PERFORMANCE DESIGN PARAMETERS: STRENGTH VS. DUCTILITY DEMAND

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SUMMARY

The objective of the study described in this paper was to establish a reliable method to correlate design strength with ductility demand. The engineering profession appears increasingly to be moving toward some type of performance-based design, where we are advertising that we can design building structures for a desired level of earthquake damage, or rather non-damage. It is not at all clear that we have yet mastered an understanding of the relationship between damage and ductility; but at least it is clear that less damage implies lower ductility demands. It also appears clear that less damage implies higher strength, but how much higher? The authors performed the study described herein in an effort to answer that question. The study involved nonlinear analyses of a family of single-degree-of-freedom (SDOF) nonlinear systems subjected to a series of earthquake time histories. The SDOF systems were selected to represent a range of stiffness (initial elastic periods of 0.2, 0.5, 1.0, 2.0 and 3.0 seconds); a range of strengths (each system yields at 10%, 20%, 40%, 60%, 80%, or 100% of the maximum elastic strength required to resist a particular ground motion record); and a range of damping values (2% and 5% of critical damping). Each system was subjected to a series of ground motion recordings measured at soft soil sites (6 records), intermediate soil sites (14 records), and rock sites (10 records). These combinations resulted in 300 linear and 1500 nonlinear computer runs using the program NONLIN. The results were averaged for each soil type and plotted as a percent of the maximum elastic strength versus the ductility demands. Statistical analysis of the results for all of the SDOF systems yields some general relationships between strength and ductility demand that help clarify several issues related to performance-based design. The study shows that reduction factors in current use are oversimplified, since they depend only on the type of structural system, and generally too large to limit ductility demands to acceptable levels. It is important that designers understand the strength requirements implicit in an offer to design a building that will withstand a major earthquake with little damage, or low ductility demands. A vastly more ambitious effort to correlate structural damage with strength and ductility demands for a broad range of structures is sorely needed, but the current study offers a contribution toward that end.

INTRODUCTION

In order for the concept of performance-based design to be implemented successfully, the design architect and engineer need to sit down with the building owner at the beginning of a project to discuss a wide variety of topics including: proposed use for the project, the owner's operational requirements and expectations for damage following both a service level earthquake and a major earthquake at the site, the extent of nonstructural elements or equipment whose damage might compromise operations or be especially costly to repair, the owner's construction budget and expectations for post-earthquake costs associated with damage and business interruption over the life of the project, site characteristics, service level and maximum level earthquakes to be used for design, the dynamic characteristics for the proposed lateral-force-resisting system, life-cycle costs for the proposed system, and the relationships between damage, ductility demands, and design strength for the proposed system. The designers and the owner must understand that, as a general rule, an increase in design strength will

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result in lower ductility demands, less damage, and lower life-cycle costs. The parties must agree on the performance objectives, i.e. the acceptable level of damage, correlate the damage level with ductility demands for the proposed system, and then select an appropriate strength level to use for design that corresponds with the target ductility demands. A tall order, given the current state-of-the-art.

The current paper addresses only one of these issues, namely, what is the appropriate strength level to use for design given a target ductility demand. While this is only one piece of the puzzle, it is a critical piece. Designers must understand that for conventional construction, without the use of specially designed energy dissipation devices, it is not possible to limit ductility demands without a corresponding increase in the design strength. Further, the results of this study show that for many buildings, it is not possible to limit ductility demands without a significant increase in the design strength.

NONLINEAR ANALYSIS

In order to study the relationship between design strength and global ductility demands, the authors devised a series of nonlinear computer runs using single-degree-of-freedom (SDOF) models. The program NONLIN version 5.5 (Charney 1997) was used for all of the analyses. Dynamic characteristics for the five SDOF models are shown in Table 1. Earthquake records were chosen to represent varying frequency content and peak amplitudes. The records were selected from soft soil, alluvium, and rock sites and have PGA's ranging from 0.10g to 1.17g. Descriptions of the 30 earthquake records are shown in Table 2.

