SEISMIC RESPONSE SPECTRA

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Introduction

Strong motion accelerometers are used to measure the acceleration time history from an earthquake or other seismic event. The time history may be reduced to a Peak Ground Acceleration (PGA) level, which is the peak amplitude of the time history.

The damage potential of an earthquake, however, also depends on the frequency content of the signal. Spectral data is needed to design buildings that can withstand the maximum expected earthquake. This data may also be required for the testing of equipment mounted inside the building.

The shock response spectrum is a function that is used to determine the damage potential of the acceleration measured at the building foundation. This function is also referred to as the spectral acceleration. It is also called the design spectrum when used for design purposes.

Shock Response Spectrum Model

The shock response spectrum is a calculated function based on the acceleration time history. It applies an acceleration time history as a base excitation to an array of single-degree-of-freedom (SDOF) systems, as shown in Figure 1. Note that each system is assumed to have no mass-loading effect on the base input.

The damping of each system is typically assumed as 5%, which is equivalent to Q = 10. The natural frequency is an independent variable. Thus, the calculation is performed for a number of independent SDOF systems, each with a unique natural frequency.

Any arbitrary set of unique natural frequencies can be used for the shock response spectrum calculation. A typical scheme, however, is based on a proportional bandwidth, such as 1/6 octave. This means that each successive natural frequency is $2^{1/6}$ times the previous natural frequency.

As an alternative, the shock response spectrum may be plotted as a function of period.

The calculation algorithm is given in Reference 1.

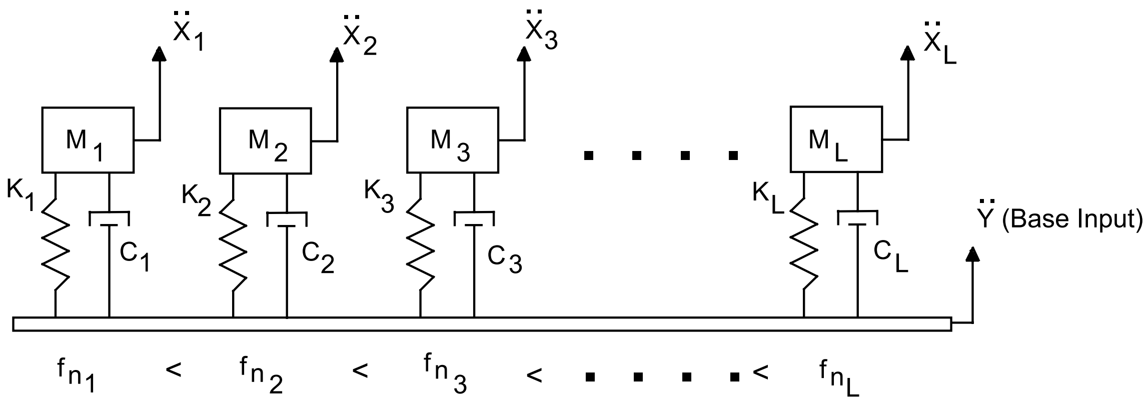

Figure 1. Shock Response Spectrum Model

M_i is the mass
C_i is the damping coefficient
K_i is the stiffness for each system
f_{n_i} is the natural frequency for each system

$\ddot{Y}$ is the common base input for each system
$\ddot{X}_i$ is the absolute response of each system to the input

The double-dot denotes acceleration.

Pseudo Velocity

Response spectra are sometimes given in terms of pseudo velocity rather than peak response of the absolute acceleration.

The pseudo velocity is calculated from the relative displacement between the mass and the moving base. Note that the relative displacement is also the spring strain displacement.

Pseudo-velocity is the maximum relative displacement multiplied by the natural frequency ω, which has units of (radians/sec).

The pseudo velocity is nearly equal to the maximum relative velocity for systems with moderate or high frequencies (short periods) but may differ considerably from the maximum relative velocity for very low frequency systems (long periods).

