Risk Analysis II

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New data for seismic hazard analysis

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Abstract

Recently, there has been great progress in the estimation and evaluation of ground motion levels caused by earthquakes, through the development of new methodologies based on deterministic or probabilistic approaches. However, large earthquakes revealed that conditions such as crustal waveguide effects, hanging-wall effects, near-fault rupture directivity effects, sedimentary basin response effects, relief effects, basin-edge and focusing effects play an important part in the amplification of the ground motion levels and in their variability at different places. Furthermore, they result in the performance of extent damage and the increase in the uncertainty of estimates. Therefore, it is a necessity to include the above parameters in the evaluations of ground motions in order to achieve the most convenient earthquake design of the constructions and the optimum building codes.

1 Introduction

Research in the course of past decades has provided significant insight into earthquake occurrence, the spatial distribution of seismic energy and the geographical distribution of earthquake magnitudes. Particularly, important steps have been taken towards the localization of seismic faults, the definition of focal mechanism solutions, the distribution of seismic energy, the evaluation of wave attenuation and the estimation of soil and rock response. New methods, based on either deterministic or probabilistic approaches, have been developed for the accurate prediction of the ground motion levels in an area.

Despite the great progress in the evaluation of ground motion, recent earthquakes have proved that there are more parameters such as crustal waveguide effects, hanging wall effects, near-fault rupture directivity effects, sedimentary basin response effects, relief effects and so on, that increase the uncertainty level. Thus, all these parameters must be incorporated in the prediction of ground motions and generally in the estimation of seismic hazard. In the following paragraphs, after a quick overview of the new methodologies for ground motion estimation, all the parameters that exert an important influence on ground motions will be presented, together with some recent examples.

2 Ground motion prediction and earthquake source characterization

In the process of seismic hazard evaluation, three are the key features: the identification of the seismic sources that are likely to nucleate future earthquakes, the prediction of the magnitudes and frequency of occurrence of earthquakes on each source, and the determination of the orientation and the distance from each source to the affected site. If we use a deterministic approach to characterize the ground motions, then the seismic hazard is represented by a simple earthquake scenario and the frequency of occurrence does not influence the hazard level directly. When a probabilistic approach is used, then the ground motions of a series of earthquakes are taken into account and their repeat times are central to the analysis.

Earthquakes can be characterized by their magnitude or their seismic moment, which is mostly used because it corresponds to the product of the fault rupture area by its average displacement. Therefore, it can be easily calculated from the length, breadth and average displacement on the fault. Seismic moment can also be estimated from empirical relationships between seismic moment and fault characteristics such as rupture area, length and average displacement, which are based on average estimates from a large number of seismic events (Wells [1], Somerville [2]).

The dimensions of the activated fault are necessary for the measuring of the distance between the source and a given site. In the case of a distant source, the linear source representation is adequate for the distance estimation; however, the dimensions of the fault must be taken into account, in near-field events.

If a scenario earthquake is taken as the basis of the evaluation of ground motions and the design of constructions, the magnitude and the seismic moment are the main source parameters that are taken into account. In a deterministic analysis, the scenario earthquake is typically the largest earthquake expected to occur on each source, which in turn controls the seismic hazard. However, this is usually complicated by the fact that many fault systems are usually segmented. Although each segment usually ruptures individually, producing a characteristic earthquake sequence (Schwartz [3]), more than one may rupture simultaneously producing a larger seismic event than otherwise expected, was as the case of the Landers earthquake of California in 1992 (Wald [4]). Therefore, the estimation of maximum earthquake magnitude and other parameters that participate in seismic hazard analysis are accompanied by a degree of uncertainty.

In the case of a probabilistic approach for the evaluation of ground motions and the design of constructions, the already described source characterization is repeatedly performed for all earthquake magnitudes on every potential seismic source. Logic trees (Kulkarni [5]) are available for constraining the uncertainties of such source parameters. The probabilistic approach is in good accordance with the modern trends of earthquake mechanics and the development of earthquake codes, which are based on performance-based design. The latter demands accurate prediction of building response for each level of ground motions.