Table 1 Model Characteristics

Model	Weight, k	Stiffness, k/in	Period, sec	Damping	
1	100	255.426	0.2	2%	5%
2	100	40.868	0.5	2%	5%
3	100	10.271	1.0	2%	5%
4	100	2.554	2.0	2%	5%
5	100	1.135	3.0	2%	5%

Table 2 Earthquake Records

No.	Soil Type	Description	PGA cm/sec2	PGA (g)
1	Soft Soil	Loma Prieta 1989, Oakland Outer Harbor, Ch. 1	270.36	0.28
2	Soft Soil	Loma Prieta 1989, Oakland Outer Harbor, Ch. 3	215.50	0.22
3	Soft Soil	Mexico City 1995, Station 1, 180deg	167.92	0.17
4	Soft Soil	Mexico City 1995, Station 1, 270deg	97.97	0.10
5	Soft Soil	Loma Prieta 1989, SF Int'l Airport, Ch. 1	325.80	0.33
6	Soft Soil	Loma Prieta 1989, SF Int'l Airport, Ch. 3	230.77	0.24
7	Alluvium	Imperial Valley 1940, El Centro, 180deg	210.10	0.21
8	Alluvium	Imperial Valley 1940, El Centro, 270deg	341.70	0.35
9	Alluvium	Loma Prieta 1989, Capitola Fire Station, Ch. 1	390.79	0.40
10	Alluvium	Loma Prieta 1989, Capitola Fire Station, Ch. 3	462.92	0.47
11	Alluvium	Northridge 1994, Newhall Fire Station, Ch. 1	571.62	0.58
12	Alluvium	Northridge 1994, Newhall Fire Station, Ch. 3	578.19	0.59
13	Alluvium	Loma Prieta 1989, Corralitos, Ch. 1	469.38	0.48
14	Alluvium	Loma Prieta 1989, Corralitos, Ch. 3	617.70	0.63
15	Alluvium	Northridge 1994, Hollywood Storage, Ch. 1	227.00	0.23
16	Alluvium	Northridge 1994, Hollywood Storage, Ch. 3	381.39	0.39
17	Alluvium	Northridge 1994, Santa Monica City Hall, Ch. 1	865.97	0.88
18	Alluvium	Northridge 1994, Santa Monica City Hall, Ch. 3	362.62	0.37

No.	Soil Type	Description	PGA cm/sec2	PGA (g)
19	Alluvium	Northridge 1994, Sylmar County Hospital, 90deg	592.64	0.60
20	Alluvium	San Fernando 1971, 8244 Orion, 90deg	250.00	0.26
21	Rock	San Fernando 1971, Pacoima Dam, 196deg	1054.90	1.08
22	Rock	San Fernando 1971, Pacoima Dam, 286deg	1148.10	1.17
23	Rock	Loma Prieta 1989, Gilroy #1, Ch. 1	433.62	0.44
24	Rock	Loma Prieta 1989, Gilroy #1, Ch. 3	426.61	0.44
25	Rock	Kern 1952, Taft Lincoln Tunnel, 339deg	175.90	0.18
26	Rock	Northridge 1994, Castaic, Ch. 3	504.22	0.51
27	Rock	Northridge 1994, Pacoima Dam downstream, Ch. 1	425.55	0.43
28	Rock	Northridge 1994, Pacoima Dam downstream, Ch. 3	407.11	0.42
29	Rock	Northridge 1994, Pacoima Kagel Canyon, Ch. 1	295.17	0.30
30	Rock	Northridge 1994, Pacoima Kagel Canyon, Ch. 3	424.21	0.43

For each model in Table 1, one linear and five nonlinear runs were made for each earthquake and for each damping value. The linear runs were used to determine the elastic strength required to resist the given earthquake record for each damping value. Then, this elastic strength was reduced to 80%, 60%, 40%, 20%, and 10% in turn and supplied as the yield strength for the five subsequent nonlinear runs. The post-yield stiffness was taken as zero for all cases. In this way, 10 linear and 50 nonlinear runs were made for each earthquake record. For the 30 earthquake records together, a total of 300 linear and 1500 nonlinear runs were made for this study. The ductility demand was recorded for each of the 1500 nonlinear runs.