The pseudo velocity function is mentioned only for reference. The remainder of this report will focus on the absolute acceleration response spectra.

Seismic Loads During Pre-Launch at Vandenberg AFB

An important facility for the launch of space vehicles in the United States is located at Vandenberg Air Force Base (VAFB) in California. Delta, Titan, Taurus, and other rocket vehicles are launched from this base.

There were plans to launch the Space Shuttle from VAFB, in the early days of the Space Shuttle program. This plan was ultimately abandoned. Nevertheless, careful consideration was given to the possibility that a Space Shuttle would be exposed to earthquake while mounted at the launch pad. Note that VAFB is close to several faults, including the San Andreas.

Admittedly, the probability is very low that a significant earthquake would actually occur during the brief time window in which the Space Shuttle is at the launch pad. Nevertheless, caution is taken.

A particular concern was the lateral loads that would be applied to the base of the Space Shuttle by seismic induced horizontal motions of the launch pad. Another concern was the seismic loads applied to a variety of ground support equipment (GSE) and solid rocket motors in nearby storage.

A study was thus undertaken to determine an appropriate shock response spectrum for design and testing purposes. The resulting level is shown in Figure 2, as taken from Reference 2.

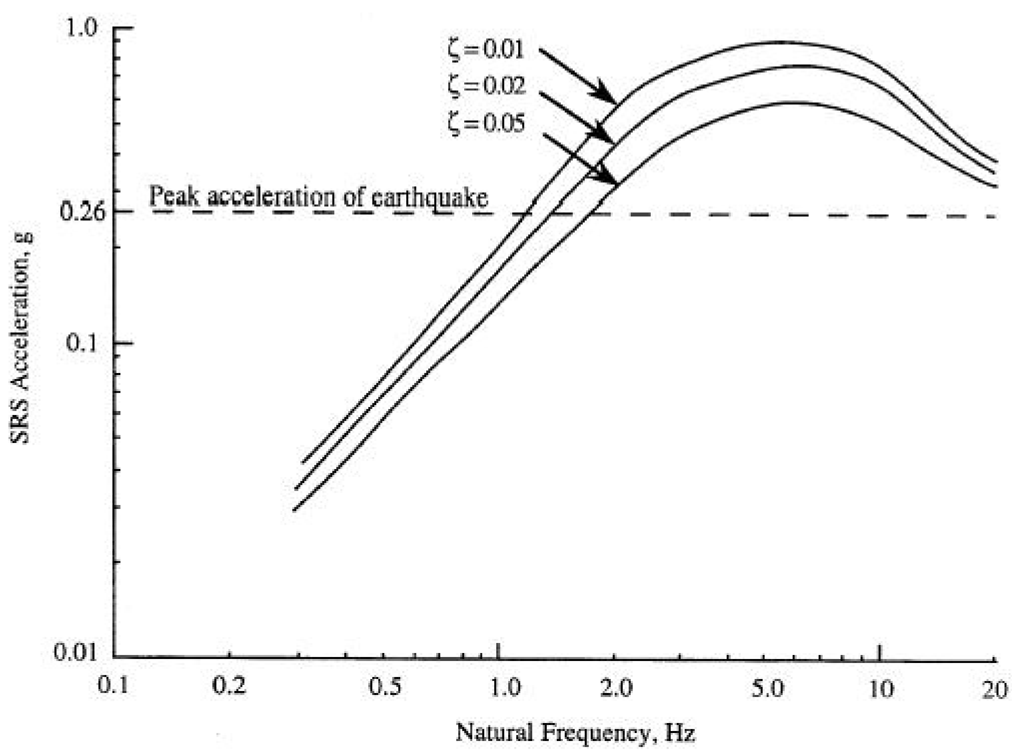

Figure 2. VAFB Seismic Shock Response Spectra

Curves are given in Figure 2 for each of three damping values.

