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Scaled accelerographs for design of structures in Quetta, Baluchistan, Pakistan

Abdul Qadir Bhatti[1,2]

Abstract Structural design for seismic excitation is usually based on peak values of forces and deformations over the duration of earthquake. In determining these peak values dynamic analysis is done which requires either response history analysis (RHA), also called time history analysis, or response spectrum analysis (RSA), both of which depend upon ground motion severity. In the past, PGA has been used to describe ground motion severity, because seismic force on a rigid body is proportional to the ground acceleration. However, it has been pointed out that single highest peak on accelerograms is a very unreliable description of the accelerograms as a whole. In this study, we are considering 0.2- and 1-s spectral acceleration. Seismic loading has been defined in terms of design spectrum and time history which will lead us to two methods of dynamic analysis. Design spectrum for Quetta will be constructed incorporating the parameters of ASCE 7-05/IBC 2006/2009, which is being used by modern codes and regulation of the world like IBC 2006/2009, ASCE 7-05, ATC-40, FEMA-356 and others. A suite of time history representing design earthquake will also be prepared, this will be a helpful tool to carryout time history dynamic analysis of structures in Quetta.

Keywords Accelerographs · Seismic design of structures · Response spectrum analysis · Response history analysis · Design spectrum

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Introduction

Quetta an active seismic region of Pakistan, The largest earthquake to strike the region occurred on 31st May 1935. The Quetta earthquake, as it was named, completely devastated the city of Quetta, more than 35,000–60,000 people were buried under the debris of the city and beside the high death toll thousands were injured and a similar number rendered homeless and destitute. This loss can never be forgotten, as 11 people were killed in the brutal natural hazard, their names are still written in the memorial at Jinnah Road Quetta, in 18th Jan 2011 an earthquake generated from Dalbandin attenuated to Quetta city in late hours at night and people of the area were horrified and were forced to vacate their homes in cold weather, about 200 homes were recorded destroyed and wide cracks appeared on buildings, adding up to the high damage potential caused by earthquakes 29th Oct, 2008 Ziarat Earthquake cannot be forgotten, registering 6.4 magnitude on the Richter scale, in just a moment 166 people were killed, 322 people injured, 7612 houses destroyed, and over 68,000 people were rendered homeless (Bhatti 2016). Loss of such amplitude can also be seen in different areas of Pakistan, the Makran coast earthquake of magnitude 8.0 in 1945, Pattan earthquake of magnitude 6.0 in 1974 and Muzaffarabad earthquake of magnitude 7.5 in 2005 bears testimony to the active seismicity of the area (Bhatti 2013a). The 1925 Santa Barbra earthquake (M 6.2) which caused 13 deaths raised the need for earthquake engineering and strong motion observation. In 1931, on the other hand earthquakes of large magnitudes more commonly occurred in countries like Japan, Taiwan, and USA, etc., where the death toll seldom crosses double figures. The obvious difference lies in preparedness to face earthquakes. Preparedness can be improved by constantly updating

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building codes, design standards, construction practices and of course by social awareness. Rehabilitation of the affected areas is still in progress by local and foreign agencies, cautious and detailed work is required to resist the damage potential of the area.

Seismic loading defined in Building Code of Pakistan (BCP 2007) is based on peak ground acceleration (PGA) values and seismic zones are in line with 1997 edition of Uniform Building Code (UBC 1997). Modern codes like International Building Code (IBC 2009) defines static and dynamic seismic loading in terms of two spectral acceleration values at 0.2 and 1 s. Currently studies were conducted by different researchers to compile a narrative study for the values, few are able to predict and plot these values for Islamabad, but none have documented values for Quetta City (Bhatti et al. 2011; Bhatti 2015).

Hence IBC 2009 cannot be adopted in Pakistan. In this study, acceleration values will be calculated for area surrounding Quetta and their utility will be assessed for adoption by BCP (Ali et al. 2015). Furthermore, the area will be assessed for vulnerability to Seismic hazards for certain return period. A set of time histories suitable for Quetta will be prepared; which will enable us to carry out state-of-the-art linear and nonlinear dynamic analysis for buildings to be constructed in Quetta (Bhatti 2013b). Professor Suehiro from Earthquake Research Institute, University of Tokyo, Japan, gave a lecture on engineering seismology at the meeting of ASCE. This lecture accelerated the development of strong motion seismometer/accelerographs in the US. By 1932 a number of accelerographs were constructed and installed at various locations (Ohsaki 1983). One of these instruments succeeded to record the motion of 1933 Long Beach earthquake. This is the first strong motion record in the world.

In Pakistan seismic stations are operated by Micro Seismic Zonation Program MSSP of Kahuta Research Laboratories KRL, Seismological division of WAPDA and Pakistan Meteorological Department (PMD). In Pakistan first accelerographs was installed in 1990 (Mona 2005). Most of the agencies have analogue apparatus of the pattern. In the analogue apparatus PGA can be easily read, but a long process of digitization needs to be adopted to extract a complete time history of an event. Presently in all these networks a transition phase is going on where digital accelerographs are being installed parallel to older versions of equipment. Now with operation of few digital seismometers, data acquisition has become much simple and a complete time history is extracted using simple software compatible with the equipment. In PMD the first digital accelerograms was available in 2000 for Peshawar region. In Quetta area of study PMD is recently planning to install digital accelerograms. Nevertheless, the data bank is

presently too small and will go a long way to be used for engineering/research purpose.