ANALYTICAL RESULTS

The results are presented graphically below in Figures 1 and 2. Results have been averaged for each soil type and then results for all soil types have been averaged. Figure 1 presents the averages for both 2% and 5% damping. We are unable to include all of the analytical data in the current paper, due to space limitations, but a statistical analysis of the data is presented in Table 3 (below). This table shows average ductility demands for each soil type as well as the standard deviation. A high standard deviation indicates that the model was highly sensitive to the ground motion characteristics. In other words, results for some models are difficult to predict and a designer may need to envelope results from a suite of records in order to be assured of meeting the target ductility demand. Figure 2 presents results for 5% damping for the average ductility demand plus two standard deviations (2*Sigma). Ductility capacities for normal well-designed buildings are on the order of 4 to 6 and the authors feel it is unrealistic to expect that we can achieve ductilities in excess of 4 to 6 with conventional construction. Table 3 has been shaded to indicate values the authors consider unacceptable for design—the table is shaded grey where the average ductility demand exceeds 6; the table is shaded blue where the sum of the average ductility demand plus two standard deviations exceeds 6. Table 4 summarizes the strength required to achieve a ductility capacity of 4 for 5% damping for the average and for the average plus two standard deviations.

Table 4 Percent of Elastic Strength Required to Achieve Ductility of 4 With 5% Damping

Period (sec)	Average				Average + 2*Sigma			
	Soft Soil	Alluvium	Rock	All	Soft Soil	Alluvium	Rock	All
0.2	79	42	50	69	89	57	58	80
0.5	59	35	27	44	75	39	38	78
1.0	46	34	30	35	64	42	37	56
2.0	19	28	32	29	34	37	46	39
3.0	27	27	27	27	33	39	36	38