Note that earthquakes in the region near Vandenberg AFB in central California typically have durations of less than 30 seconds, although longer durations are possible. These events produce ground accelerations concentrated in the frequency range below 20 Hz

Furthermore, the levels in Figure 2 are also appropriate for unmanned vehicles launched from VAFB.

Launch Site Soil Conditions

Reference 2 also gives some guidelines for seismic analysis at generic launch sites, depending on whether the ground is hard or soft.

Consider a launch pad supported by a hard rock site. A conventional dynamic analysis of the vehicle on its pad may be performed to determine vehicle loads and deflections during an earthquake.

On the other hand, the pad might be built on soft ground. In this case, the soft soil supporting the pad may permit an excess of translational and especially rotational motion at the pad/vehicle interface. This motion may cause a reduction of the system natural frequencies, leading to an increase in the relative displacements between vehicle and GSE elements. The motion may also and also increase the vehicle loads. As a trade-off, system damping is greatly increased due to the response-induced generation of seismic waves back into the soil.

El Centro Earthquake Data

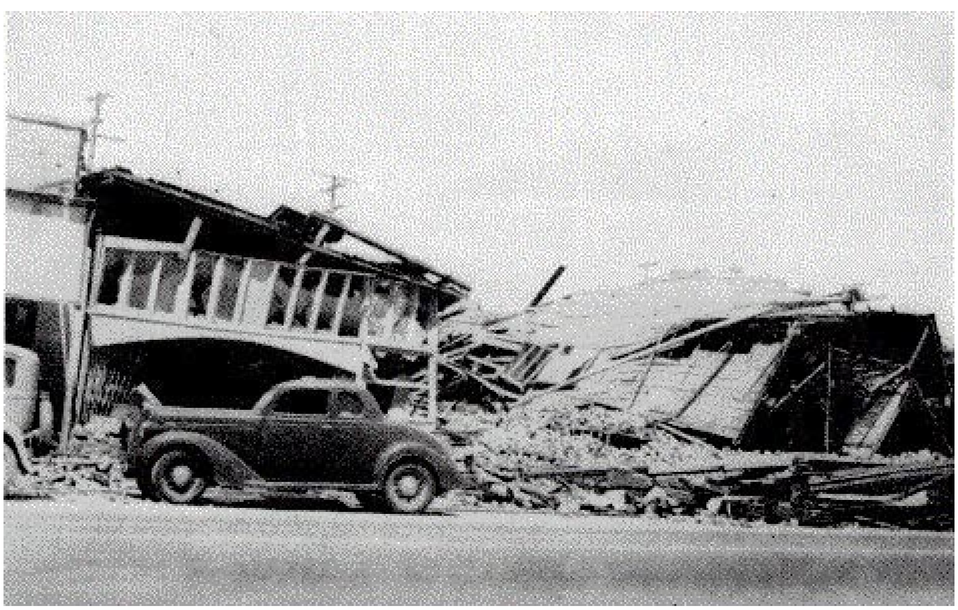

Figure 3. Damage from Imperial Valley Earthquake
Photo: U.S. Coast and Geodetic Survey

A devastating earthquake struck Imperial Valley on May 19, 1940. Nine people were killed. The shock caused 40 miles of surface faulting on the Imperial Fault, part of the San Andreas system in southern California.

This earthquake was the first strong test of public schools designed to be earthquake-resistive after the 1933 Long Beach quake. Fifteen such public schools in the area had no apparent damage. Total damage has been estimated at about $6 million. Magnitude 7.1.

Eighty percent of the buildings were damaged to some degree in the town of Imperial. Severe damage also occurred in the business district of Brawley, where all structures suffered damaged, and about fifty percent had to be condemned.

This earthquake provided an opportunity to obtain important engineering data. A seismometer was attached to the El Centro Terminal Substation Building's concrete floor. The measured acceleration time history from this location is shown in Figure 4. The velocity time history, obtained by integration, is shown in Figure 5. The corresponding shock response spectrum is shown in Figure 6.

