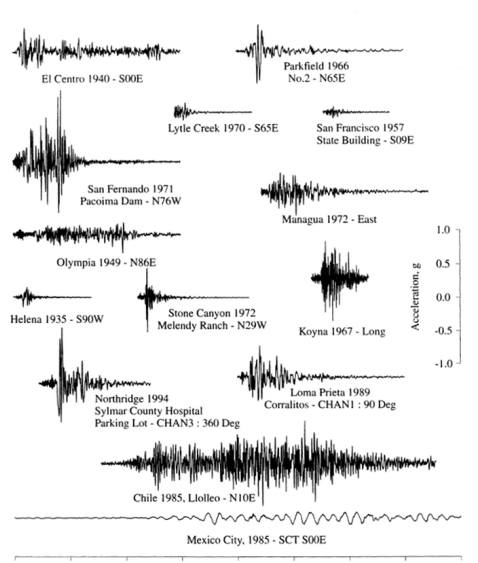


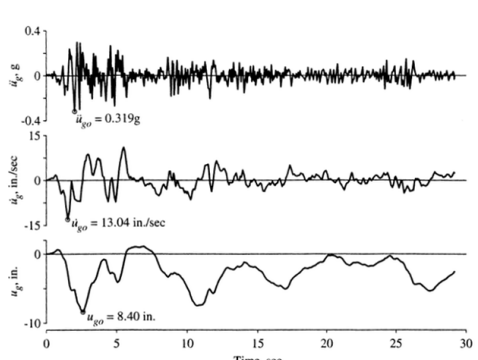
<div data-bbox="292 197 1147 275" data-label="Section-Header"> <h1>Earthquake excitation</h1> </div> <div data-bbox="624 322 809 356" data-label="Text"> <p>Giacomo Boffi</p> </div> <div data-bbox="462 392 968 423" data-label="Text"> <p>http://intranet.dica.polimi.it/people/boffi-giacomo</p> </div> <div data-bbox="427 448 1005 506" data-label="Text"> <p>Dipartimento di Ingegneria Civile Ambientale e Territoriale Politecnico di Milano</p> </div> <div data-bbox="622 535 810 575" data-label="Text"> <p>April 17, 2018</p> </div>	<div data-bbox="1203 76 1310 120" data-label="Text"> <p>Earthquake excitation</p> </div> <div data-bbox="1192 132 1324 156" data-label="Text"> <p>Giacomo Boffi</p> </div> <div data-bbox="1177 181 1331 244" data-label="Text"> <p>Earthquakes and Earthquake Response</p> </div> <div data-bbox="1177 253 1275 297" data-label="Text"> <p>Response Spectrum</p> </div> <div data-bbox="1177 306 1313 369" data-label="Text"> <p>Response Spectrum Characteristics</p> </div>
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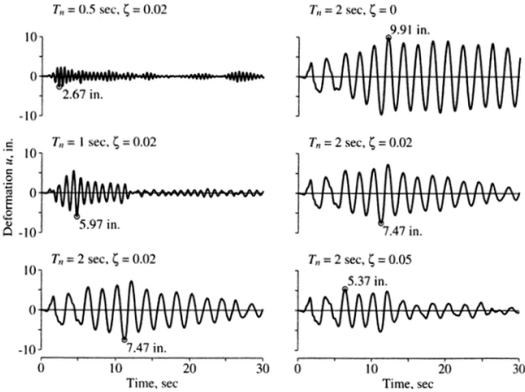
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<div data-bbox="268 1507 563 1550" data-label="Section-Header"> <h2>Seismic Excitation</h2> </div> <div data-bbox="284 1718 1134 1957" data-label="Text"> <p>The most important quantity related to earthquake excitation is the ground acceleration. Ground acceleration can be recorded with an accelerometer, basically a SDOF oscillator, with a damping ratio $\zeta \approx 70\%$, whose displacements are proportional to ground accelerations up to a given frequency. Instrument records of <i>strong ground motion</i> first became available in the '30s, the first record of a destructive ground motion being the 1940 records of El Centro earthquake.</p> </div>	<div data-bbox="1203 1509 1310 1554" data-label="Text"> <p>Earthquake excitation</p> </div> <div data-bbox="1192 1565 1324 1590" data-label="Text"> <p>Giacomo Boffi</p> </div> <div data-bbox="1177 1615 1331 1677" data-label="Text"> <p>Earthquakes and Earthquake Response</p> </div> <div data-bbox="1177 1686 1275 1731" data-label="Text"> <p>Response Spectrum</p> </div> <div data-bbox="1177 1740 1313 1803" data-label="Text"> <p>Response Spectrum Characteristics</p> </div>
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Seismic Excitation	<p>Earthquake excitation</p> <p>Giacomo Boffi</p> <p>Earthquakes and Earthquake Response</p> <p>Response Spectrum</p> <p>Response Spectrum Characteristics</p>
<p>Historically, most of the strong motion records were recorded for a few earthquakes, in California and Japan, in different places and different locations (in the free field, on building foundations, on different building storeys etc), while a lesser number of records were available for different areas.</p> <p>In more recent years, many national research agencies installed and operated networks of strong motion accelerometers, so that the availability of strong motion records, recorded in different geographic areas and under different local conditions is constantly improving.</p> <p>Moreover, in many countries the building codes require that important constructions must be equipped with accelerometers, further increasing the number of available records.</p> <p>http://ngawest2.berkeley.edu/site, http://itaca.mi.ingv.it/ItacaNet/.</p>	