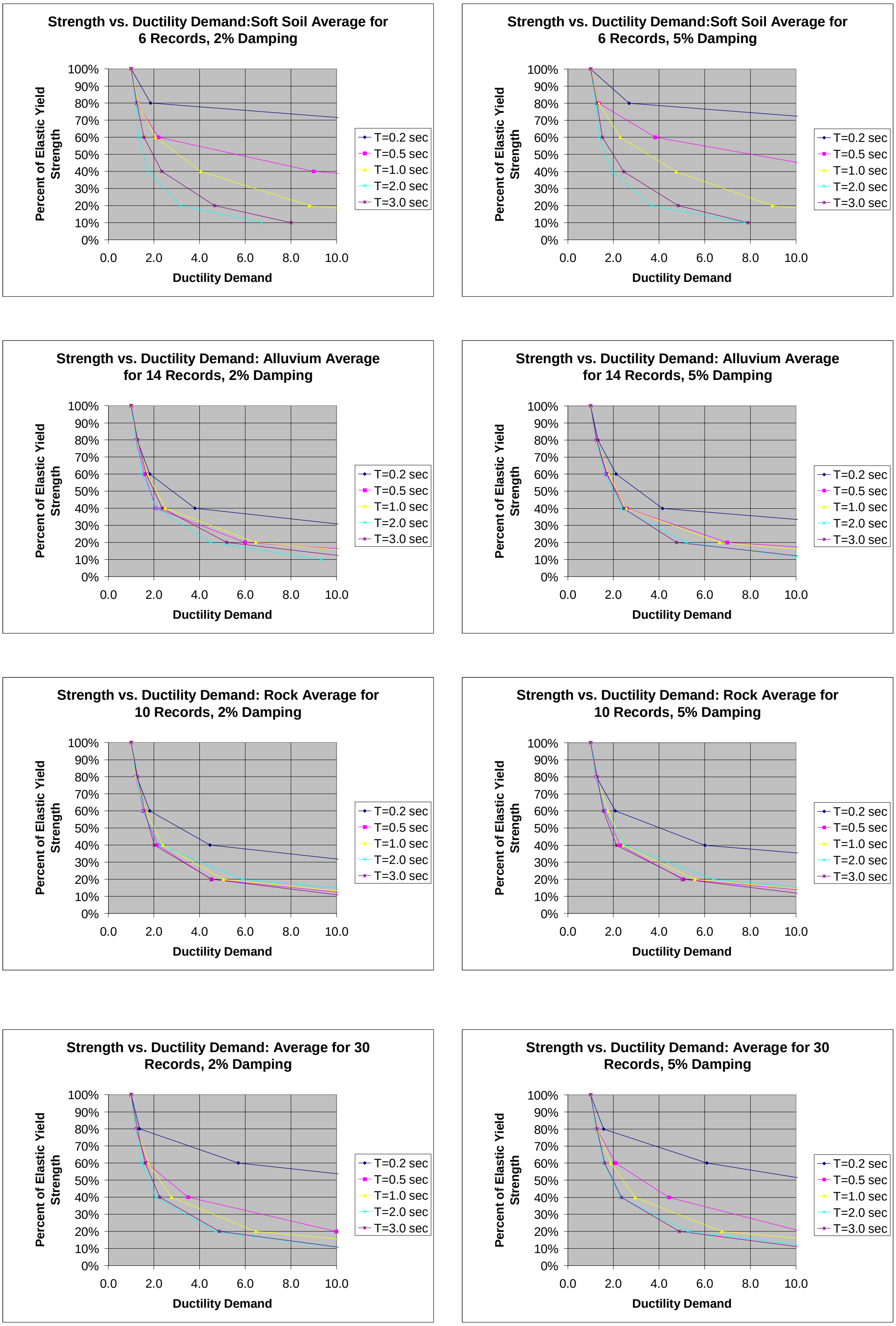

Figure 1- Strength vs. Ductility Demand, 2% and 5% Damping

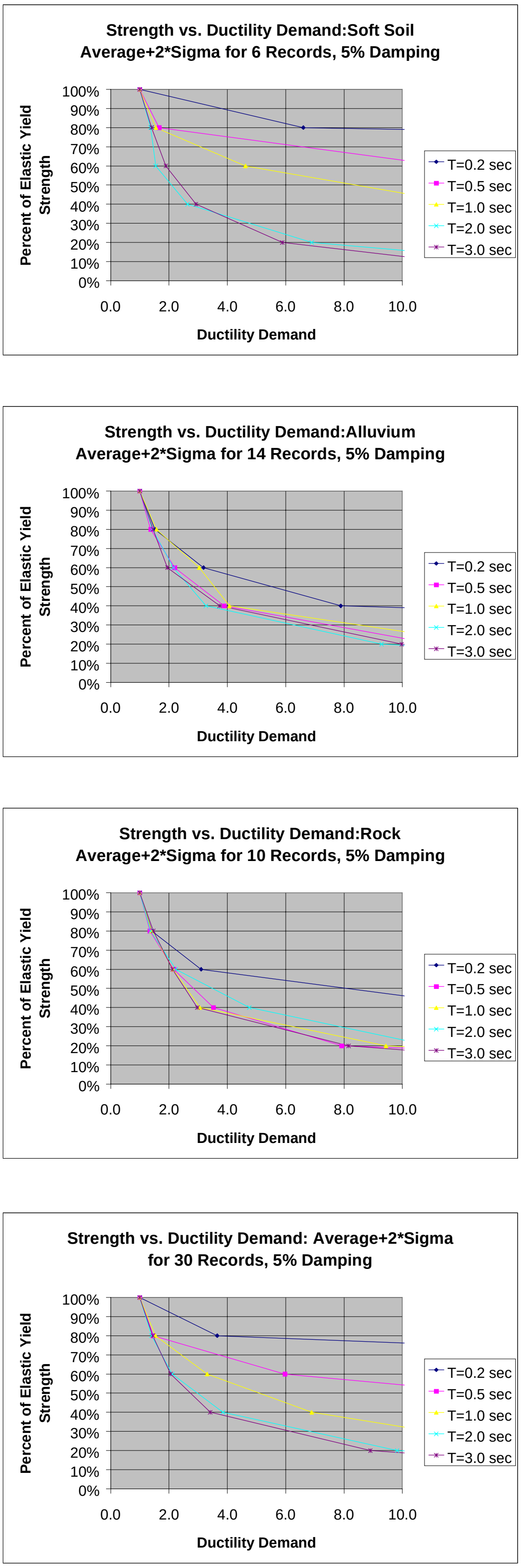

Figure 2- Strength vs. Ductility Demand, 5% Damping, Average + 2*Sigma

TABLE 3 AVERAGE DUCTILITY DEMAND AND STANDARD DEVIATION

Period sec	Strength Ratio	Soft Soil Records (6)				Alluvial Records (14)				Rock Records (10)				All Records (30)			
		Average		Std. Deviation		Average		Std. Deviation		Average		Std. Deviation		Average		Std. Deviation	
		2%	5%	2%	5%	2%	5%	2%	5%	2%	5%	2%	5%	2%	5%	2%	5%
0.2	1.0	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000
	0.8	1.848	2.682	0.994	1.959	1.261	1.320	0.075	0.096	1.240	1.264	0.090	0.074	1.372	1.574	0.510	1.040
	0.6	21.203	22.042	26.087	30.328	1.813	2.122	0.415	0.532	1.809	2.091	0.384	0.506	5.690	6.096	14.014	15.740
	0.4	81.039	57.503	102.372	69.372	3.795	4.150	1.946	1.868	4.459	6.009	2.879	3.541	19.465	15.440	55.213	37.567
	0.2	200.773	150.664	213.174	145.106	17.365	22.349	15.173	14.375	18.107	23.916	13.047	13.788	54.294	48.534	120.900	83.541
	0.1	410.245	318.320	395.683	273.809	63.434	65.497	40.874	30.255	59.258	61.426	42.176	38.319	131.404	114.704	228.313	162.108
0.5	1.0	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000
	0.8	1.242	1.371	0.069	0.145	1.214	1.251	0.055	0.062	1.203	1.226	0.063	0.061	1.216	1.267	0.062	0.100
	0.6	2.199	3.833	1.139	3.835	1.578	1.685	0.238	0.253	1.533	1.624	0.330	0.272	1.687	2.094	0.623	1.937
	0.4	8.997	12.319	13.110	15.222	2.095	2.581	0.409	0.652	2.163	2.304	0.698	0.611	3.498	4.436	6.494	7.887
	0.2	28.456	26.631	31.951	28.635	5.988	6.985	1.564	2.065	4.508	5.019	1.586	1.449	9.988	10.259	17.084	15.312
	0.1	49.097	54.960	52.803	52.944	16.957	18.585	3.336	4.689	11.762	13.268	6.092	6.196	21.653	24.087	27.726	28.766
