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SEISMIC INPUT MOTIONS FOR NONLINEAR STRUCTURAL ANALYSIS

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ABSTRACT

A major challenge in the characterization of the seismic demand for large critical structures has occurred in the last decade. The ground motion parameterization and estimation procedure now reflect more realistically the seismological properties of the fault source, three-dimensional wave path, and wave generation. In the usual design analysis, input motions for the selected safety evaluation earthquake are scaled to peak ground acceleration. For the linear response of important structure, both amplitude response spectra and standard accelerograms ("time-histories") are used as supplements. With stimulus from seismological studies of recent earthquakes, this approach is now significantly modified. Assessment of the onset and evolution of nonlinear structural deformations in large bridges, dams, and other critical structures requires also consideration of the complementary velocity and displacement input seismic motions, including their phase response spectra, directivity pulses, and fling. Attenuation relations, largely limited in the past to peak ground acceleration, have become dependent on frequency and source mechanism; and work is progressing on the estimation of the (seismically defined) duration and the phase characteristics of ground velocity and displacement. Earthquake-resistant design of multi-supported large structures requires consideration of the incoherency of horizontal-component wave motion and the time variation of strain at long periods. Also, vertical seismic motions that satisfy wave theoretic compatibility and coherency constraints are needed.

Recent damaging earthquakes, including the 1989 Loma Prieta, 1994 Northridge, and 1992 Landers, California, the 1995 Kobe, Japan, and the 1999 Chi-Chi, Taiwan, earthquakes have provided many free-field accelerograms over a wide range of distances. The resulting spatio-temporal correlations allow for the joint application of seismological and engineering expertise. The seismic response of numerous structures predicted from design procedures can now be compared with the actual seismic demand. The history of cracking, crushing by rocking, and other nonlinear degradations of large structures will, in the future, be able to be followed in the records of digital accelerometer and displacement devices on the shaken structure: analysis will need forensic skills in engineering seismology.

These changes mandate a close integration of strong-motion seismology and structural and geotechnical engineering if the full value of structural response recordings on structures in future earthquakes is to be gained and transferred into codes and improved nonlinear dynamic analysis procedures. In particular, near-fault directivity, fling-pulse contributions in velocity time histories and response spectra are now accepted as critical for engineering design in relevant hazard zones. Examples will be discussed for large bridges in the San Francisco Bay region.

KEYWORDS: Coherency, Fling, Ground Motion, Nonlinear Response, Plate Tectonics

THE IMPORTANCE OF PLATE TECTONICS TO SEISMIC HAZARD ASSESSMENT IN INDIA

Plate tectonics should form the basis of all seismic hazard studies. In some regions, this geological formation cannot provide much details on the estimation, but in others important characteristics of the threatening seismic fault sources can be defined (Molnar, 1984). In this paper large near-source attributes of the seismic ground motion are considered so that the highly seismic thrust fault belts (Bolt, 1993) of the southern margin of the Himalayas (Yeats et al., 1997) are highly relevant.

This is particularly true for the seismic hazard as it relates to long bridges and large dams in the vicinity of the Himalayas. There are two challenging problems involved both of which have received less attention than analogous ones in other parts of the world. The first is the quantification of the seismic hazard along a convergent plate boundary of continent-to-continent collision type; the second is the development of an optimum assessment methodology which will define the seismic demand adequately for appropriate engineering design of critical structures in such a region (see Youngs et al. (1997)).

The Himalayan mountains are classified (see Ni and Barazangi (1986)) with the Zagros region (from south-western Iraq to northeastern Iraq) and the Alpine belt (from Turkey to Spain) as prototypes of the process of continental collision during the Tertiary and Quaternary times (i.e., the last 65 million years). There are important and unique factors on seismic risk common in these seismotectonic regions.

Table 1: Examples of Near-Fault Strong-Motion Recordings from Crustal Earthquakes with Large Peak Horizontal Ground Motions

Earthquake	Magnitude M_W	Source Mechanism	Dist.* (km)	Acc. (g)	Vel. (cm/sec)	Disp. (cm)
1940 Imperial Valley (El Centro, 270)	7.0	Strike-Slip	8	0.22	30	24
1971 San Fernando (Pacoima 164)	6.7	Thrust	3	1.23	113	36
1979 Imperial Valley (EC #8, 140)	6.5	Strike-Slip	8	0.60	54	32
Erizican (Erizican, 000)	6.9	Strike-Slip	2	0.52	84	27
1989 Loma Prieta (Los Gatos, 000)	6.9	Oblique	5	0.56	95	41
1992 Landers (Lucerne, 260)	7.3	Strike-Slip	1	0.73	147	63
1992 Cape Mendocino (Cape Mendocino, 000)	7.1	Thrust	9	1.50	127	41
1994 Northridge (Rinaldi, 228)	6.7	Thrust	3	0.84	166	29
1995 Kobe (Takatori, 000)	6.9	Strike-Slip	1	0.61	127	36
1999 Kocaeli (SKR, 090)	7.4	Strike-Slip	3	0.41	80	205
1999 Chi-Chi (TCU068, 000)	7.6	Thrust	1	0.38	306	940