Seismic Excitation Samples	<p>Earthquake excitation</p> <p>Giacomo Boffi</p> <p>Earthquakes and Earthquake Response</p> <p>Response Spectrum</p> <p>Response Spectrum Characteristics</p>
 <p>A number of different strong motion records, recorded at different sites and due to different earthquakes, are plotted with the same scale, both in time and in acceleration. Appreciate the large variability in terms of amplitudes, duration and frequency content of the different records. We need a method to categorize this variability.</p>	

Detailed Sample	<p>Earthquake excitation</p> <p>Giacomo Boffi</p> <p>Earthquakes and Earthquake Response</p> <p>Response Spectrum</p> <p>Response Spectrum Characteristics</p>
 <p>Above, the acceleration recorded at El Centro during the Imperial Valley 1940 e.q., along with the velocity and displacements obtained by numerical integration. For meaningful results, the initial conditions of integration and the removal of linear trends from the acceleration record are of capital importance (read: don't try this at home).</p>	

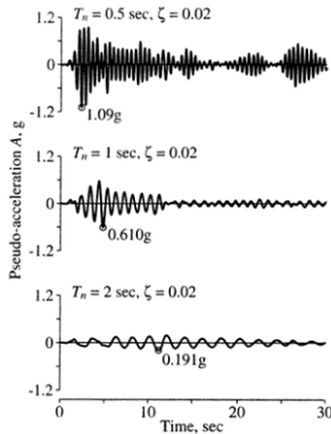
<h2>Detailed Sample</h2> <p>Strong motion being a very irregular motion, a high sampling frequency is required to accurately describe it.</p> <p>Modern digital instruments record the acceleration at a rate of 200 and more samples per second and minimize the need for sophisticated correction of the accelerations before the time integration.</p>	<div>Earthquake excitation</div> <div>Giacomo Boffi</div> <div>Earthquakes and Earthquake Response</div> <div>Response Spectrum</div> <div>Response Spectrum Characteristics</div>
<h2>About Ground Motion</h2> <p>In the following, we consider the so called <i>free-field</i> records. A free-field record is recorded on ground free surface in a position that is deemed free from effects induced by building response.</p> <p>Tough accelerations vary with time in a very irregular manner, the variation is fully known, and for an individual record we can write the equation of motion in terms of the displacement response function $D(t)$,</p> $\ddot{D} + 2\zeta\omega\dot{D} + \omega^2 D = -\ddot{u}_g(t).$ <p>Clearly, the displacement response function, for assigned \ddot{u}_g, depends on ζ and ω only.</p> <p>Of course, due to the irregular nature of ground excitation the response must be evaluated numerically.</p> <p>Our first step will be to explore the dependency of D on ω (or rather T_n as it is usual in earthquake engineering) and ζ.</p>	<div>Earthquake excitation</div> <div>Giacomo Boffi</div> <div>Earthquakes and Earthquake Response</div> <div>Response Spectrum</div> <div>Response Spectrum Characteristics</div>
<h2>T_n and ζ dependency</h2> <p>Leftmost column, fixed $\zeta = 0.02$ and $T_N = 0.5, 1.0, 2.0$ s. Although the ground motion is irregular, the responses have a similarity, each one having a period close to T_n.</p>  <p>Centre column, fixed $T_n = 2.0$ s and $\zeta = 0, 0.02, 0.05$. For a fixed period the shapes are similar while the maximum response values depends on ζ.</p> <p>Displacement response functions for the El Centro 1940 NS acceleration record.</p>	<div>Earthquake excitation</div> <div>Giacomo Boffi</div> <div>Earthquakes and Earthquake Response</div> <div>Response Spectrum</div> <div>Response Spectrum Characteristics</div>

Pseudo Acceleration

From deformation response, we can compute the equivalent static force

$$f_s(t) = m\omega^2 D(t) = mA(t)$$

where $A(t)$ is the pseudo acceleration, $A(t) = \omega^2 D(t) = (2\pi)^2 D(t)/T_n^2$. Again, note that f_s is proportional to $A(t)$ and not to the acceleration $\ddot{D}(t)$.