Response spectrum

Response spectrum is simply a plot of the peak or steady-state response (displacement, velocity or acceleration) of a series of oscillators of varying natural frequency, that are forced into motion by the same base vibration or shock, and in earthquake engineering it is the peak response of a structure, having a specific natural time period and damping property, to an earthquake excitation, also called seismic response spectra. Time period of series of structures is plotted on x-axis and response on y-axis. There are three types of response spectrum namely: acceleration response spectrum, velocity response spectrum and displacement response spectrum. The first one is most commonly used. Acceleration response spectra for any earthquake can be drawn by solving equation of motion:

$$\ddot{x}(t) + 2hw_o\dot{x}(t) + w_0^2 x(t) = -a(t), \qquad (1)$$

where $x(t)$ is relative motion of an oscillator with respect to the ground, w_o is natural frequency of oscillator, h is damping coefficient, $\ddot{x}(t)$, $\dot{x}(t)$ and $x(t)$ are acceleration, velocity and displacement of structure/oscillator as a function of time respectively. The maximum values of these are defined as acceleration response spectrum Sa (T, h), velocity response spectrum Sv (T, h) and displacement response spectrum Sd (T, h). Parameter T is natural time period of oscillator. A plot of T versus Sa is called acceleration response spectrum. Figure 1 shows a response spectra for Imperial Valley Earthquake of magnitude 6.53, this will be matched to the spectra for Quetta in later section of this chapter.
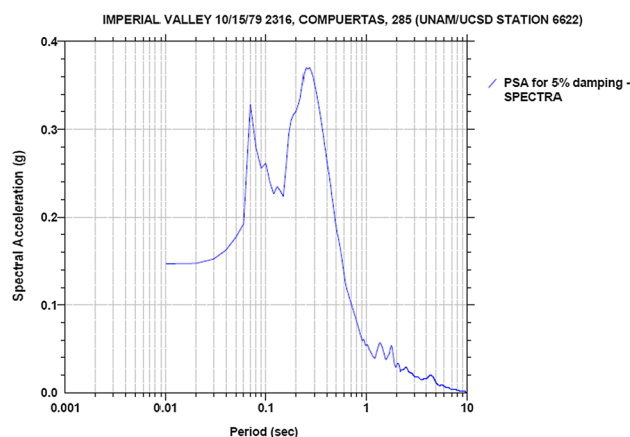
Fig. 1 Response spectra developed for Imperial Valley Earthquake 1979 (Courtesy http://peer.berkeley.edu/nga)

Design spectrum

In order to develop a design spectrum, the vibration properties of the structure is assessed that is natural frequencies, natural modes and modal damping ratio. The problem faced by designer is to design a safe and economical structure subjected to an unknown future earthquake, whose time history cannot be predicted with certainty. Each earthquake is different and design cannot be based on a single earthquake time history record. One can derive pertinent information from past earthquakes and apply those to design. The response spectrum method is a popular dynamic analysis method and yields lucrative results. The method was originally proposed by Biot (1943) and popularized as design tool by Housner and Biot, and further improved by Newmark and Hall (1982).

Response spectra plotted for any single event is jiggered as shown in Fig. 1. When an ensemble of spectra from different earthquakes is plotted together then crest and troughs compensate each other and a smooth response spectra curve is achieved (Dadashi and Nasserasadi 2015)

Hence design spectra are representative of a suite of earthquakes recorded at a site. However, in Pakistan time history accelerograms are very scarce. Veletsos and Newmark (1960) proposed design spectrum to be constructed from estimates of peak acceleration, peak velocity and peak displacements, once these peak values are designated then for a damping factor of 2% the corresponding maximum response values is 4a, 3v, and 2d. At very short periods the spectral acceleration is equal to max ground acceleration and at long time periods spectral displacement is equal to maximum displacement. By applying these simplifications a smooth response spectrum can be constructed.

IBC 2009 design spectrum for Quetta

In the method for obtaining a five-percent-damped response spectrum from the site, design acceleration response parameters S_{DS} and S_{D1} should be known. In order to define an IBC design spectrum for Quetta, the parameters for the region should be defined.

Maximum considered earthquake (MCE)

It is the maximum possible earthquake which can be experienced on the site. Such earthquake might not have come as yet. If PSHA is carried out then MCE is an earthquake with 2% probability of exceedance in 50 years. This has a return period of 2475 years. Spectral acceleration values are considered at 5% damping (ASCE 7-05).