*Surface distance from fault source

NONLINEAR STRUCTURAL RESPONSE: THE DEMAND FOR GROUND VELOCITY AND DISPLACEMENT RECORDS

Because of the generally successful earthquake engineering program of the last decades to design for linear elastic response, major attention is now being directed toward nonlinear behavior of structures. In his far-reaching Earthquake Engineering Research Institute Distinguished Lecture in 2000, Professor Joseph Penzien summarized these advances:

> "The revolutionary changes in seismic design criteria…are the result of technological advances made over the past 50 years, namely (1) developing digital computers, (2) advancing numerical methods applicable to linear and nonlinear modelling and dynamic analysis of structures, (3) improving the quality, quantity, and processing of strong motion recordings, (4) understanding and applying the concept of allowing controlled inelastic deformations to occur in structural components during

> seismic events, (5) changing design detailing to satisfy strength/ductility requirements and to avoid brittle failures, (6) applying statistical and probabilistic methods to characterizing expected ground motions and structural behavior, and (7) recognizing and quantifying uncertainties in all aspects of bridge engineering."

He pointed out that the greatest stimulant to developing these technological advances, for example in bridge engineering, was the 1971 San Fernando, California, earthquake, which, for the first time, demonstrated the vulnerability of bridges to seismically-induced vibratory motions. More recent seismic events, such as the 1989 Loma Prieta and 1994 Northridge, California, earthquakes, 1995 Kobe, Japan, earthquake, and the 1999 Chi-Chi, Taiwan earthquake, further added to improved methodology to increase the seismic performance of transportation structures.

The present methodology, as summarized by Penzien, in addition to setting "rock-outcrop" response spectra representing the FEE and SEE events at a specific site, is to generate corresponding response spectrum-compatible time histories of the motion for use in the design of structures expected to experience "inelastic" deformations. Such motions can be computed by modifying "rock-outcrop" recorded time-histories using the time-domain procedure of adjustment, or by using the frequency-domain procedures (Lilhanand and Tseng, 1988). The recorded motions selected as "seeds" for modification must be chosen to possess peak ground accelerations, durations, and ground velocities and displacements, similar to those of the target design seismic event (see Table 1). For a near-field seismic event (e.g., within about 1-15 km of the site), the seed motions selected should have phase spectra that entail a definite velocity pulse or "fling".

COHERENCY OF GROUND MOTION

Structures with multiple supports respond so as to average the free-field accelerations applied to the supports. It follows that a complete dynamic analysis of such structures requires suitably phased time-histories applied at each support or equivalent modal response analysis with complete phase information appropriate to the local tectonic zone. In common practice, the usual engineering response spectrum describes only the amplitude of the acceleration motion and does not define the wave phase behavior incident to bridges and dams. Yet out-of-phase wave motions cause differential ground accelerations and differential rotations along the base of the structure. The concept of incoherency has been introduced into earthquake engineering to deal with these problems (Hao et al., 1989).

The appropriate measurement of the likeness of two wave trains is given the technical name "coherency", and quantitative measures can be obtained in the time domain through simple cross-correlation, and in frequency by using time-dependent spectra. In the frequency (w) domain, the complex coherency (see Abrahamson and Bolt (1987)) between input points 1 and 2 is

$$C_{12}(w) = S_{12}(w)/[S_{11}(w)s_{22}(w)]^{1/2} \tag{1}$$

where S denotes the cross-spectral matrix. General curves have been derived from observations of strong motion instrument arrays in recent years and applied to synthesized earthquake ground motions as realistic inputs to structures. Wave coherency, including the lag due to the passage of the waves across the structures, was incorporated, for example, in soil-structure interaction calculations for the 1998 seismic safety evaluation by PG&E of the Diablo Canyon nuclear reactor in California, and in response analysis of long toll bridges for the California Department of Transportation. It has been shown that there is a high degree of transferability of these curves between different geologic sites. Specifically, a comparison of coherency functions for both vertical and horizontal motions indicated no significant difference in coherency reductions in the range 1-10 Hz for separation distances between input points of 400, 800, and 1500 m (Chiu et al., 1995). For 4 Hz horizontal wave motions and a separation of input points of 400 m, a typical coherency reduction factor is 60 percent. The effect of incoherency of the onset of the directivity fling pulse (see below) does not yet seem to have been studied.

NEAR-FAULT SEISMIC WAVES

As mentioned earlier, near-fault ground motions often contain significant wave pulses (see Figure 1). For strike-slip fault sources they dominate the horizontal motion and may appear as single or double pulses with single or double-sided amplitudes. The duration (period) of the main pulse may range from

0.5 to 5 sec or more for the greatest magnitudes. These properties depend on the type, length, and complexity of the fault rupture. There are two causes of these long-period pulses: first, constructive shear wave interference in the dynamic ground shaking due to the movement of the fault rupture; second, displacement of the ground associated with the permanent offset of the rocks. Azimuthal dependence in both cases is a consequence of the elastic rebound of the rupturing fault (see Bolt (2003)). A useful descriptive term is the rapid "fling" of the ground during the fault slip. Below it is explained that the terms "directivity pulse" and "fling-step" have been used for the fault-rupture directivity and elastic rock rebound effects, respectively (see Bolt and Abrahamson (2003)). The pulses from the two effects may attenuate differently from one another so that their separate measurements should not be statistically combined in a single sample for the regression fits of attenuation curves.