Left, pseudo accelerations computed for varying T_n . Compare with previous page's figure. The relative magnitudes are reverted: for $T_n = 0.5$ s we have a maximum force and a minimum displacement, while for $T_n = 2.0$ s the force is minimum and the displacement maximum.

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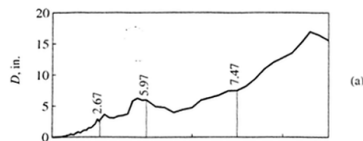
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Response Spectrum

Introduced by M.A. Biot in 1932, popularized by G.W. Housner, the concept of response spectrum is fundamental to characterize e.q. response.



The response spectrum is a plot of the peak values of a response quantity, say the displacement response function, computed for different values of T_n and the same ζ , versus natural period T_N .

A graph where several such plots, obtained for different values of ζ , representative of different damping ratios that characterize different structures, are plotted close to each other represents the e.q. characteristics from the point of view of peak structural response (wait later slides for examples).

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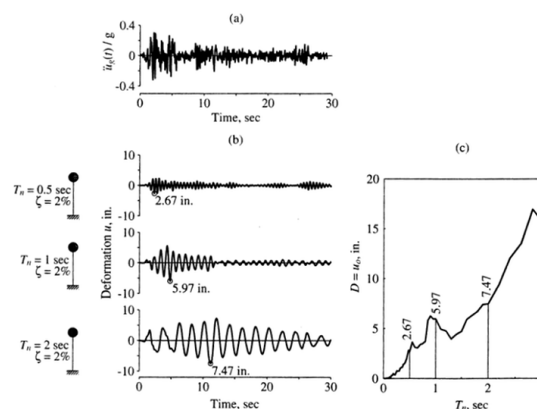
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Computing the DRS



For a fixed values of ζ (usually one of 0% 0.5% 1% 2% 3% 5% 7% 10% 15% and 20%) and for variable values of T_n (usually ranging from 0.01 s to 20 s)

1. the displacement response function is numerically integrated,
2. the peak value is individuated,
3. the peak value is plotted.

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Only the Deformation Response Spectrum (DRS) is required to fully characterize the peaks of deformations and equivalent static forces.

It is however useful to study also the pseudo acceleration (PARS) and pseudo velocity (PVRs) spectra, as they are useful in understanding excitation intrinsic characteristics, in constructing *design spectra* and to connect dynamics and building codes.

We have already introduced $A(t)$, consider now the quantity

$$V(t) = \omega_n D(t) = \frac{2\pi}{T_n} D(t)$$

that is, the pseudo velocity.

The peak value of V is connected with the maximum strain energy,

$$E_{s,0} = \frac{1}{2} m V_0^2$$

being $E_{s,0} = \frac{1}{2} D_0 m \omega^2 D_0$. Once again, $V \neq \dot{x}$, the relative velocity.

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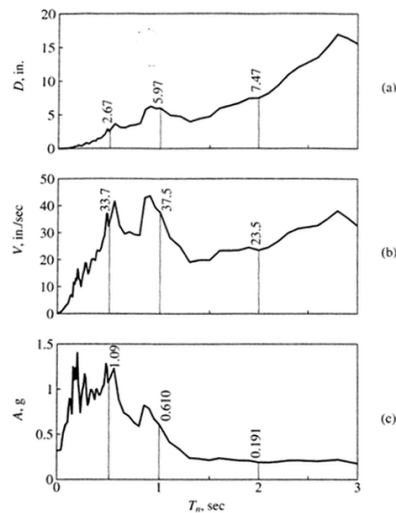
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Deformation spectrum, pseudo velocity and pseudo acceleration spectra for El Centro 1940 NS, $\zeta = 2\%$.