Mapped acceleration parameters

Parameters S_S and S_1 are determined from Fig. 2 for Quetta. S_S is short spectral acceleration, determined for MCE at structural period of 0.2 s. S_1 is spectral acceleration value at structural period of 1.0 s (ASCE 7-05). Such maps are not available for Pakistan. PSHA has been carried out and these parameters have been determined as given in Table 1 for different parts of Quetta and its surrounding. If the structure is considered in sector Q-1, as having high value in plots, then:

$$S_S = 14.828 \text{ m/s}^2 = 1.513 \text{ g}$$

$$S_1 = 2.704 \text{ m/s}^2 = 0.276 \text{ g}$$

Site class

Site class is determined from the properties given in code, ranging from S_A to S_F for rock to very soft soil, respectively (ASCE 7-05/IBC-2009 1613.5.2). For every structure to be constructed site class will be determined after detail soil investigation according to ASCE 7-05 Chapter 20 which is also reproduced as Chapter 4 in BCP 2007. Since a typical design has been developed for spectrum S_D is assumed the most general site class in Quetta city.

Adjusted MCE spectral response acceleration parameters

S_S and S_1 are initially calculated for rock site and are modified for site class by following formulas:

$$S_{MS} = F_a S_S \quad (*\text{equation } 16 - 36 \text{ IBC} - 2009) \quad (2)$$

$$S_{M1} = F_v S_1 \quad (*\text{equation } 16 - 37 \text{ IBC} - 2009) \quad (3)$$

'F_a' is site coefficient defined in Table 2. 'F_v' is site coefficient defined in Table 3. In this case 'F_a' is 1 and 'F_v' is 1.848. Therefore,

$$S_{MS} = 1 \times 1.513 \text{ g} = 1.513 \text{ g} \quad \text{and}$$
$$S_{M1} = 1.848 \times 0.276 \text{ g} = 0.51 \text{ g}.$$

Design spectral acceleration parameters

Design earthquake spectral acceleration response parameters at short period and 1-s period are determined as following:

$$S_{DS} = \frac{2}{3} S_{MS} \quad (4)$$

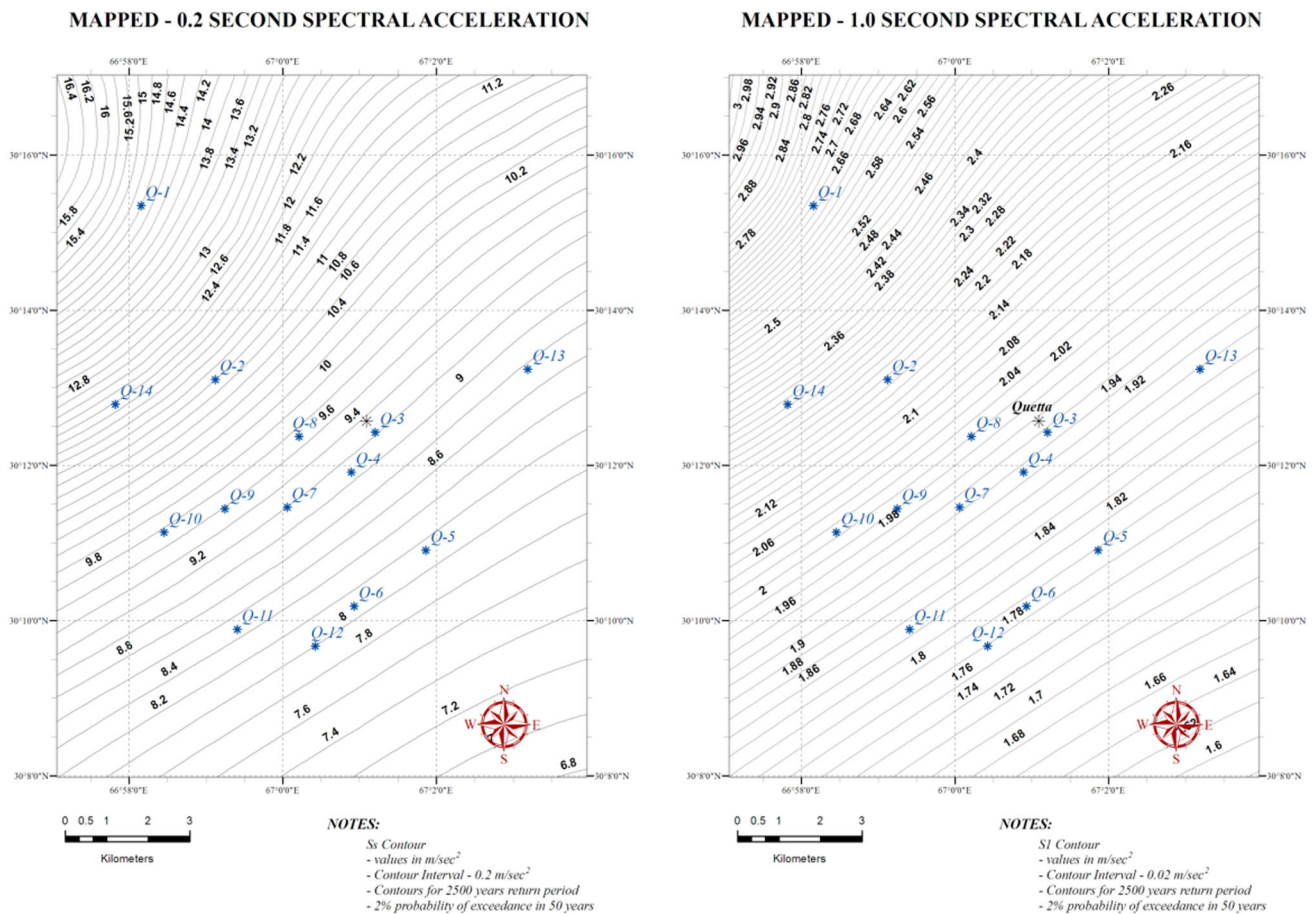$$S_{D1} = \frac{2}{3} S_{M1} \quad (5)$$