Note that the record may have under-represented the high frequency motions of the ground because of soil-structure interaction of the massive foundation with the surrounding soft soil.

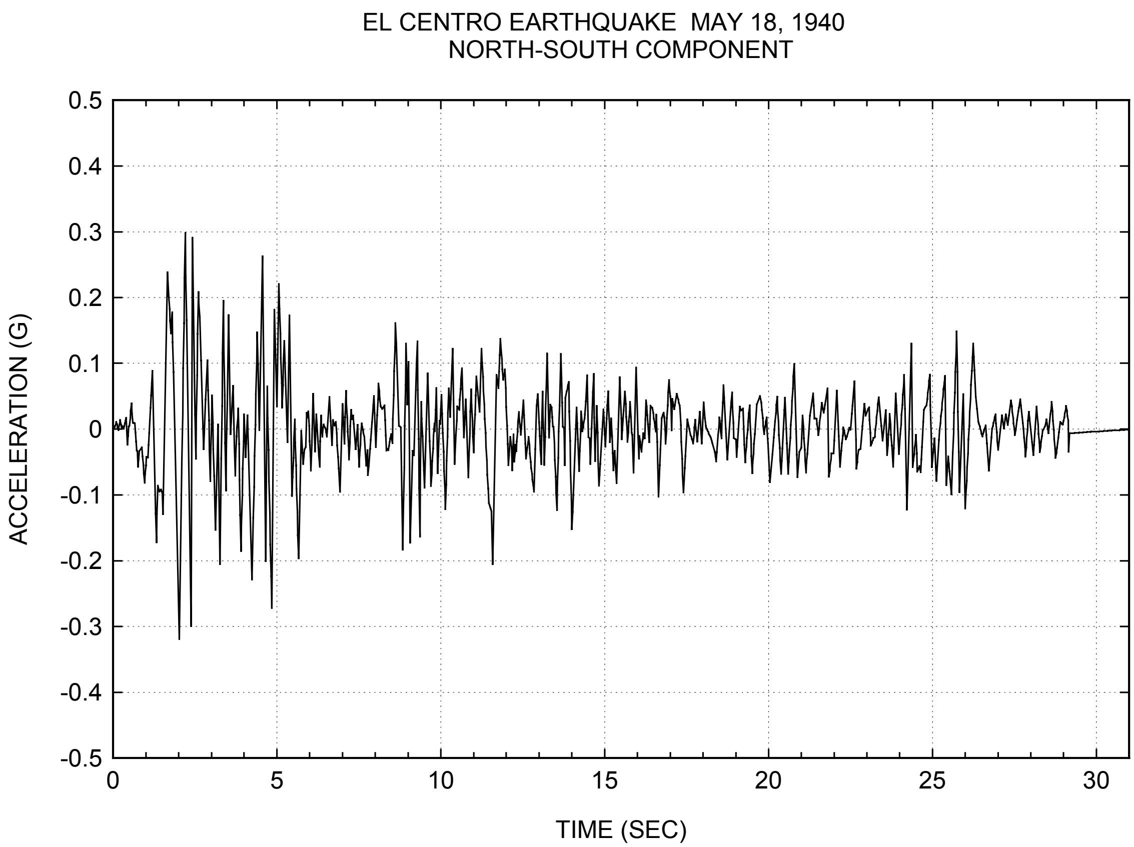

Figure 4. Acceleration Time History

The peak ground acceleration is 3.2 G.