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Combined $D - V - A$ spectrum

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In the following, we will use the symbols D , V and A to represent the values of the DRS, PVRs and PARS spectra, respectively, with

$$V = \omega_n D, \quad A = \omega_n^2 D$$

While D , V and A represent the same information, nonetheless it is useful to maintain a distinction as they are connected to different response quantities, the maximum deformation, the maximum strain energy and the maximum equivalent static force.

Moreover, it is possible to plot all three spectra on the same logarithmic plot, giving what is regarded as a fundamental insight into the ground motion characteristics.

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Constant A

Consider a plane with axes $\log T_n$ and $\log V$, and the locus of this plane where A is constant, $A = \hat{A}$:

it is

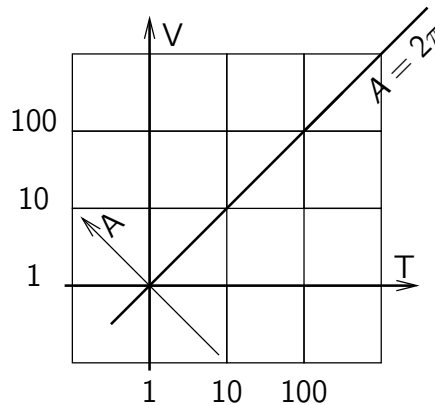
$$A = 2\pi V / T_n = \hat{A}$$

taking the logarithm

$$\log \frac{\hat{A}}{2\pi} = \log V - \log T_n$$

or

$$\log V = \log T_n + \log \frac{\hat{A}}{2\pi}.$$



In the log-log plane straight lines at 45° are characterized by a constant value of A .

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Constant D

In the same plane with axes $\log T_n$ and $\log V$ we seek the locus where D is constant, $D = \hat{D}$:

it is

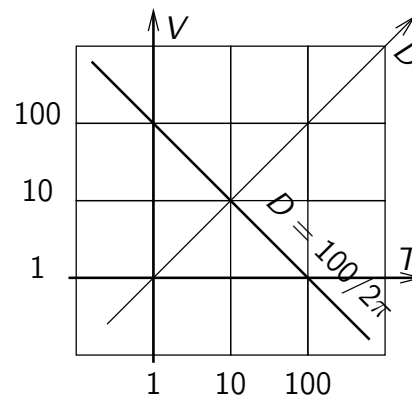
$$D = T_n V / 2\pi = \hat{D}$$

taking the logarithm

$$\log 2\pi \hat{D} = \log V + \log T_n$$

or

$$\log V = \log 2\pi \hat{D} - \log T_n.$$



In the log-log plane straight lines at -45° are characterized by a constant value of D .

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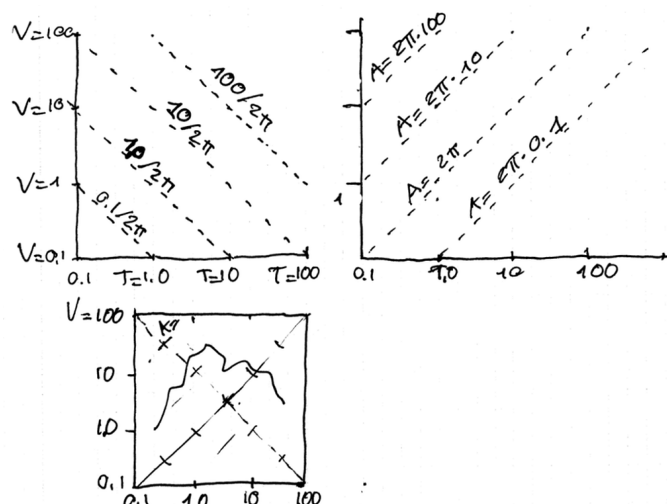
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Example of Construction, 1



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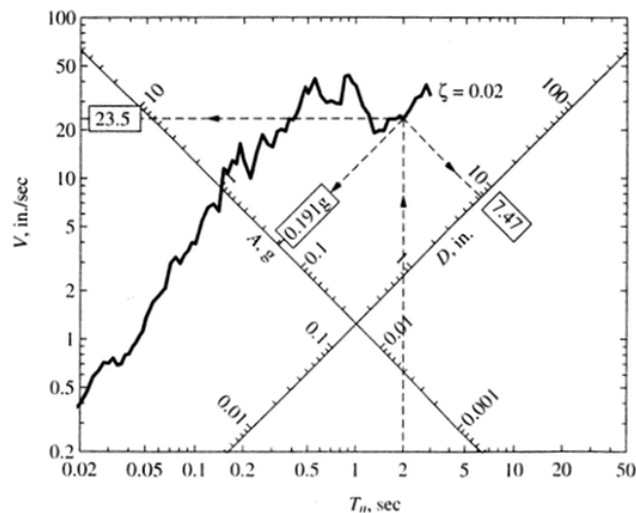
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Example of Construction, 2



Combined $D - V - A$ response spectrum, El Centro 1940 NS record, $\zeta = 0.02$.