Fig. 2 Mapped second spectral acceleration for Quetta

Table 1 PGA and spectral acceleration values for different areas of Quetta

City areas	Symbol	PGA 500[a]	PGA 2500[a]	S_s 2500[a]	S_1 2500[a]
Sheikh Manda	Q-1	3.96	6.61	14.8280	2.7041
Jinnah Town	Q-2	3.02	4.82	11.3030	2.2249
St: Mary's Church Cantt	Q-3	2.41	3.87	9.2664	1.9615
Jinnah Road	Q-4	2.37	3.81	9.1273	1.9378
Mehr Abad	Q-5	2.10	3.38	8.1693	1.8035
Pashtoon abad	Q-6	2.09	3.37	8.1334	1.7973
Railway Colony	Q-7	2.40	3.87	9.2517	1.9536
Cantt Board Colony	Q-8	2.55	4.11	9.7760	2.0291
Brewery	Q-9	2.51	4.05	9.6440	2.0088
Hazara Town, Essa Nagri	Q-10	2.57	4.13	9.8323	2.0373
Sariab	Q-11	2.19	3.55	8.5337	1.8548
Satellite Town	Q-12	2.06	3.33	8.0421	1.7847
Staff College Cantt	Q-13	2.30	3.65	8.8020	1.9044
Kharotabad	Q-14	3.31	5.28	12.2820	2.3407

[a] PGA, Ss and S_1 values are in m/s^2

Table 2 Site coefficient 'F_a'. (Adopted from ASCE 7-05/IBC 2009 table 1613.5.3(1))

Site class	Mapped MCE spectral response acceleration parameter at short period				
	$S_S \leq 0.25$	$S_S = 0.5$	$S_S = 0.75$	$S_S = 1.0$	$S_S \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.0	1.7	1.2	0.9	0.9
F	See ASCE 7-05 section 11.4.7				

Table 3 Site coefficient 'F_v'. (Adopted from ASCE 7-05/IBC 2009 table 1613.5.3(2))

Site class	Mapped MCE spectral response acceleration parameter at 1 s period				
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	See ASCE 7-05 section 11.4.7				

In this case;

$$S_{DS} = 0.66 \times 1.513 = 1.008 \text{ g} \quad \text{and}$$
$$S_{D1} = 0.66 \times 0.51 = 0.34 \text{ g}$$

Design response spectrum

Design response spectrum curve is developed as indicated in Fig. 3 (ASCE 7-05 Chapter 11). Time period T is plotted on abscissa and spectral acceleration S_a is plotted as ordinate.

$$S_a = S_{DS}\left(0.4 + 0.6\frac{T}{T_0}\right) \quad \text{for } T < T_0 \tag{6}$$
$$\text{where } T_0 = 0.2\frac{S_{D1}}{S_{DS}}$$

$$S_a = S_{DS} \quad \text{for } T_0 \leq T \leq T_S \quad \text{where } T_S = \frac{S_{D1}}{S_{DS}} \tag{7}$$

$$S_a = S_{D1}/T \quad \text{for } T_s \leq T \leq T_L \quad \text{where } T_L = 8 \text{ s} \tag{8}$$

$$S_a = S_{D1}T_L/T^2 \quad \text{for} \quad T > T_L \tag{9}$$

Based on these formulas, a design response spectrum has been calculated as shown in Fig. 4a. Design spectrum once plotted with a log scale on x-axis, is easier to read in lower limits of time period. Sometimes design spectrum drawn on linear scale is not comprehendible; therefore, it is better to plot time period on a log scale as in Fig. 4b.
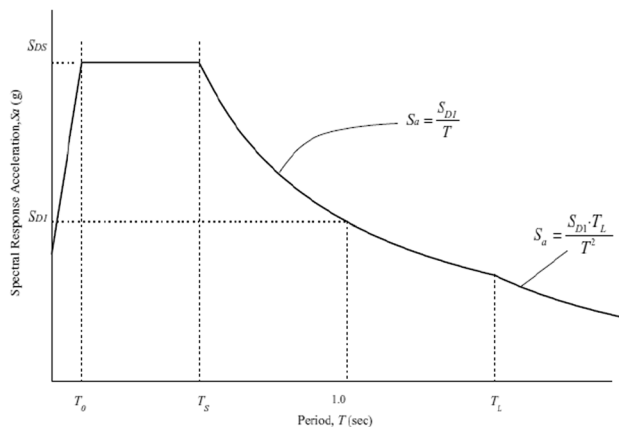

Fig. 3 Typical design response spectrum. (Adopted from ASCE 7-05)

Time history records

Time history record is also referred as strong motion observation. In a typical time history record time is plotted on x-axis and acceleration is plotted on y-axis. Such plots are obtained from strong motion observatory/seismic station where accelerometers are installed and the record obtained is called accelerograms. Usually three components of each event are recorded. Two are recorded in orthogonal horizontal directions and one in vertical direction (Varum et al. 2013).