Note that the time history data file for Figure 4 is available at:

http://www.vibrationdata.com/elcentro.htm

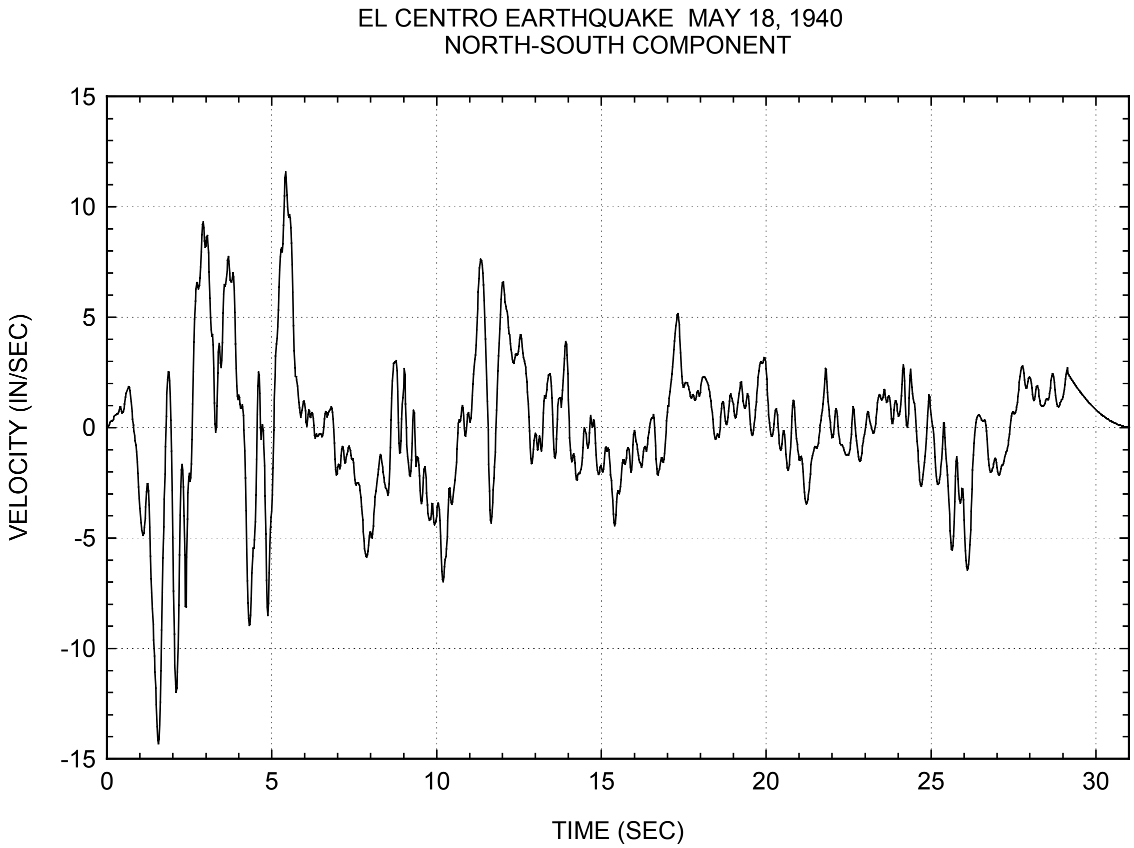

Figure 5. Velocity Time History, Integrated from Acceleration

The peak ground velocity is 14 in/sec.