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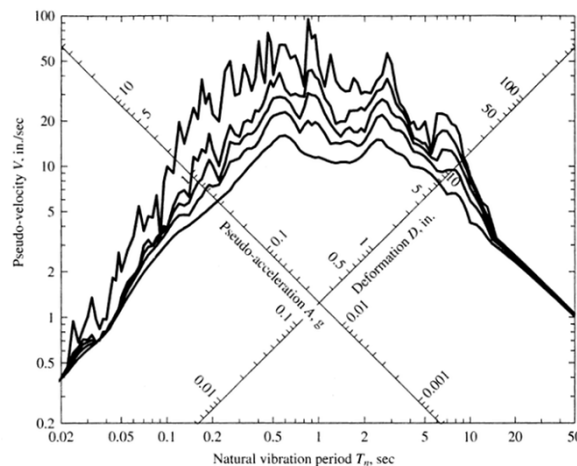
Combined $D - V - A$
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Example of $D - V - A$ spectrum



Combined $D - V - A$ response spectrum, El Centro 1940 NS record,
for $0 \leq \zeta \leq 20\%$ and full range of periods.

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Peak Structural Response

The peak deformation u_0 is given by

$$u_0 = D$$

and the peak of the equivalent static force $f_{S,0}$ is given by

$$f_{S,0} = ku_0 = m\omega^2 u_0 = kD = mA$$

It is required to know the peak of the base bending moment for the structure on the right, when subjected to the NS component of the El Centro 1940 record.

The mass is $m = 2360 \text{ kg}$, the stiffness is $k = 36.84 \text{ kN m}^{-1}$, the natural period of vibration is computed as $T_n = 1.59 \text{ s}$.

The damping ratio is assumed to be $\zeta = 5\%$.

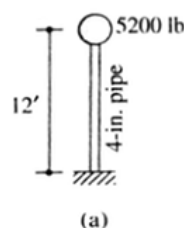
On the graph of the relevant $D - V - A$ spectrum, for $T_n = 1.59$, we find the value $A = 0.20 \text{ g}$.

The equivalent static force is

$f_{S,0} = 2360 \text{ kg} \cdot 0.20 \cdot 9.81 \text{ m s}^{-2} = 4.63 \text{ kN}$ and the peak

base bending moment is

$M_{b,0} = 4.63 \text{ kN} \cdot 12 \cdot 0.305 \text{ m} = 16.93 \text{ kN m}$



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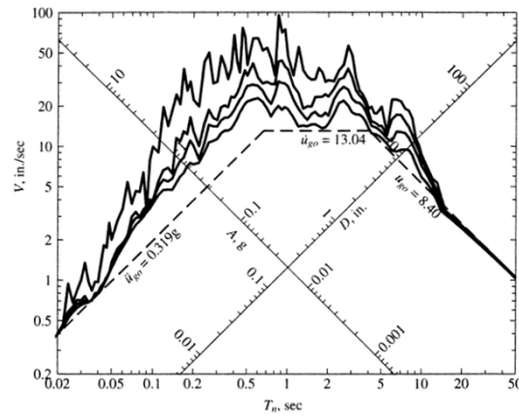
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The El Centro 1940 NS $D - V - A$ spectrum, *plus* three lines corresponding to the peak values of the ground acceleration, ground velocity and ground displacement.

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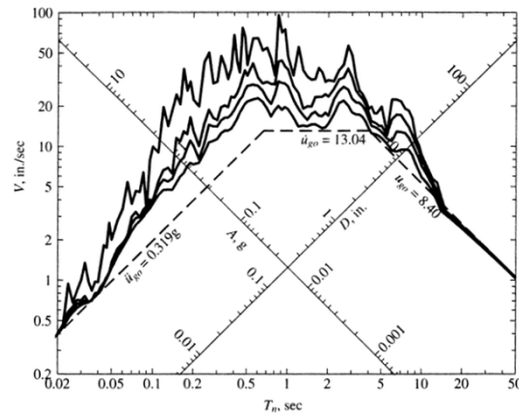
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For each value of the damping ratio, from theoretical considerations

$$\lim_{T_n \rightarrow 0} A = \ddot{u}_{g,0}, \quad \lim_{T_n \rightarrow 0} D = u_{g,0}.$$