Furthermore, probabilistic approach asks for a large amount of information, such as the anticipated frequencies of occurrence of all the earthquakes on each possible source. This parameter can be represented by the release rate of the overall seismic moment in relation to a model of earthquake recurrence, which describes the partition of the release rate for earthquakes of different seismic moment. The release rate of seismic moment on each fault is the product of fault rupture area, the slip rate and the fault zone shear modulus.

The release rate of the seismic moment can be assessed through a number of data series. The first category is that of historical seismicity and is most reliable in tectonically active areas with a long data set of in historical recordings. The second category is the slip rate of active faults and is usually applied to individual faults in tectonically active areas. In order to constrain the range of seismic magnitudes, especially the large ones, additional geological data can be used, such as the slip-per- event and the average recurrence intervals of seismic events. The third category, which is the geodetic strain rates, is theoretically available in all tectonic environments and is used in order to constrain the seismic moment rate for an extended area. Ward [6] gave a description of how historical seismicity, geological slip rates and geodetic measurements can be incorporated in the definition of earthquake recurrence.

3 Evaluation of ground motions

The ground motion parameters can be derived from ground motion attenuation relations using simplified models in which (i) source processes are connected to the seismic magnitude, and (ii) wave propagation effects from the source to the affected site depend on the distance.

The severity of an earthquake is best represented by its magnitude which, in turn, is directly associated to the seismic moment and consequently to the rupture features, as for example average fault displacement. When the recurrence rates of earthquakes are based on historical seismicity instead of instrumental data only, then other measures are required since the already available dataset is not adequate (e.g. seismic moment). Moreover, the distance between the source and the given site can be identified in many ways as, for instance the distance between the site and the fault rupture trace, the hypocenter, the epicenter, the vertical projection to the surficial expression of the fault and so on.

It is obvious that there are distinct deviations among the various methods used for the ground motion evaluation, given that different calculations and parameters are used in each one. Empirical models, based on instrumental recordings of strong ground motions in large and medium earthquakes reduce these uncertainties. These ground motion models have been grouped for different categories of earthquakes such as shallow, crustal and subduction earthquakes, which are discreetly characterized by certain attenuation characteristics.

Despite all these categorizations, sometimes further refinement is needed in order to clarify the nature of ground motion variability. The simple parameterization of magnitude, distance and site category is not satisfactory enough to evaluate the ground motions in case of "sensitive" areas of special use and specialized development needs. For this reason, new methods have been developed, as the "random effects" approach (Abrahamson [7]) which has been applied to the strong motion data base to separately quantify two sources of variability: the variability in the average ground motions between two consecutive earthquakes, and the variability in ground motions between two sites at the same shortest distance in the same earthquake. The event-to-event variability is much lower than the intra-event one (Youngs [8]) for earthquakes of particular type and above a magnitude of 6. In this sense, there is considerable decrease in the overall variability for the larger magnitudes, and this can significantly influence our estimates of ground motions for engineering analysis and design.

This suggests that the average ground motions at a given site are very similar in large earthquakes whereas there are conditions that cause considerable ground motion variations between two different sites for the same seismic event. Such variations are attributed to seismic source processes, wave propagation and site response, which are excluded from the simple parameterization of magnitude-distance-site category of the attenuation relations.

4 New data for parameters that influence ground motions

So far, it is obvious that there is an uncertainty in the models of ground motion evaluation, which however allows the development of earthquake regulations for ordinary constructions. Moreover, it is important to notice that some essential factors for motion evaluation are ignored. These factors are related to aspects of the source effects of near-fault rupture directivity, crustal waveguide effects, site effects, sedimentary basin response effects, basin edge effects, hanging wall effects, focusing effects, relief effects, and so on. These parameters are analyzed below accompanied by examples of recent earthquakes.