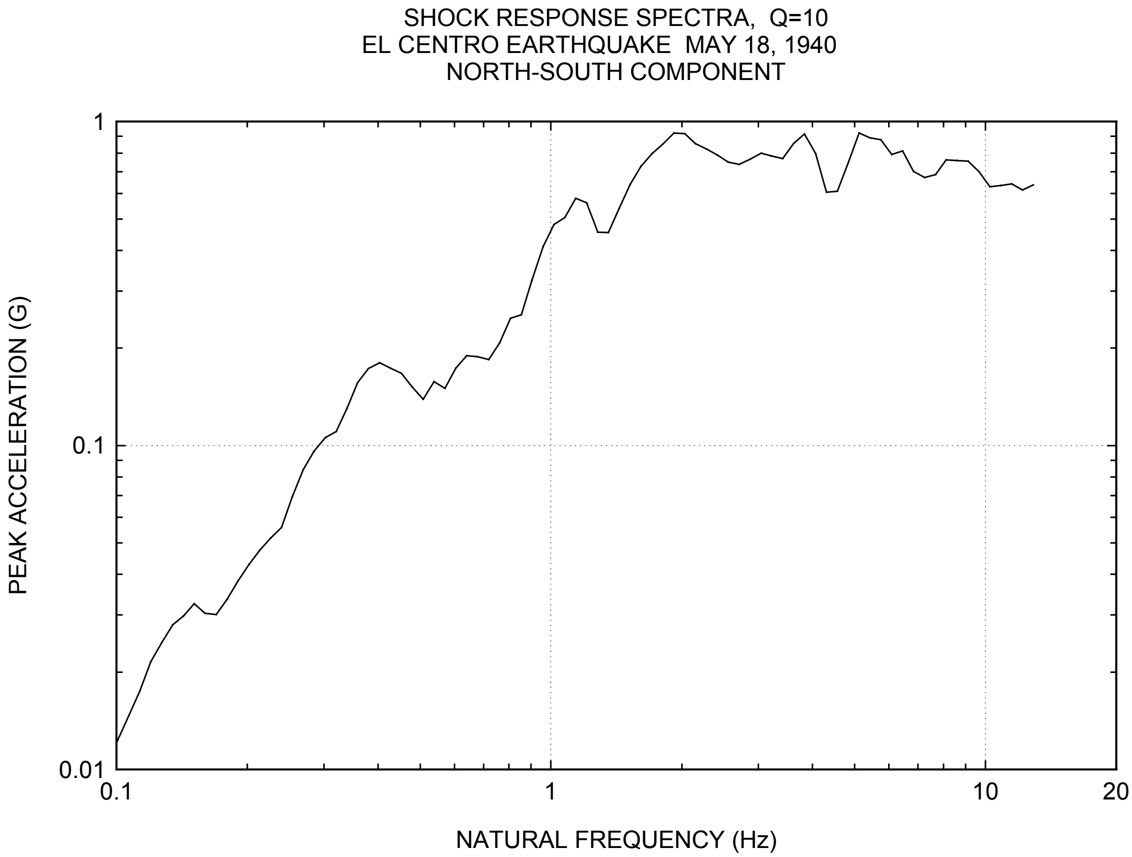

Figure 6. Shock Response Spectrum

The amplification factor for the curve in Figure 6 is Q=10, which is equivalent to a damping ratio of 0.05. Note the level in Figure 6 is somewhat higher that the corresponding VAFB level in Figure 2.

Historical data for California earthquakes is given in Table 1. This data can be used as a basis for determining the probability associated with the levels in Figures 4 and 5.

Furthermore, the data in Figures 4 and 5 is often used as a reference for designing structures and equipment to withstand California earthquakes. More conservative levels are used in certain cases, however, as discussed in the next section.

Table 1.

Earthquakes in California and Bordering Areas from 1900 to 2002, Ranked by Magnitude

Rank	Location	Date (UTC)	Magnitude
1	San Francisco	04/18/1906	8.3
2	Kern County	07/21/1952	7.7
3	Pleasant Valley, Nevada	10/03/1915	7.3
3	West of Eureka	01/31/1922	7.3
3	Cedar Mountain, Nevada	12/21/1932	7.3
3	Lompoc	11/04/1927	7.3
3	Landers	06/29/1992	7.3
8	West of Eureka	11/08/1980	7.2
8	Cape Mendocino	04/29/1992	7.2
10	Volcano Lake, B.C., Mexico	11/21/1915	7.1
10	Imperial Valley	05/19/1940	7.1
10	Fairview Peak, Nevada	12/16/1954	7.1
10	Loma Prieta	10/17/1989	7.1
10	West of Crescent City	08/17/1991	7.1
10	Hector Mine	10/16/1999	7.1
16	Colorado R. delta	12/31/1934	7.0

The data in Table 1 is compiled from data in References 3 through 5.

