118	Brisbane 6 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
119	Brisbane 7 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
120	Brisbane 8 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
121	Brisbane 9 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
122	Brisbane 10 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
123	Brisbane 11 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
124	Brisbane 12 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
125	Brisbane 13 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
126	Brisbane 14 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
127	Brisbane 15 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
128	Brisbane 16 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
129	Brisbane 17 of 17	0.11	19.8	13.5	0.68	U		1	No apparent damage		U	Cooper 1997
130	Gilroy 1	0.50	24.4	8	0.33	U	0.95	1	No apparent damage	Water tank assumed nearly full		Cooper 1997
131	PG&E Moss Landing 1	0.24	17	12.2	0.72	U	0.9	4	Failed at floor / shell connection. Junction possibly corroded. Tank drained rapidly. Top shell course buckled	Tank assumed mostly full. Pga based on attenuation	UA	Cooper 1997, USGS 1998
132	PG&E Moss Landing Distilled 1	0.24	17	12.2	0.72	U	0.9	2	failure of pipe couplings	dimensions assumed. PGA based on attenuation	U	Cooper 1997, USGS 1998

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
133	PG&E Moss Landing Distilled 2	0.24	17	12.2	0.72	U	0.9	2	failure of pipe couplings	dimensions assumed, PGA based on attenuation	U	Cooper 1997, USGS 1998
134	Los Gatos SJ 1	0.28	U	U	U	U	0.95	4	Elephant foot buckling	Bolted water tank, 1966	UA	Cooper 1997, USGS 1998
135	Los Gatos SJ 2	0.28	U	U	U	U	0.95	4	IO pipe underneath tank separated from floor plate	700,00 gal tank welded steel		Cooper 1997, USGS 1998
136	Watsonville 1	0.54	U	U	U	U	0.95	3	Buckled at roof / shell, no leak	1,000,000 gal tank		Cooper 1997
137	Watsonville 2	0.54	U	U	U	U	0.95	1	No damage	600,000 gal tank, AWWA D100		Cooper 1997
138	Santa Cruz 1/ Scotts Valley	0.47	U	U	U	U	0.95	2	Roof damage. Wood roof. Tanks drained due to broken inlet/outlet pipes	750,000 gal	UA	Cooper 1997, USGS 1998
139	Santa Cruz 2 / Scotts Valley	0.47	U	U	U	U	0.95	2	Roof damage. Wood roof. Tanks drained due to broken inlet/outlet pipes	400,000 gal	UA	Cooper 1997, USGS 1998
140	Santa Cruz 3	0.47	U	U	U	U	0.95	1	No damage	1,250,000 gal, AWWA D100 1983		Cooper 1997
141	Hollister	0.1					0.95	1	No damage	Built in 1960s. Pga based on attenuation		USGS 1998

Comments
Richmond. Gasoline, diesel, turbine fuel, heavy fuel oil. Actual tank dimensions vary from 34 m Dx 14.8m H to 3.7m D x 15.4m H
Richmond tanks use cone roofs, CIP, F roof systems. Site is marine area with possibly poor soils. All tanks on pile foundations with pile caps
Richmond. No apparent roof damage at this site
Lube 1 to 60. Most tanks assumed 25% full (from report which states "less than half full")
San Jose. Actual tank dimensions vary from 38 m D x 14.6 m H to 7.5 m D x 9.8 m H. Initial construction of these tanks was in 1965
Brisbane. Located firm ground, hillside location (assumed rock). All tanks have C, F or CF roofs; all tanks built before seismic codes. No damage
PG&E Moss Landing. DS set to 4, reflecting buckling of top shell, tearing of bottom course and loss of contents". Other tanks at this site had no damage. PGA = 0.24g based on attenuation.
Several other tanks at this site (include 2 MG oil tank) did not have major damage. PGA = 0.39g suggested in EERI (1990 p210) based on a recording located 15 km away
The EBMUD water utility operated about 50 water steel tanks at the time of the earthquake. All were shaken with ground motions between PGA = 0.03g and PGA = 0.10g. Most of these tanks were anchored and designed per AWWA with seismic provisions. The only reported damage was 2 tanks with internal roof damage (There were no specific seismic designs of the roof systems)
All these tanks are located on rock with concrete ring foundations. About half have wood roofs and half have integral steel roofs
Most of the tanks were welded steel; a few were either riveted or bolted steel
Most of the tanks use bottom entering inlet / outlet pipes. No pipe damage was noted for any tank
Not all tanks have been inspected for internal damage to roof systems, so some unknown damage to roof systems may have occurred
San Lorenzo. Near epicentral region. 5 redwood tanks were lost (10,000 to 15,000 gallons each)
Santa Cruz mountains (in epicentral region). Several small bolted steel tanks failed, broken inlet / outlet pipes, some tanks collapsed [USGS 1998]
Watsonville. 8 other water storage facilities performed well (unknown types)
Richmond - Hercules - Rodeo - Martinez - Benicia - Avon locations include about 1,700 flat bottom steel tanks. PGA ranges from about 0.03g (rock outcrop sites) to at most 0.13-0.15g (soft soil sites)
This report covers only 80 of these 1,700 tanks. All damage to tanks were for tanks at soft soil sites, and nearly full tanks