Crustal waveguide effects

The maximum ground motions are caused by waves that travel upward from the earthquake source to the site, but this is valid for distances shorter than 40km, as with increasing distance, the direct waves become weaker, and the reflections of downgoing waves from interfaces below the source reach the critical angle and undergo total internal reflection. These interfaces, especially the Moho, display sharp contrast in elastic moduli and cause these critical reflections to have large amplitudes. These reflections first arrive at a distance of about 50 km, causing a reduction in the rate of attenuation of ground motion up to distances of about 100 km (Burger [9]). While the increased ground motion amplitudes in this distance range are usually not large enough themselves to cause damage, they may be quite harmful if combined with the amplifying effects of soft soils. This effect was dramatically demonstrated in the 1989 Loma Prieta earthquake (Somerville [10]), in which to buildings and bridges were severely damaged in the San Francisco Bay area, 80 km from the earthquake.

Earthquake depth, the thickness and velocity profile of the crust are responsible for the reduction in the rate of attenuation caused by the crustal waveguide, and the distance range over which it occurs. Consequently, the attenuation characteristics of ground motion vary and depend on the crustal structure and the depth of earthquake. In contrast to earlier models that used simple half-space approximations for the attenuation of ground motions, all current models now take account of the effect of the crustal waveguide.

Hanging wall effects

When a fault is dipping, then the sites on its hanging wall are closer to the fault as a whole than are sites at the same short distance on the footwall. This gives rise to shorter period ground motions on the hanging wall than on the footwall for a given distance at earthquakes generated by reverse and thrust faults. Short period ground motions are 1.3-1.4 times larger on the hanging wall of a dipping fault than in the case of strike slip faults where the ground motions are usually the same on both blocks. The empirical model of Abrahamson [11] distinguishes the ground motions that occur on the hanging wall from those on the footwall. This effect is more obvious (x 1.45) for distances 8-18 km and period ranges 0-0.6 sec, and decreases gradually to 1 at the period of 5 sec.

An example of ground motion variability between two fault blocks is the case of Taiwan earthquake, which occurred on 21 September 1999. According to instrumental data obtained from a dense station network in the wider area of the W-S reverse Chelongpu fault that was activated, the eastern, upthrown hanging wall was characterized by significantly larger accelerations that the western footwall. Besides the instrumental data, the whole picture is verified by the damage pattern. According to it, the damage was more intense and extensive on the western hanging wall than on the eastern footwall (Lekkas [12]).

Near-fault rupture directivity effects

Two conditions are necessary for forward rupture directivity effects: the propagation of rupture front towards the site, and the direction of slip on the fault being collinear with it. The necessary conditions for this type of effect exist in strike-slip faulting, where the rupture propagates horizontally along strike either unilaterally or bilaterally, and the fault slip direction is parallel to the fault strike. It should be noted, though, that not all locations close to the fault experience forward rupture directivity effects. Besides, there are also backward directivity effects that take place when the rupture propagates away from the site and generate the opposite effect: long duration, low-amplitude motions at long periods. Dip-slip faulting, both normal and reverse may also give rise to forward-directivity effects.

Forward rupture directivity increases the level of the response spectrum of the horizontal component normal to the fault strike at periods longer than 0.5 seconds. Consequently, the peak response spectral acceleration of the strike-normal component shifts to longer periods. The uniform scaling of a fixed response spectral shape cannot describe adequately these effects, because the shape becomes richer in long periods as the level of the spectrum increases. The severity of near-fault directivity effects can be higher at periods longer than 1 sec. and at distances shorter than about 40 km, with the size of the effect depending on the earthquake magnitude and on the geometry of the site in relation to the fault.

Somerville [13] based on an empirical analysis of near fault effects, modified the empirical attenuation relations of strong ground motions, which show the influence of the rupture directivity effects on the strong motion amplitudes and durations. In the near-fault rupture directivity model, it is the geometrical parameters that are responsible for the amplitude variations due to rupture directivity: the angle between the direction of rupture propagation and wave direction (small angle leads to large amplitude) and the portion of the fault between the focus and the site.