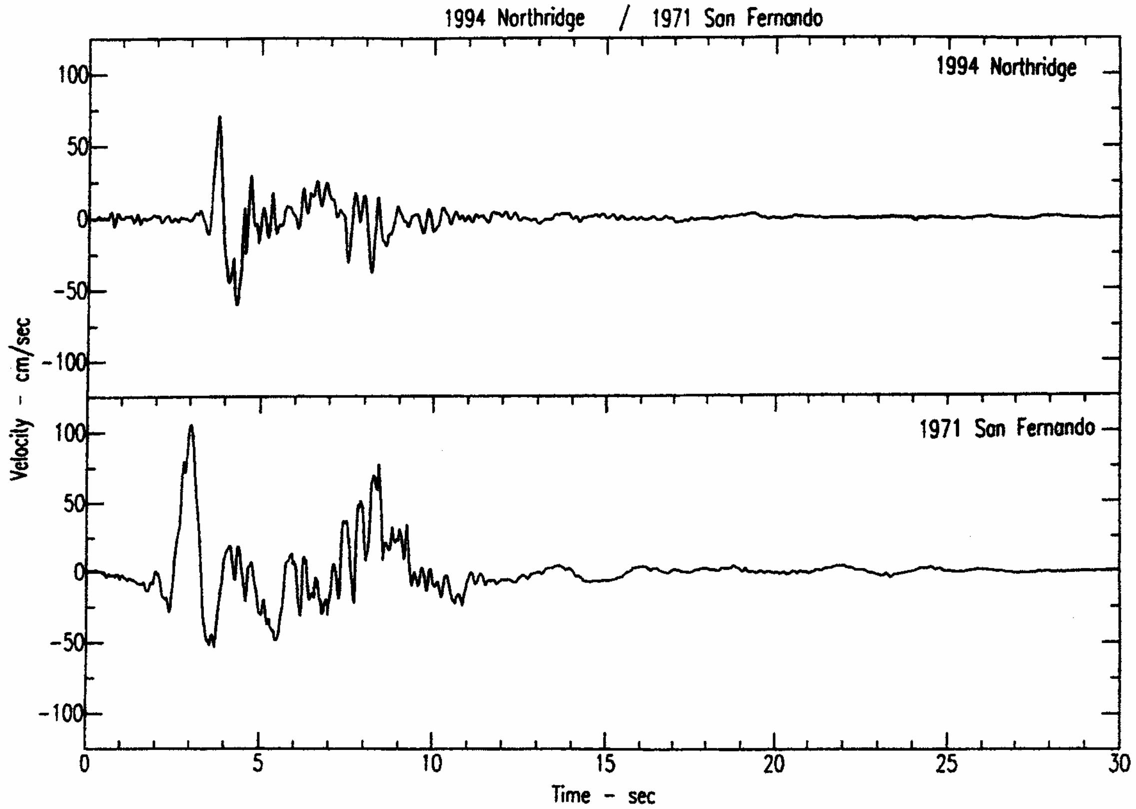

Fig. 1 Strong-motion velocity recordings (S16E component) at the Pacoima Station, California, in the 1994 Northridge (top) and 1971 San Fernando (bottom) earthquakes

Let us consider the implications of these pulses for seismic-resistant design. "Rupture directivity" effects are greatest when the fault rupture source is toward the site and the slip direction (on the fault plane) is aligned with the rupture direction (Somerville et al., 1997). The horizontal recordings of stations in the 1966 Parkfield, California, earthquake, and the Pacoima station in the 1971 San Fernando, California, earthquake (see Figure 1) were the first to be discussed (Bolt, 1975) in the literature as showing near-fault velocity pulses. These cases, with maximum amplitudes of 78 and 113 cm/sec, respectively, consisted predominantly of horizontally polarized SH-wave motion and were relatively long period (about 2-3 sec).

Additional recordings (compare Figure 1) in the near field of large sources have confirmed the pervasive presence of energetic pulses of this type and they are now included routinely in synthetic ground motions for appropriate seismic design purposes. Often transition from elastic to plastic behavior of high-rise buildings coincides with the loading by the long-period pulses (Heaton et al., 1995). Most recently, the availability of instrumented measured ground motions close to the sources of the 1992 Landers, California, earthquake (see Figure 2), the 1994 Northridge, California, earthquake (Heaton et al., 1995), the 1995 Kobe earthquake (Nakamura, 1995), and particularly the 1999 Chi-Chi, Taiwan, earthquake (Chen et al., 2001) provided important recordings of the velocity pulse under different conditions. Many detailed relevant studies of the Chi-Chi source and ground motions have already been published in a special volume of the "Bulletin of the Seismological Society of America" journal (Teng et al., 2001).