1.0	1.0	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000
	0.8	1.294	1.355	0.100	0.098	1.237	1.265	0.076	0.154	1.203	1.250	0.068	0.074	1.237	1.278	0.085	0.128
	0.6	2.058	2.302	0.799	1.159	1.711	1.778	0.530	0.629	1.622	1.760	0.150	0.192	1.751	1.877	0.540	0.715
	0.4	4.053	4.744	2.958	3.722	2.504	2.561	0.748	0.756	2.380	2.440	0.383	0.310	2.772	2.957	1.572	1.967
	0.2	8.802	8.968	6.889	7.024	6.455	6.644	3.461	3.150	5.043	5.557	1.993	1.939	6.454	6.746	4.263	4.149
	0.1	17.208	16.771	16.619	14.356	14.916	15.151	8.375	6.634	12.353	13.549	7.380	5.948	14.520	14.941	10.450	8.654
2.0	1.0	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000
	0.8	1.206	1.231	0.090	0.069	1.198	1.262	0.110	0.083	1.223	1.233	0.071	0.069	1.208	1.246	0.096	0.077
	0.6	1.332	1.388	0.147	0.078	1.477	1.613	0.153	0.268	1.501	1.637	0.210	0.298	1.456	1.576	0.184	0.270
	0.4	1.747	1.945	0.389	0.344	2.096	2.353	0.398	0.456	2.250	2.487	1.080	1.133	2.077	2.316	0.725	0.766
	0.2	3.164	3.647	1.411	1.622	4.452	5.156	1.765	2.065	5.847	6.345	2.446	2.311	4.659	5.251	2.187	2.283
	0.1	6.744	7.754	3.637	3.357	9.351	10.871	5.724	5.467	14.010	14.217	7.074	6.854	10.382	11.363	6.492	6.107
3.0	1.0	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000
	0.8	1.249	1.276	0.029	0.065	1.275	1.268	0.084	0.091	1.278	1.287	0.064	0.087	1.271	1.276	0.070	0.085
	0.6	1.566	1.511	0.190	0.191	1.660	1.709	0.178	0.118	1.596	1.560	0.283	0.280	1.620	1.620	0.224	0.217
	0.4	2.342	2.449	0.429	0.239	2.370	2.457	0.571	0.638	2.020	2.132	0.516	0.419	2.248	2.347	0.551	0.532
	0.2	4.652	4.842	0.913	0.520	5.190	4.770	3.203	2.602	4.538	5.095	1.640	1.528	4.865	4.893	2.438	2.003
	0.1	8.005	7.902	2.443	1.815	11.564	11.523	5.265	4.332	10.570	11.180	3.313	2.803	10.521	10.684	4.423	3.741