The data shows that an earthquake will occur once every ten years in California with magnitude greater than or equal to the 1940 Imperial Valley Earthquake.

San Francisco-Oakland Bay Bridge

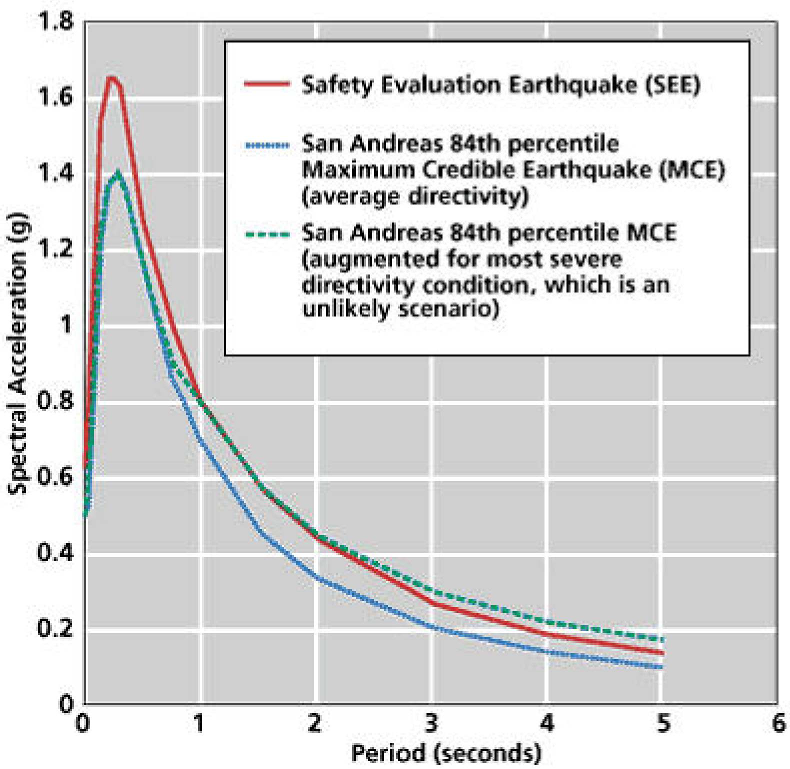

Figure 7. Bridge Design Spectrum

The state of California is replacing the aging and earthquake-vulnerable east span of the San Francisco-Oakland Bay Bridge. Dr. Bruce Bolt of UC Berkeley has recommended the levels in Figure 7 for design of the new span.

Note that the horizontal axis is represented in terms of period, rather than natural frequency.

The natural frequency fn is related to the period T by

$$fn = \frac{1}{T} \quad (1)$$

Furthermore, the damping value is omitted in Figure 7, although perhaps implied by the context.

The levels in Figure 7 are necessarily greater than those for the El Centro quake in Figure 6 and the VAFB levels in Figure 2. Obviously, a bridge must be design to withstand earthquakes over a continual period of perhaps 100 or more years. In contrast, a given space vehicle at VAFB would only spend perhaps a few days at the launch pad.

Additional Terms

Design Basis Earthquake (DBE). That level of ground shaking that has a 10% probability of being exceeding in 50 years (475-year return period earthquake)

Maximum Capable Earthquake (MCE). The maximum level of ground shaking that may ever be expected at the building site. This may be taken as that level of ground motion that has a 10% probability of being exceeded in 100 years (1000-year return period earthquake).

References

1. T. Irvine, An Introduction to the Shock Response Spectra, Vibrationdata, 2000.
2. NASA-HDBK-7005, Dynamic and Environmental Criteria, 2001.
3. http://wwwneic.cr.usgs.gov/neis/states/california/california.html
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