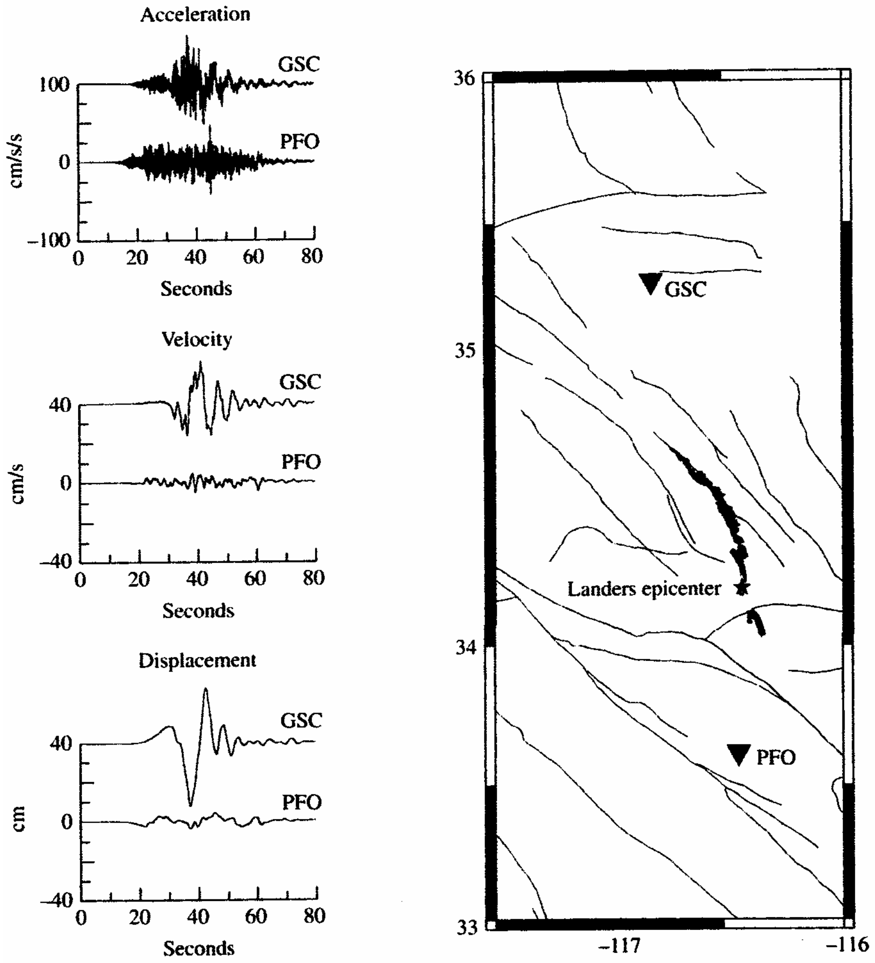

Fig. 2 Ground acceleration, velocity, and displacement at two stations in the 1992 Landers, California, earthquake (GSC – rupture approaching; PFO – rupture receding) (Courtesy: D. Dreger)

The physics of the pattern of wave generation is clear. In the case of a fault rupture toward a site at a more or less constant velocity (almost as large as the S-wave velocity), most of the seismic energy from the extended fault rupture arrives in a short time interval. This results in a single long-period pulse of velocity (and displacement), which occurs near the beginning of the record. This wave pulse represents the cumulative effect of almost all of the seismic radiation from the moving dislocation. The coincidence of the radiation-pattern is maximum for tangential motion, and the wave focusing due to the oncoming rupture produces a large displacement pulse normal to the fault strike (see Page 443 of Bullen and Bolt (1985)).

In summary, the directivity of the fault rupture causes spatial variations in ground motion amplitude and duration around the fault source and produces systematic differences between the strike-normal and strike-parallel components of horizontal ground motion. These variations generally grow in size with increasing period. Modifications to empirical strong ground motion attenuation relations have been developed to account for the effects of rupture directivity on strong motion amplitudes and durations based on an empirical analysis of near-fault recordings (Somerville et al., 1997). The ground motion parameters that have been modified include the average horizontal response spectral acceleration, the duration of the acceleration time history, and the ratio of strike-normal to strike-parallel spectral acceleration.

Key results are that when rupture propagates toward a site, the response spectral amplitude is larger for periods longer than 0.6 sec. For sites located close to faults, the strike-normal spectral acceleration is larger than the strike-parallel spectral acceleration at periods longer than 0.6 sec in a manner that depends on magnitude, distance, and azimuth (see Figure 2).