A spectacular example of near fault-rupture directivity effects was that of the Kobe earthquake in 1995. Fault propagation was observed from SW towards NE. The propagation was so fast that the damage was heavier and ground motion levels higher towards NE, around the city of Kobe, than towards SW, Awaji Island, where the damage was limited (Lekkas [14]).

Near-fault rupture directivity effects were present, too, at the earthquake that occurred in Athens on 7th September 1999. The Parnitha fault rupture propagated from the west towards the east. Therefore, higher intensities were observed in the eastward prolongation of the fault than in the opposite direction, where intensities were at least 0.5 times smaller.

Strong ground motions in sedimentary basins

Sediment-filled basins have been convenient for the foundation and expansion of many urban centers. These basins are commonly filled with alluvial deposits and sedimentary formations characterized by low seismic velocities, compared to the underlying rocks on which they are deposited. The thickness of such sedimentary sequences varies from tens of meters to some kilometers. These basins can trap seismic waves, thus increasing their destructive potential.

In this case, the geometrical parameters are essential, as the waves that enter a basin through its edge, may become trapped within the basin if post-critical incidence angles develop. The amplification of ground motions is greater when P and S waves enter the edge of the basin, become trapped and generate a surface wave that travels across the basin. Most empirical ground motion attenuation relations do not distinguish between sites located on shallow alluvial fill and those in sedimentary basins, thick and tend to underestimate the recorded ground motions.

The amplification of ground motions in sedimentary basins was well manifested in the Izmit earthquake that occurred on 17 August 1999. In the wider area of Adapazari, which is founded within a sedimentary basin filled with loose post-alpine deposits, there are indications that seismic waves were trapped within the surficial sediments and the intensities in the area increased dramatically. City blocks were razed by the shaking that lasted even for some minutes. The effects of strong ground motions were visible on the ground surface, where significant displacements and characteristic deformational morphotectonic structures were produced (Lekkas [15]).

Basin edge effects

This effect became obvious at the Northridge (1994) and Kobe (1995) earthquakes, where the existence of strong ground motions at the fault-bounded edges of the basins was ascertained. In the Los Angeles basin, the stronger motions were recorded south of the Santa Monica fault during the Northridge earthquake. Despite the similarity in surficial geology, the sites north of the fault and closer to the source are characterized by relatively low frequency amplitudes. On the other hand, more distant sites south of the fault experienced larger amplitudes with the amplitude increasing near the fault trace. The amplification of ground motions near the fault scarp led to the conclusion that tectonic structures controlling the basin are responsible for ground motion response.

In the Kobe earthquake (1995) severe damage in the buildings was recorded along a zone about 30 km long and 1 km wide, which was offset for about 1 km SE of the activated fault. The ground motions produced by the rupture were further amplified by the "basin edge" effect, the interference among direct waves crossing the basin fill upwards and vertically, and the diffracted waves at the basin edge that propagated laterally into the basin (Kawase [16], Pitarka [17], Lekkas [14]).

In the Parnitha earthquake of September 1999, heavy damage was observed in Thracomakedones area, which is located on the edge of a post-alpine basin (Athens basin) lying south of the alpine Mt. Parnitha. Despite the fact that the foundation formations of the area are expected to perform satisfactorily during an earthquake (cohesive marls and cemented scree), severe damage occurred even in earthquake-designed constructions built to meet the current earthquake building codes. This fact is attributed to the direct impact of the seismic waves and the reflection they underwent on older fault surfaces, buried under recent deposits, which bound the tectonic basin (Lekkas [15]).

Focusing effects

In the Northridge earthquake the damage distribution followed a pattern that included localized sites of high intensity, which were not directly related to the surficial soil conditions (Hartzell [18]) but were significantly influenced both by the deeper geological and structural configuration and the upper few tens of meter of sediment cover, commonly used for site characterization. Several are the geological and tectonic structures that contribute to this effect, as the relief of the substratum, buried faults, folding within the sediment fill, buried basins, and so forth. All these may focus the energy in restricted areas and strongly influence the distribution of ground motion amplitudes and intensities.