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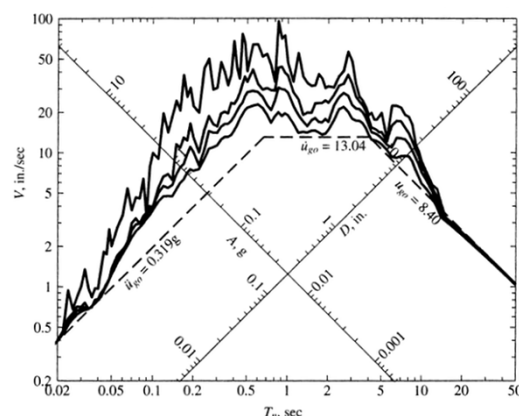
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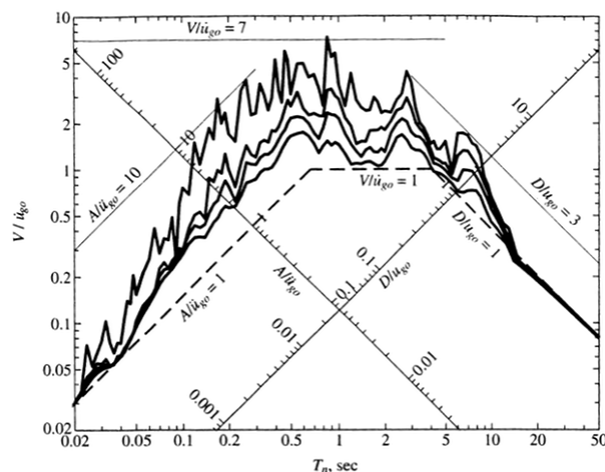
Elastic Design Spectra
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For intermediate values of T_n it is apparent that

- ▶ $A > \ddot{u}_{g,0}$, $V > \dot{u}_{g,0}$ and $D > u_{g,0}$;
- ▶ $V_{\max} \approx \text{constant}$ for each value of ζ ,
- ▶ there is a clear dependency on ζ .

Idealized Response Spectrum, 1



First step in the construction of an idealized $D - V - A$ response spectrum is to make a tripartite plot with all three ordinate axes normalized with respect to $u_{g,0}$, $\dot{u}_{g,0}$ and $\ddot{u}_{g,0}$.

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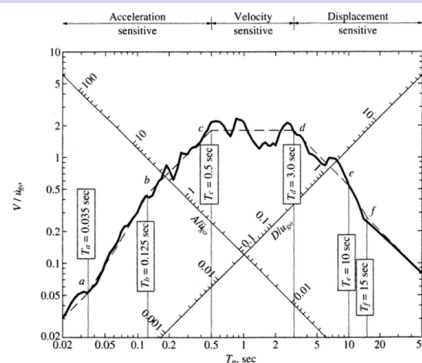
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Idealized Response Spectrum, 1



Next,

- ▶ draw the $\zeta = 5\%$ spectrum,
- ▶ individuate the intervals where a) $A \approx \ddot{u}_{g,0}$, b) $A \approx a_A \ddot{u}_{g,0}$, c) $V \approx a_V \dot{u}_{g,0}$, d) $D \approx a_D u_{g,0}$, e) $D \approx u_{g,0}$ and
- ▶ individuate approximate amplifications factors, a_A , a_V and a_D ,
- ▶ connect the constant value intervals with straight lines.

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Idealized Response Spectrum

Our procedure results look good in the log-log graph, but should we represent the same piece-wise linearization in a lin-lin graph it will be apparent that's a rather crude approximation.

This consideration is however not particularly important, because we are not going to use the idealized spectrum in itself, but as a guide to help developing design spectra.

Finally, consider that the positions of the points T_a, \dots, T_f and the amplifications factors a_A , a_V and a_D are not equal for spectra of different earthquakes recorded at different sites, they depend in complex and not fully determined ways on different parameters, for example the focal distance and the focal mechanism and, very important, the local soil characteristics, showing in the whole a large variability.

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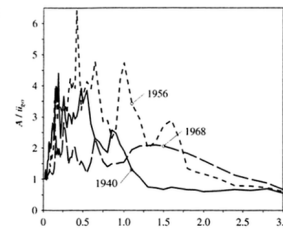
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On the right, the $\ddot{u}_{g,0}$ normalized A response spectra for 3 different earthquakes NS records, recorded at the same El Centro site. Clearly, it is not possible to infer the jagged appearance of the 1968 spectra from the 1940's and 1956's ones.