As in acoustics, the amplitude and frequency of the directivity pulse have a geometrical focusing factor which depends on the cosine of the angle between the direction of wave propagation from the source and the direction of the source velocity. Instrumental measurements show that such directivity focusing can modify the amplitude velocity pulses by a factor of up to 10, while reducing the dominant wave duration by a factor of 2. Whether single or multiple, the pulse may vary in the impulsive nature of its onset and in its half-width period. A clear illustration is the recorded ground velocity of the 15 October, 1979 Imperial Valley, California, earthquake generated by a strike-slip fault source (see Bolt and Abrahamson (2003)). In this case, the main rupture front moved toward El Centro and away from Bonds Corner. Similar effects hold for thrust fault sources (see Somerville and Abrahamson (1995)).

"Fling-step" components occur when the site is located close to a seismogenic fault with significant surface rupture. The fling-step pulse occurs on the ground displacement component "parallel" to the slip direction. As described by Bolt and Abrahamson (2003), for strike-slip earthquakes, the rupture directivity is observed on the fault normal component and the static displacement fling-step is observed on the fault parallel component. Thus, for strike-slip earthquakes, the rupture directivity pulse and the fling-step pulse will separate themselves onto the two orthogonal horizontal components. For dip-slip earthquakes, such as are common in the plate collision of India, the vectorial resolution is more complicated: although the rupture-directivity pulse is strongest on the fault normal component at a location directively up-dip from the hypocenter, a fling-step pulse may also occur on the horizontal component perpendicular to the strike of the fault. Thus for many Indian earthquakes directivity-pulse effects and fling-step effects may occur on the same component.

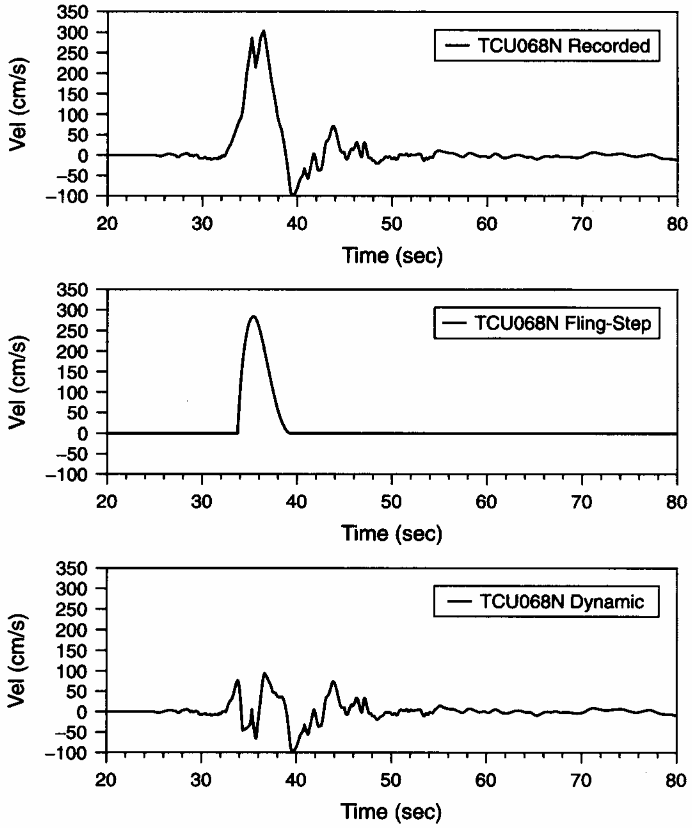

Fig. 3 Velocity-time histories for the north-south component of near-fault station TCU068 in the 1999 Chi-Chi earthquake separated into dynamic shaking and fling step components (taken from Bolt and Abrahamson (2003))

Prior to the 1999 Turkey and Taiwan earthquakes, nearly all of the observed large long-period pulses in near-fault ground motions were caused by rupture directivity effects. A clear example that illustrates this is the Lucerne recordings from the 1992 Landers, California, earthquake. They contain a directivity pulse on the fault normal component and a very long-period fling-step pulse on the fault parallel component. Also, the ground motion data from the 1999 Izmit, Turkey, and Chi-Chi, Taiwan, earthquakes contain examples of large long-period velocity pulses due to the fling-step. As a relevant illustration for the thrust fault sources of India taken from Bolt and Abrahamson (2003), a horizontal component of velocity recorded at station TCU068 of the Chi-Chi earthquake is shown in Figure 3. These ground motions occur on the hanging wall near the northern end of the fault rupture and have the largest horizontal peak velocities yet recorded (300 cm/s on the north-south component). The velocity pulse from the fling-step effect velocity at TCU068 can be seen to be one-sided. If the fling-step is separated from the dynamic shaking, the peak velocity of the dynamic component of shaking is reduced to about 100 cm/s, a more characteristic value of the amplitude of seismic S-waves with this period. A further discussion of the important Taiwan strong-motion observations can be found in Chen et al. (2001).

Robust estimates that predict the peak velocity from fling-steps are not available at this time. In estimating the displacement ground motion, the fling-step can be parameterized simply by the amplitude of the tectonic deformation and the "rise-time" (the time it takes for the fault to slip at a point). A suggested algebraic form for this permanent near-fault strain is

$$y = a \cot^{-1} bx \tag{2}$$

where y is the horizontal surface fling displacement parallel to the rebounded fault and x is the perpendicular distance away from the fault.