(a)

(b)
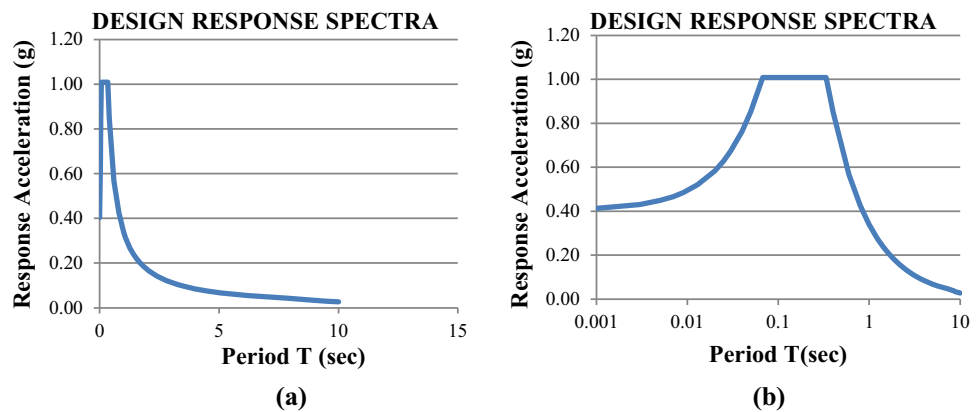
Accelerograms

When a time history dynamic analysis is to be carried out
then seismic loading is to be applied in terms of a time
history record/accelerograms. Accelerograms are treasure
of information and ground motion is characterized by many
parameters, few of which are described here.

Real accelerograms

These are the time history recorded during an actual
earthquake. These records truly represent an earthquake.
Each earthquake record is different from the other even if
their magnitude is same. The inherent variability of real
records necessitates that a large number of dynamic anal-
ysis should be run to get stable estimates on inelastic
response of the structure (Hancock et al. 2008). Moreover,
real records are scarce and they do not cover the entire
range of magnitude, distance, fault mechanism and depth,
etc. Digital records available for this study area are even
less as the digitized records are available since 2007 only
(Beyer and Bommer 2007; Bommer and Acevedo 2004).

Scaled real accelerograms

Two methods are commonly used to match the time history
spectrum with target spectrum, namely frequency domain
Fourier amplitude method and time domain wavelet
method. Computer program RSPMatch 2005 was used in
this study which is based on time domain wavelet method.
The original program code was written by Abrahamson
(1992), based on the methodology of Lilhanand and Tseng
(1987, 1988). It was subsequently modified by Hancock
et al. (2008). In this method the mismatch between target
response spectra and time history spectra are determined
first. The original record is divided into small segments and
wavelets of appropriate amplitude are added at periods
where mismatch is there till the required match is achieved

(Grant 2010). The wavelet adjustment preserves the long
period non-stationary phasing of the original time history
(RSPMatch 2005).

Seed accelerograms

Real accelerograms from WAPDA data base, PMD data
base and NGA (Next Generation Attenuation) data base
available on http://peer.berkeley.edu/nga/search were
searched and accelerograms were selected for scaling,
based on match in magnitude, fault mechanism, depth of
earthquake, epicentral distance and rough matching with
MCE response spectrum (Ekström and Dziewonski 1988).

Essentially accelerograms from rock site were searched
but due to shortage of data, accelerograms recorded on soft
rock was also accepted. Quetta area has a shallow seis-
micity hence earthquakes of focal depth less than 30 km
were considered. Most of earthquakes in our area of study
are generated by reverse and reverse oblique fault mecha-
nism; however, due to presence of Chaman Fault some
earthquakes are also generated by strike slip fault mecha-
nism. Earthquakes of these two fault mechanisms were
only considered. To account for seismicity of all types of
mechanism in area of study a mixed suite of records was
finalized. A magnitude of 6.9 at a distance of 20–30 km
was required, but the search window was relaxed for
magnitude ±0.3 on Mw scale. Source to site distance has
less effect on the spectral shape and in this aspect earth-
quakes of even up to 40 km were also considered. Spectral
match of design spectrum and seed accelerograms were
seen visually and also quantified by calculating RMSE
(root mean square error) as recommended by Kottke and
Rathje (2007) and incorporated in program SHAKE 2000
by Ordonez (2004) available on http://www.geomotions.
com. Components, fault normal and fault parallel were
dealt simultaneously with same scaling factor so that SRSS
of both matches the target spectra as recommended by
ASCE7-05.

Scaled accelerograms

Input files were prepared using RspMatchEDT a product of GeoMotions http://www.geomotions.com. In the input file target spectrum was specified as per IBC 2009/ASCE 07 to which seed accelerograms were scaled.