Table B-15. Loma Prieta 1989 M7

No.	Tank ID	PGA (g)	Diameter, D (m)	Height, H (m)	H / D	H Liq (m)	Pct Full	DS	Damage Observed	Remarks	Tank Anchors	Source
1	701	0.35	44.21	9.76	0.22	9.12	0.93	2	Roof damage, fire caused by tank 792	Welded steel	UA	Ballantyne and Crouse 1997
2	704	0.35	44.21	12.20	0.28	11.52	0.95	2	Roof damage	Welded steel	UA	Ballantyne and Crouse 1997
3	705	0.35	44.21	12.20	0.28	11.52	0.95	2	Roof damage	Welded steel	UA	Ballantyne and Crouse 1997
4	708	0.35	21.16	9.76	0.46	9.30	0.95	3	Elephant foot buckling	Welded steel	UA	Ballantyne and Crouse 1997
5	709	0.35	21.16	9.76	0.46	9.30	0.95	3	Elephant foot buckling	Welded steel	UA	Ballantyne and Crouse 1997
6	715	0.35	29.70	12.20	0.41	11.49	0.94	2	Roof damage	Welded steel	UA	Ballantyne and Crouse 1997
7	717	0.35	17.87	11.43	0.64	11.28	0.99	2	Roof damage	Welded steel	UA	Ballantyne and Crouse 1997
8	725	0.35	17.87	11.43	0.64	11.28	0.99	2	Roof damage	Welded steel	UA	Ballantyne and Crouse 1997
9	726	0.35	17.87	11.43	0.64	11.28	0.99	2	Roof damage, tank lateral movement	Welded steel	UA	Ballantyne and Crouse 1997
10	728	0.35	40.85	12.20	0.30	11.77	0.97	3	Shell buckling near roof, tank lateral movement	Welded steel	UA	Ballantyne and Crouse 1997
11	Unknown	0.35	40.85	12.20	0.30	11.43	0.94	2	Tank lateral movement	Welded steel	UA	Ballantyne and Crouse 1997
12	738	0.35	14.63	9.76	0.67	9.48	0.97	4	Elephant foot buckling	Welded steel. See note below about assumed EFB failure	UA	Ballantyne and Crouse 1997
13	745	0.35	10.37	9.76	0.94	9.45	0.97	3	Elephant foot buckling	Welded steel	UA	Ballantyne and Crouse 1997
14	792	0.35	4.79	4.85	1.01	4.85	1.00	5	Overturned tank, explosion	Welded steel	UA	Ballantyne and Crouse 1997
15	Holanda Chem Plant	0.35	5.53	5.53	1.00			3	Slight Elephant foot buckle	New API 650 tank	UA	Spectra, Vol 7, B, 1991
16	Holanda Chem Plant	0.35	10.06	10.06	1.00			2	Slid 20 cm		UA	Spectra, Vol 7, B, 1991