THE NEED FOR STRONG-MOTION INSTRUMENTATION IN INDIA

For engineering seismology use, it is advantageous to record directly either the ground acceleration or the ground displacement. If the natural period of the recording seismometer is very short compared with the predominant period of the ground motion, the recorded signal is directly proportional to the acceleration of the ground. In this case also, sensitivity of the accelerometer is small which is an advantage in recording strong-ground motion. Because instrument design can produce relatively small devices (e.g., most recently MEMS silicon chip instruments) that are not sensitive to long-term tilts and drifts of the ground, accelerometers have been the preferred type of recorder rather than displacement meters. The latter, however, are now being installed on large bridges. Recording is now digital, but in past decades the recording used an analogue signal on paper or film. Such recordings are still obtainable by the reliable AR-240s, of which many thousands remain in service around the world.

Because large earthquakes are rare events, many strong-motion accelerometers do not record continuously but are triggered by the initial P-wave in the earthquake. The result is to lose part of the initial ground motion, and cross-correlation of ground motions between neighboring instruments cannot be performed. Also, analogue records require automatic digitalization to allow integration to ground velocity and displacement, and conversion to frequency spectra.

Nowadays, instruments in both the free field of earthquakes (i.e., away from structures) and in the near field (i.e., near the rupture fault), and in structures, record digitally with pre-event solid-state memories. Absolute time marking is usually obtained from GPS satellite clocks. The digital signals are usually streams of 12- or 16-bit words. The common 12-bit word uses 72dB (i.e., $20\log_2{}^{12}$) dynamic range and is immediately accessible for processing in computers.

Corrections must be carried out, even with digital recordings, to allow for nonlinear response of the accelerometer device. For engineering purposes fidelity must be ensured in the integration to ground velocity and displacement, now essential as demand inputs for nonlinear response studies. Various procedures have been suggested to establish a zero-acceleration line, such as assuming second-degree polynomial for the base line followed by subtraction. Another method for processing digital seismic wave histories (Iwan and Chen, 1994) is to compute the average ordinates of the acceleration velocity over the final segment of the record and to equate them to zero. It is important when considering motions damaging to large structures that in standard datasets, filters are applied to remove all waves with periods greater than about 8-10 sec. Above such long periods users are warned not to assume that the response spectrum from such filtered records or the modified time-histories are complete. Recently, it has been established that even with high dynamic-digital records and recorders and with special care in the choice of filters, displacement ground motions up to DC levels can be obtained. This ability has been checked in the case of the 1999 Chi-Chi, Taiwan, earthquake for strong-motion recordings near the Chelungpu fault against direct field measurements of the fault offset and adjacent GPS measurements made adjacent to the fault.

Digital datasets in various countries and from various earthquake engineering groups often have different formats and processing methods. Important sets have been obtained in the United States by the U.S. Geological Survey (USGS) and the California Strong-Motion Instrumentation Program (CSMIP) of the Division of Mines and Geology (CDMG) (renamed in 2002 as the California Geological Survey (CGS)). Recordings of these organizations and others in the U.S. are now available on the Consortium of Strong-Motion Observation Systems' (COSMOS) Virtual Data Center (VDC) maintained at the University of California, Santa Barbara. COSMOS has set up uniform standards for processing and provides a number of services for the web-user (http://www.cosmos-eq.org). As of early 2002, the COSMOS VDC contained over 12,000 acceleration traces for 210 earthquakes and 2000 stations. The center contains important recordings from the Chi-Chi, Taiwan, earthquake and sets from Turkey, Armenia, Costa Rica, New Zealand, and India. The web-page provides checks of data quality and a connection directory to the original sources for large downloads. Another important dataset (ISESD) became available in 2000 at http://www.isesd.cv.ic.ac.uk for strong-motion recordings from Europe and the Middle East.

FUTURE DIRECTIONS

As to the future, I am critical of two recent tendencies in strong-motion assessment. The first is to accept outlying observations of ground motion as guiding parameters for broad hazard assessment. Abnormal intensity values occur in almost every large earthquake. Erratic outliers from the central tendency are to be expected because of both the mechanical complexity of seismogenic processes on large fault sources and also the geological complexity along the propagation paths. With rare exceptions, these outliers, whether very large or very small, should not control a selection of parameters for the prediction of ground motion and design spectra. Of course, some previous dismissals of what is "normal", such as the fling in the 1971 Pacoima Dam record, are now accepted as critical information. The rule should be that any abnormal ground measurements, such as at Lucerne Valley in the 1992 Landers earthquake, need to have a mechanical explanation before adoption (see Bolt (1996)). Considerable fault source complexity of mechanism has been found, for example, in the major eruption of the Denali fault in Alaska in 2002 (see Bolt (2003)).

Secondly, the potential of numerical seismic wave modelling as a calibration basis for future estimation of appropriate hazard functions and design motions is increasing rapidly (e.g., Heaton et al., 1995). At this stage, however, there are difficulties still associated with synthesizing site-specific near-field ground motions, particularly from reverse faults. Modelling should not be used as a drunken man uses lamp posts — for support rather than for illumination.