Two passes were applied for scaling. Both components of NGA 95 resulted in matched accelerograms EQ 11 (Fig. 5) and EQ 12 (Fig. 6), NGA 167 was adjusted to give EQ 21 (Fig. 7) and EQ 22 (Fig. 8), whereas NGA 458 produced EQ 31 (Fig. 9) and EQ 32 (Fig. 10). Figures 5, 6, 7, 8, 9, 10 show a comparison of seed accelerograms and resultant matched accelerograms along with target and matched spectrum as shown in Table 4. Due to addition of wavelets the seed accelerograms has changed to some extent and their energy content as represented by Arias

Intensity has increased. This increase should be kept as minimum as possible, which is possible by careful selection of those accelerograms which are best fit to target spectrum prior to scaling. However, the end result of achieving a scaled time history whose response spectrum is closest to the target spectrum was achieved for all cases. The SRSS of both components of matched record shall not be more than 10% less than the 1.3 times the design response spectra over a period of range of interest. Period of range of interest is defined as 0.2–1.5 T, where T is predominant period of structure. An upper limit is laid down in view of minimum usable frequency. The adjustment beyond this frequency is more of white noise and less of earthquake signal. Maximum usable frequency for NGA 95 is 0.425 Hz, for NGA 167 is 0.25 Hz and for NGA 458 is 0.625 Hz.
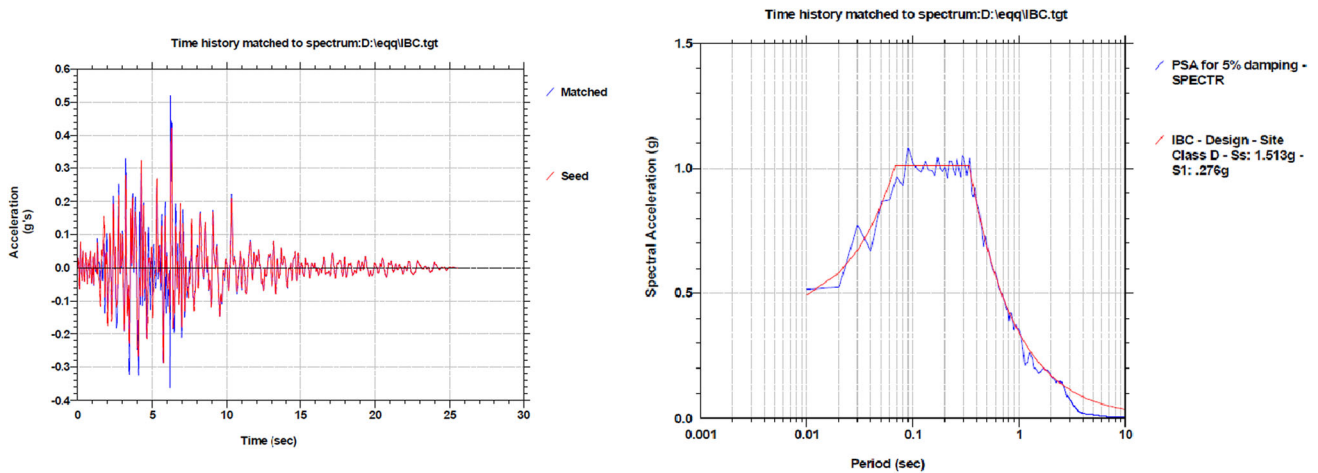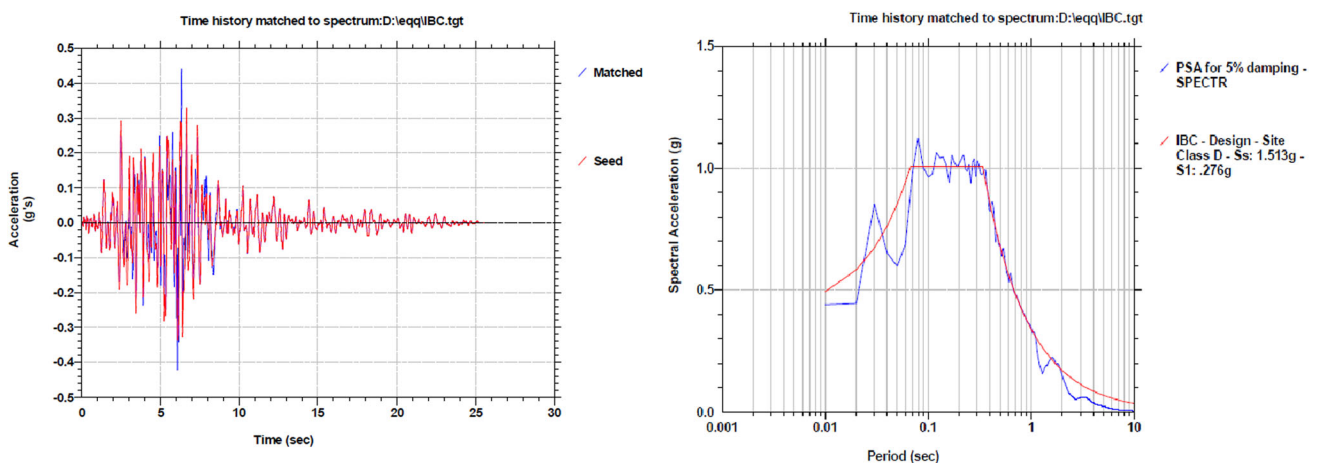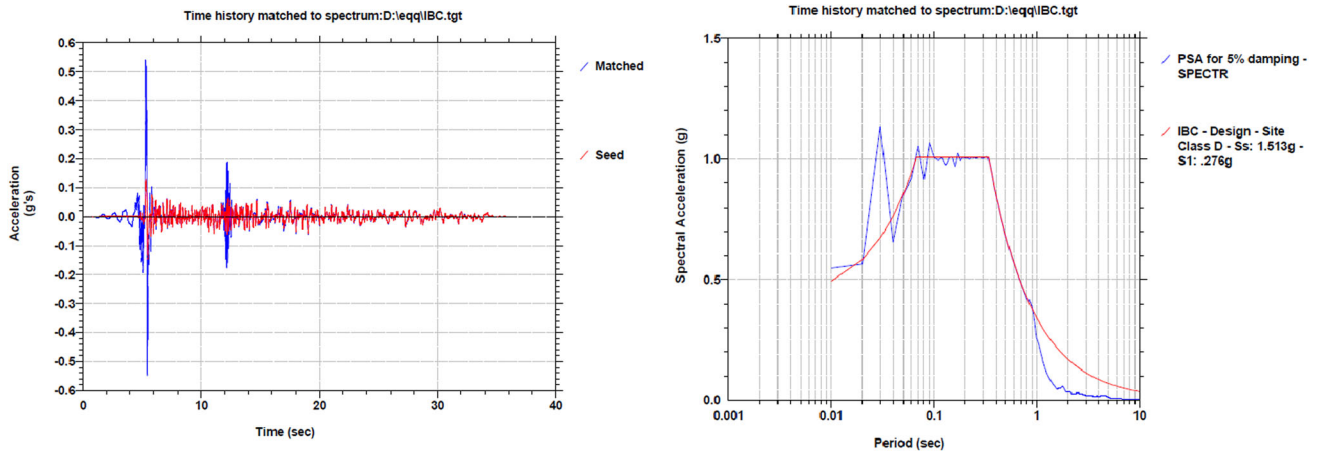