In the Athens earthquake of September 1999, the areas of Liosia and Menidi, about 5 km west of the epicenter, experienced high intensities in spite of the fact that the foundation formations did not perform poorly. Geophysical, geotechnical and neotectonic researches reveal that these high intensity pockets of damage lie on small-scale horsts and other tectonic structures buried under recent deposits.

Relief effects

Morphological variations play an important part in ground motion variability produced by an earthquake in a given area. This is identified by the high variability of intensity in areas characterized by intense relief. This is also confirmed by instrumental data, according to which the ground motion variability in two different areas with the same epicentral distance, the same geological structure and the same geotechnical conditions but significant relief variations can quite significant exceeding a factor of 1.5 (Yahata [19]) in some frequency amplitudes.

The recent Athens earthquake caused very heavy damage in the urban structure of the capital. On both sites of Helidonou torrent, intensities were particularly increased locally because of the morphological characteristics along the stream. On the contrary, almost no amplification was observed along stream of different orientation despite the fact that the soil conditions in all cases were seismically favourable.

5 New trends in ground motion hazard prediction

A probabilistic method would be the most appropriate way to estimate the expected ground motions because of the uncertainty of time, location, magnitude and ground motion level by an earthquake at a given location. In the probabilistic approach the chance of exceedance of any hazard level, is taken into account. However, there has to be some balance between cost and risk. A probabilistic seismic hazard analysis (PSHA) takes into account the ground motions caused by earthquakes of every possible magnitude during the activation of a fault or fault zone. The seismic hazard is estimated by the frequency of earthquake occurrence, the focal distance and the ground motion attenuation towards the site. The PHSA integrates numerically these parameters using the probability theory and calculates the annual frequency of exceedance of each different ground motion level for each ground motion parameter. In this sense, for each fault or fault zone, the PSHA method takes into account: (i) the average annual frequency of occurrence of each seismic event, (ii) the average frequency per event for each possible focal distance and (iii) the average frequency per event of each ground motion level for each magnitude-distance pair.

Within the PSHA all the aforementioned factors are numerically integrated using the probability theory, in order to produce the annual frequency of exceedance of each ground motion level for each ground motion parameter. All the parameters incorporated in this method, such as location, geometry, faulting mode and maximum magnitude, slip rates, earthquake recurrence and ground motion attenuation relationships, are accompanied by uncertainties, which directly affect the results and consequently must be highlighted in the analysis. The latter is accomplished through logic trees (Kulkarni [5]), which assign probability values to potential values of these parameters.

Additionally, the aforementioned parameters that are connected to these effects must be included in this methodology, although two basic difficulties are met. The first is associated to the extent that these parameters influence the final results, which can be addressed through a satisfactory amount of previous cases and instrumental recordings. The second is connected to the difficulty of localizing these effects, which necessitates a satisfactory knowledge of the neotectonic-geological structure.

In each case, the products of a PSHA can satisfactorily address the problem of performance-based design, because they quantify the ground motions that are expected to occur for a range of different annual probabilities (or return periods). Each performance objective is associated with an annual probability of occurrence, with increasingly undesirable performance characteristics caused by increasing levels of strong ground motion having decreasing annual probability of occurrence.

6 Conclusions

Despite the modern techniques applied to the evaluation of ground motions produced by an earthquake, there is a degree of uncertainty in these estimations. Ground motion parameters predicted by models including earthquake source effects, magnitude, wave propagation and ground motion location are not adequate enough.

Based on recent earthquake data, there are more conditions that are known to exert an important influence on ground motions, such as near-fault rupture directivity, morphology, sedimentary basin and basin edge effects, the influence of tectonic structures that accompany faulting, focusing, crustal waveguide and hanging wall effects, and so on.

All these data should be incorporated into the estimation of potential ground motion, so that enhanced earthquake design and regulations can be achieved, through the utilization of performance-based design that results from probabilistic analysis and seems to be the most effective methodology so far.

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