For example, the use of simplistic impulse functions to simulate the rock structure's response to rupture has been shown to lead to unrealistic wave coherencies, which incorrectly amplify peak accelerations and velocity pulses. In addition, the wave scattering adopted to model local site conditions and the damping along the fault source zone are often unrealistically low, so that many calculated wave amplitudes are over-predicted and durations are underpredicted (see Novikova and Trifunac (1994)). The moral for earthquake engineers is to be cautious in accepting such synthetics alone in controlling structural design and retrofit.

On the other hand, there are considerable advances taking place in the numerical modelling of seismic waves in 3D structures. The computations confirm, for example, that the seismic response of deep alluvial basins is profoundly affected by the energetic wave reflections and refractions at the boundaries of the basin and at its sloping bottom. In the response of the 1989 Loma Prieta earthquake around the Bay Area, the relatively high intensities at certain wave frequencies in San Francisco and Oakland were striking. Dr. Lomax and I were the first to demonstrate that a part of this effect was due to the lateral refraction of waves by large differences in rock types across the San Andreas fault and deep alluvial basins in the South Bay (Lomax and Bolt, 1992). Such effects can be generalized so that we can foretell that there will be long durations of ground motions in the next great earthquake in the Los Angeles basin and similar geological conditions in India.

More refined seismological modelling now shows the sequential development along the rupturing fault of the wave fronts as they pass through different geological structures (illustrations were shown in the oral presentation by means of color snapshots of the pattern of the spreading of intense shaking from a repetition of the 1868 Hayward fault rupture in California, from ongoing computer modelling work of D. Dreger and colleagues).

For the future, the estimation of very large ground motions that lead to nonlinear response of engineered structures requires the filling of two main gaps: first, a more representative database of appropriate strong ground motions and, secondly, wider professional education of the actual situation. No magnitude 8 or greater non-subduction zone earthquake has yet been recorded near to its source and normal-fault source mechanisms are still thinly sampled (see Table 1). A broad collection of seed strong-motion time-histories represented by both amplitude spectra and phase spectra must be accumulated in computer libraries for easy access on the Internet. Such records will provide greater confidence for seismologically sound selection of ground motion representations. Above all, optimal estimates of strong ground motion depend upon an understanding of the underlying seismological and estimation theory so that critical decisions are as realistic as possible. Otherwise, key parameters may be obscured or extreme values adopted.

An encouraging point in summarizing the present status of assessment of seismic damage is that in a number of countries digital strong-motion systems linked to communication centers (via telephone, wireless, or satellite) have now been installed. These provide processed observational data within a few minutes after shaking occurs. In California usage, a “ShakeMap” is a computer-generated representation of ground shaking produced by an earthquake. The computation produces a range of ground shaking levels at sites throughout the region. These rely upon relations that depend on distance from the earthquake source, the rock and soil conditions through the region, and on variations (if known) in the propagation of seismic waves due to complexities in the structure of the Earth’s crust. One format of the maps contours peak ground velocity and spectral acceleration at 0.3, 1.0, and 3.0 sec and displays them in color.

Not only peak ground acceleration and velocity maps are computed using instrumental measurements, but by empirical correlations of the various scales, approximate Modified Mercalli Intensity estimates are also mapped. These maps make it easier to relate the recorded ground motions to the felt shaking and damage distribution. In a scheme used in the Los Angeles basin, the instrumental Intensity map is based on a combined regression of recorded peak acceleration and velocity amplitudes (see Wald et al. (1999)).

In 2001, such ShakeMaps for rapid response purposes became available publicly on the Internet (www.trinet.org/shake) for significant earthquakes in the Los Angeles region and the Bay Area of California. Similar maps are available in other countries. They represent a major advance not only for emergency response, but also for scientific and engineering purposes. Their evolution and improvement will no doubt be rapid.

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REFERENCES

1. Abrahamson, N.A. and Bolt, B.A. (1987). “Array Analysis and Synthesis Mapping of Strong Ground Motion” in “Strong Motion Synthetics (edited by B.A. Bolt)”, Academic Press, Orlando, Florida, U.S.A., pp. 55-90.
2. Bolt, B.A. (1975). “The San Fernando Earthquake, 1971. Magnitudes, Aftershocks, and Fault Dynamics”, Bulletin 196, Calif. Div. of Mines and Geology, Sacramento, CA, U.S.A., Chapter 21.
3. Bolt, B.A. (1993). “The Estimation of Seismic Risk for Large Structures in Regions like the Himalaya” in “Earthquake Hazard and Large Dams in the Himalaya (edited by V.K. Gaur)”, INTACH, New Delhi, pp. 75-92.
4. Bolt, B.A. (1996). “From Earthquake Acceleration to Seismic Displacement”, Fifth Mallet-Milne Lecture, Soc. Earthq. Civil Eng. Dyn., London, U.K.
5. Bolt, B.A. (2003). “Earthquakes”, Fifth Edition, W.H. Freeman, New York, U.S.A.
6. Bolt, B.A. and Abrahamson, N.A. (2003). “Estimate of Strong Seismic Ground Motions” in “International Handbook of Earthquake and Engineering Seismology”, IASPEI, Part B.