Fig. 5 Matching EQ 11

Fig. 6 Matching EQ 12

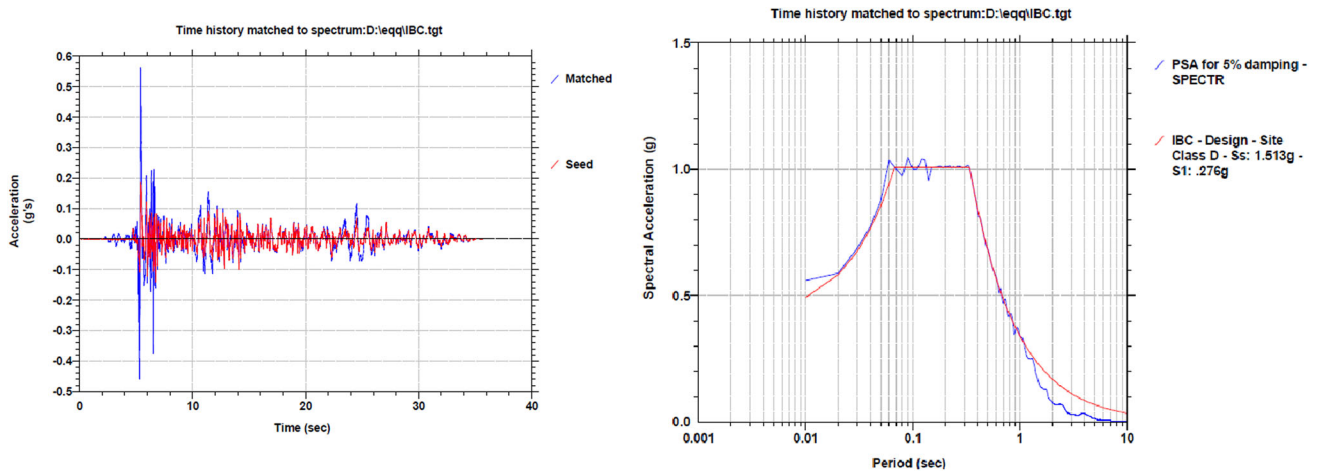**Fig. 7** Matched EQ 21
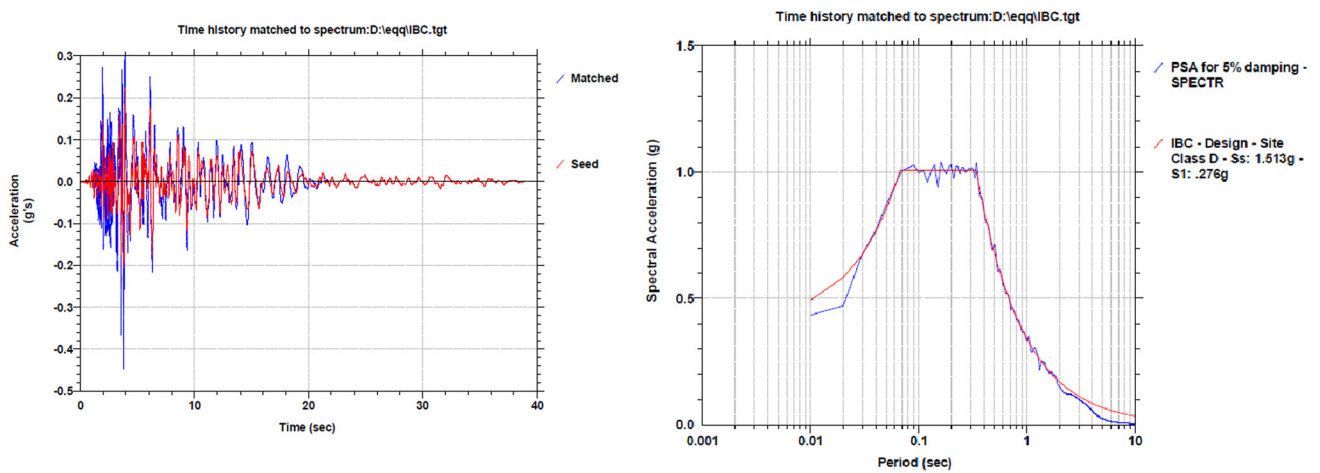