OBSERVATIONS

Many observations can be made by reviewing the results of this study:

- Significant increases in design strength are required to limit ductility demands to 4 or less. Assuming 5% damping, Table 4 shows that the strength required to achieve an average ductility demand of 4 ranges from a low of 19% (2.0 seconds, soft soil) to a high of 79% (0.2 seconds, soft soil). Considering the average ductility demand plus two standard deviations, the required strength ranges from a low of 33% (3.0 seconds, soft soil) to a high of 89% (0.2 seconds, soft soil).
- Dispersion or scatter in the results is inversely related to strength, i.e. the standard deviation decreases with increasing strength. This is true for all periods and all soil types. It is difficult to achieve reliable results at low levels of strength since the results depend heavily on the ground motion characteristics.
- In accordance with the 1997 UBC (ICBO 1997), current practice is to design for values ranging from 12% (R-value of 8.5) to 36% (R-value of 2.8). It appears that such designs may result in not only unacceptable behavior but also unreliable results. Except for long period structures on soft soil, design strengths of 20% or less resulted in ductility demands in excess of 4 and relatively high standard deviations.
- Short period structures exhibit very erratic behavior, i.e. high ductility demands and high standard deviations, unless they are designed for high strength levels. As an example, the 0.2 second period building would need to be designed for 79% of the elastic strength on soft soils, 42% on alluvium, and 50% on rock in order to obtain acceptable behavior with ductility demands of 4 or less. These values increase to 89%, 57%, and 58%, respectively, when the average plus two standard deviations is considered.
- It is clearly disadvantageous to have an initial building period shorter than the predominant site period, since any softening results in progressively higher response until the building period exceeds the site period. Short period structures are thus more sensitive to ground motion characteristics than long period structures. It is hard to provide a reliable design for short period structures unless they are designed for more than approximately 60%of the elastic strength required from a suite of appropriate records.
- Long period structures exhibit more predictable behavior for all soil types and both damping values. These structures are less sensitive to ground motion characteristics than short period structures.
- The reduction factor, R, in the 1997 UBC (ICBO 1997) is currently assigned on the basis of structure type (concrete shear wall, steel moment frame, etc.) independent of other factors. This approach is intended to recognize inherent ductility capacities for different structural systems. This study shows that the acceptable reduction also depends on the initial period, the soil type, and the ground motion characteristics, suggesting that the current code approach is oversimplified. It appears a matrix of R values would be required to account for the combination of these effects.

CONCLUSIONS

While many elements needed to successfully implement performance-based design have yet to be developed, the authors feel that the results of the present study make an important contribution to that end. A designer needs to understand what strength levels are required when offering to design a building that will be repairable or remain operational following an earthquake. Compared with current practice, significant increases in design strength may be required to limit damage and achieve target ductility demands of 4 or less. The strength required to achieve a target ductility demand depends upon the initial period, the soil type, and the ground motion characteristics—not only on the type of structural system.

REFERENCES

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