For design purposes, however, it is not necessary to know in advance and in detail the next quake's response spectra as it suffices to know some sort of an upper bound on spectral ordinates, that is a *Design Spectrum*.

Elastic Design Spectra

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A design spectrum is usually specified as an idealized response spectrum, as a set of connected straight lines on the log-log $D - V - A$ plot, and has not, in contrast with a response spectrum, a jagged appearance.

Note that straight lines on a log-log graph map on straight or curved lines on conventional $T - n - A$ plots.

The requirements of a design spectrum are manifold, but mostly important a design spectrum must be an envelope of possible peak values.

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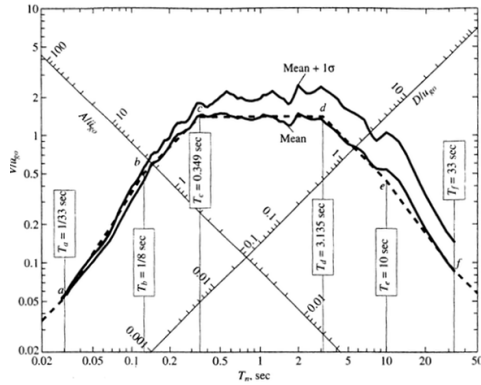
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The procedure used for computing an elastic design spectrum could be sketched as follows,

- ▶ collect earthquake records from the site under study or from similar sites (similar in local geology, in epicentral distances, duration of strong motion etc) and compute normalized response spectra,
- ▶ statistically characterize, in terms of mean values and standard deviations, the set of normalized spectral ordinates at hand,
- ▶ derive idealized spectra.

Derivation of an Elastic Design Spectra

Riddel and Newmark (1979)



In the graph, the summary of their research: the mean and mean+1σ spectra for 5% damping ratio.

In the same graph, you can see also (dashed) an idealized spectrum representation of the mean spectrum.

Riddel and Newmark

- collected a large set of records for similar sites in Southern California,
- computed the normalized response spectra for $\zeta = 5\%$ and, finally
- computed the mean value and the standard deviation of the peak response distribution.

Earthquake excitation

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Earthquakes and Earthquake Response

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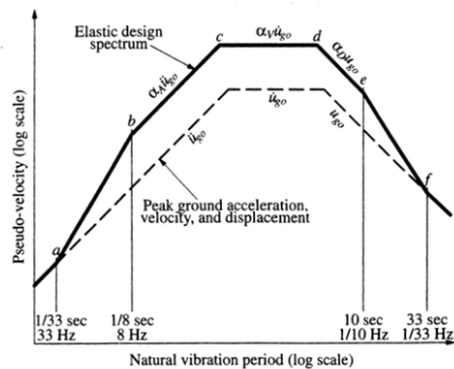
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Idealized Response Spectra

Elastic Design Spectra Example and Summary

Idealized Elastic Design Spectra

It is common practice to subdivide the design $D - V - A$ elastic spectrum in 7 segments and use 4 key vibration periods, together with given amplification factors, to draw the required idealized design spectrum.



The key periods $T_a = 0.03 \text{ s}$ and $T_b = 0.125 \text{ s}$ define the segment where A rises from 1 to α_A .
The key periods $T_e = 10 \text{ s}$ and $T_f = 33 \text{ s}$ define the segment where D decreases from α_D to 1.
The key periods T_c and T_d , instead, follows from applying the given amplification factors to pseudo accelerations, pseudo velocities and deformation.

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Response Spectrum

Response Spectrum Characteristics

Idealized Response Spectra

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Example Data

ζ (%)	Median (50 th percentile)			Median+1σ (84 th percentile)		
	α_A	α_V	α_D	α_A	α_V	α_D
1	3.21	2.31	1.82	4.38	3.38	2.73
2	2.74	2.03	1.63	3.66	2.92	2.42
5	2.12	1.65	1.39	2.71	2.30	2.01
10	1.64	1.37	1.20	1.99	1.84	1.69
20	1.17	1.08	1.01	1.26	1.37	1.38

	Median	Median+1σ
α_A	$3.21 - 0.68 \log \zeta$	$4.38 - 1.04 \log \zeta$
α_V	$2.31 - 0.41 \log \zeta$	$3.38 - 0.67 \log \zeta$
α_D	$1.82 - 0.27 \log \zeta$	$2.73 - 0.45 \log \zeta$

Source: N.M. Newmark and W.J. Hall, *Earthquake Spectra and Design*, EERC Report 1982.