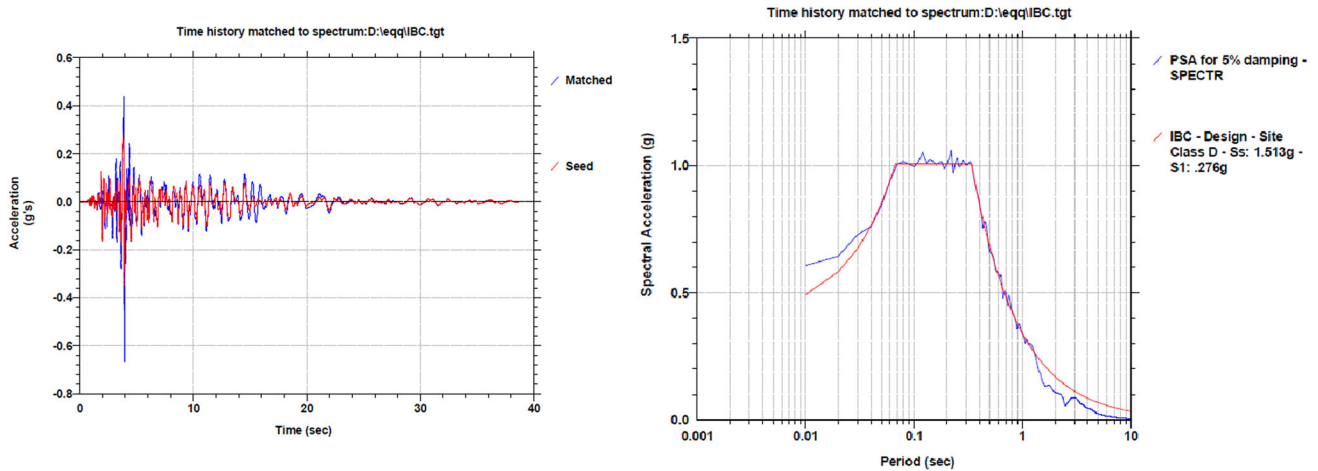**Fig. 8** Matched EQ 22

Fig. 9 Matched EQ 31

Fig. 10 Matched EQ 32

Table 4 Selected seed accelerograms and their parameters

ID—earthquake	Date	Magnitude	Fault mechanism	Depth (km)	Components	Vs_{30} (m/s)
*NGA 095 Managua Nicaragua	23-12-1972	6.24	Strike slip	8.5	MAN090 MAN180	288.5
*NGA 0167 Imperial Valley	15-10-1979	6.53	Reverse oblique	9.96	CMP015 CMP285	274.5
*NGA 458 Morgan Hill	24-4-1984	6.19	Reverse oblique	8.5	G04270 G04360	221.8

* Courtesy: http://peer.berkeley.edu/nga

Conclusions

Earthquake loads can be defined as design spectra and as time history of ground shaking; in this article both have been presented. In a comparative study of UBC and IBC, done by International conference of Building Officials (ICOB), it was stated that 2009 IBC and the 1997 UBC have both adopted the soil classification and the associated site coefficients first introduced in the 1994 NEHRP Provisions, a correlation of ground motion parameters between the two codes is possible. Therefore, a thumb rule was presented that S_{DS} of the 2000–2009 IBC is equal to $2.5 \times Ca$ and S_{D1} of the 2000–2009 IBC is equal to Cv; thus for Quetta, S_{DS} would be $2.5 \times 0.44 = 1.1$ g and S_{D1} be 0.64 g. The computed values are $S_{DS} = 1.008$ g and $S_{D1} = 0.34$ g for Quetta, Q-1. The thumb rule is not valid as the same values would be for the entire Zone 4 of soil class D with a near-source factor, which in reality is not the case; therefore, it can only give a rough estimation of the validity of the computed value. Based on the values of the most exposed area of Quetta and for typical soil class D, a design spectrum is proposed. Furthermore, three suites of time histories, each with two orthogonal components, are

suggested for time history analysis of structures in Quetta. These accelerograms are actual earthquakes of similar seismological characteristics and are scaled to match the design spectrum.

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