7. Bullen, K. and Bolt, B.A. (1985). “An Introduction to the Theory of Seismology”, Fourth Edition, Cambridge University Press, Cambridge, U.K.
8. Chen, K.-C., Huang, B.-S., Wang, J.-H., Huang, W.-G., Chang, T.-M., Hwang, R.-D., Chiu, H.-C. and Tsai, C.-C.P. (2001). “An Observation of Rupture Pulses of the 20 September 1999 Chi-Chi, Taiwan, Earthquake from Near-Field Seismograms”, Bull. Seism. Soc. Am., Vol. 91, No. 5, pp. 1247-1254.
9. Chiu, H.-C., Amirbekian, R.V. and Bolt, B.A. (1995). “Transferability of Strong Ground Motion Coherency between the SMART1 and SMART2 Arrays”, Bull. Seism. Soc. Am., Vol. 85, pp. 342-348.
10. Hao, H., Oliveira, C.S. and Penzien, J. (1989). “Multiple Station Ground Motion Processing and Simulations Based on SMART-1 Array Data”, Nuclear Eng. Design, Vol. 11, pp. 293-310.
11. Heaton, T.H., Hall, J.F., Wald, D.J. and Halling, M.W. (1995). “Response of High-Rise and Base-Isolated Buildings to a Hypothetical M_W 7.0 Blind Thrust Earthquake”, Science, Vol. 267, pp. 206-211.
12. Iwan, W.D. and Chen, X. (1994). “A Measure of Earthquake Intensity” in “Seismic Design for Nuclear Power Plants (edited by R. Hanson)”, MIT Press, Cambridge, MA, U.S.A., pp. 438-487.
13. Lilhanand, K. and Tseng, W.S. (1988). “Development and Application of Realistic Earthquake Time Histories Compatible with Multiple Damping Response Spectra”, Proc. Ninth World Conf. Earthq. Eng., Tokyo, Japan, Vol. II, pp. 819-924.
14. Lomax, A. and Bolt, B.A. (1992). “Broadband Waveform Modelling of Anomalous Strong Ground Motion in the 1989 Loma Prieta Earthquake Using Three-Dimensional Geological Structures”, Geophysical Research Letters, Vol. 19, pp. 1963-1966.
15. Molnar, P. (1984). “Structure and Tectonics of the Himalaya: Constraints and Implications of Geophysical Data”, Annual Review of Earth and Planetary Sciences, Vol. 12, pp. 489-518.
16. Nakamura, Y. (1995). “Waveform and Its Analysis of the 1995 Hyogo-ken-Nanbu Earthquake”, Report 23C, Railway Technical Research Institute, Tokyo, Japan.
17. Ni, J. and Barazangi, M. (1986). “Seismotectonics of the Zagros Continental Collision Zone and a Comparison with the Himalayas”, J. Geophys. Res., Vol. 91, pp. 8205-8218.
18. Novikova, E.I. and Trifunac, M.D. (1994). “Duration of Strong Motion in Terms of Earthquake Magnitude, Epicentral Distance, Site Conditions and Site Geometry”, Earthq. Eng. Struct. Dyn., Vol. 23, pp. 1023-1043.
19. Somerville, P.G. and Abrahamson, N.A. (1995). “Ground Motion Prediction for Thrust Earthquakes”, Proc. SMIP95 Seminar, California Division of Mines and Geology, San Francisco, CA, U.S.A., pp. 11-23.
20. Somerville, P.G., Smith, N.F., Graves, R.W. and Abrahamson, N.A. (1997). “Modification of Empirical Strong Ground Motion Attenuation Relations to Include the Amplitude and Duration Effects of Rupture Directivity”, Seismological Research Letters, Vol. 68, No. 1.
21. Teng, T.-L., Tsai, Y.-B. and Lee, W.H.K. (editors) (2001). “Dedicated Issue on the Chi-Chi, Taiwan, Earthquake of 20 September 1999”, Bull. Seism. Soc. Am., Vol. 91, No. 5.
22. Wald, D.J., Quitoriano, V., Heaton, T.H., Kanamori, H., Scrivner, C.W. and Worden, C.B. (1999). “TriNet ‘ShakeMaps’: Rapid Generation of Instrumental Ground Motion and Intensity Maps for Earthquakes in Southern California”, Earthq. Spectra, Vol. 15, pp. 537-556.
23. Yeats, R.S., Sieh, K. and Allen, C.R. (1997). “The Geology of Earthquakes”, Oxford Univ. Press, New York, U.S.A.
24. Youngs, R.R., Chiou, S.-J., Silva, W.J. and Humphrey, J.R. (1997). “Strong Ground Motions Attenuation Relationships for Subduction Zone Earthquakes”, Seismological Research Letters, Vol. 68, pp. 58-73.