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Response Spectrum

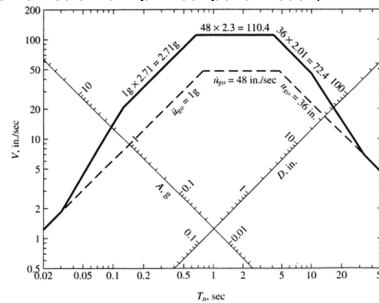
Response Spectrum Characteristics

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Procedure Summary

1. For the site in case, get an estimate of $\ddot{u}_{g,0}$, $\dot{u}_{g,0}$ and $u_{g,0}$, from an analysis of relevant data or deriving it from literature,
2. in the tripartite graph, draw a line for each of the shaking parameters,
3. for a selected value of ζ amplify the shaking parameters by appropriate amplification factor and draw a line for each amplified parameter.
4. draw vertical lines from the key periods to individuate the connection ramps,
5. draw the idealized design spectrum.



A common assumption, used when only the $\ddot{u}_{g,0}$ estimate is available, is

$$\dot{u}_{g,0} = \ddot{u}_{g,0} \frac{120 \text{ cm s}^{-1}}{g} \text{ and } u_{g,0} = \ddot{u}_{g,0} \frac{90 \text{ cm}}{g}.$$

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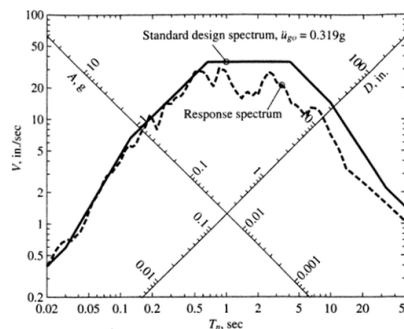
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Comparison of Design and Response Spectra, 1

In the figure, the response spectrum for the 1940 El Centro NS acceleration record, computed for $\zeta = 5\%$, and the corresponding design spectrum, with amplifications corresponding to median values of the ordinates.



The spectrum was constructed from the real value of $\ddot{u}_{g,0} = 0.319g$ and estimated values of $\dot{u}_{g,0} = \ddot{u}_{g,0} \frac{48 \text{ inch/s}}{g} = 15.3 \text{ inch/s}$ and $u_{g,0} = \ddot{u}_{g,0} \frac{90 \text{ cm}}{g} = 11.5 \text{ inch}$, estimated values that are significantly higher than the effective values.

There is a good concordance in the acceleration controlled part of the design spectrum, but spectral velocities and deformations are not very good, due to rather poor estimates of the relevant ground motion peak quantities.

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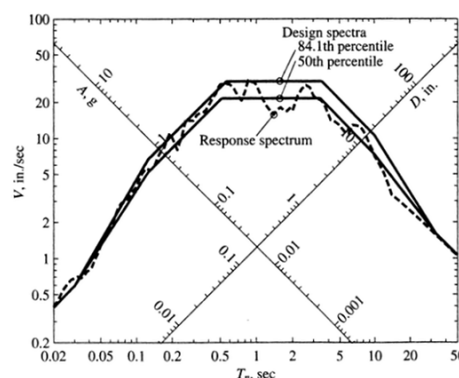
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Comparison of Design and Response Spectra, 2

In this second slide the design spectra are two, the median and the median + 1σ versions, both based on exact peak values of the ground motion. While the median spectrum is, OK, in a median position with respect to the ordinates of the elastic response spectrum, the presumed envelope spectrum does effectively a good job, maxing out most of the spikes present in the elastic response spectrum.



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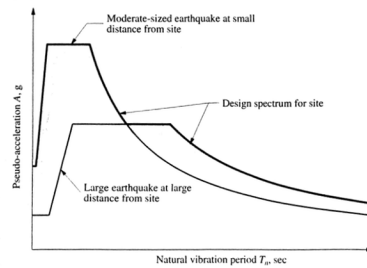
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Differences between Response and Design Spectra

The response spectrum is a description, in terms of its peak effects, of a particular ground motion.

The design spectrum is a specification, valid for a site or a class of sites, of design seismic forces.

If a site falls in two different classifications, e.g., the site is near to a seismic fault associated with low magnitude earthquakes and it is distant from a fault associated with high magnitude earthquakes, with the understanding that the frequency contents of the two classes of events are quite dissimilar the design spectrum should be derived from the superposition of the two design spectra.



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