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Seismology: Predicting Strong Ground Motion for Design

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INTRODUCTION: CLASSIFICATION OF PAPERS

The 14 papers of the session may be divided (somewhat artificially, of course) in three main subgroups:

- a significant number (5) deal with the whole process of *predicting strong ground motion for design*, starting from geological / tectonic considerations and ending at a quantitative estimate of some ground motion parameters (peak acceleration, response spectrum,...), either on a regional or national scale for zoning purposes (9.17, 9.24), or at a specific site for the design of some specific structures (papers 9.10, 9.13), or finally from a methodological point of view (9.13, 9.24, 9.26).
- the 7 papers in the second sub-group each focus on one particular aspect of earthquake hazard estimation. Paper 9.2 is concerned with the estimation of the *static* deformations induced by strike slip events. Paper 9.3 focus on the contribution of Love waves in low frequency motion. Paper 9.4 investigates the relationship between epicentral intensity and magnitude for a better use of historical seismicity. Paper 9.5 presents the main characteristics and interests for both scientific and engineering purposes, of a new, large set of high-quality digital strong motion data. Papers 9.6 and 9.25 focus on site effects, and even more particularly on the geotechnical characterization of sites for microzoning purposes. Finally, paper 9.19 draws attention on the importance of the orientation of underground geological structures with respect to the epicentral direction on the effective damage to be expected at a given site.
- the 2 remaining papers (9.20, 9.21) present very interesting cases on well documented and surveyed induced seismicity under large size dams in regions of otherwise weak natural seismicity (central-western Thailand).

These 14 papers are briefly summarized, and their conclusions shortly discussed, in the following three sections, while the fourth one, as a conclusion, lists the main outcomes and issues raised by this series of papers.

GROUND MOTION PREDICTION, GENERAL ASPECTS

Srivastava and Basu propose a new "*Seismic Zonation of India*" (**9.17**) as a revision of "Seismic Zoning Map" dated 1970 (SZM 1970). Their work relies basically on a now classical probabilistic approach. The country is divided in four broad seismotectonic zones, each one being subdivided in various, seismically homogeneous source areas, the occurence parameters and magnitude and depth distribution of which are estimated with earthquake data from 1917 onwards only since earlier events are very poorly known. The choice of an (old) attenuation law then allows to derive the pga values at a number of regularly spaced grid points, for a 50 % exceedance level probability over a 100 years life time. The ensuing rational zoning (obtained after an appropriate spatial smoothing) is rather simple (4 zones, very closely related to the initial seismotectonic zoning), and exhibits significant differences with the previous one (SZM 1970), which was based mainly on a subjective estimate of accelerations from observed macroseismic intensities. Further on, these pga values are transformed in design coefficients consistent with the present status of the antiseismic regulations in India, and which incorporate a significant amount of stress reduction, probably related with ductile behaviour of structures, although it is not explicitly written in the text.

As India, and especially its most seismically active areas (along the Himalyan belt), are very moutainous, the author also raises the problem of the modulation of pga (or design coefficients) with surface topography, and recommends the so-obtained design values to be valid for mid-slope sites; he does not propose, however, any quantitative formula to account for surface topography effects.

With the same objective of obtaining rational design seismic parameters, **Zhou Xiyuan and Su Jingyu** draw attention on the "essential" distinction between the "random" nature of earthquake occurence and the many uncertainties involved in the process of strong motion prediction or seismic zoning. Their paper "*Application of Fuzzy Set Theory in Option of Response Spectra*" (**9.24**) thus proposes a new but rather simple method for a rational selecting of design response spectra, which account for the fuzziness of regional seismic hazard and site conditions. As current design spectrum in China (and in many other countries) depends on three kinds of classification (design intensity level, 4 classes: VI to IX; site geological conditions, 4 classes; and proximity to seismogenetic zones, 2 classes: near or distant shock), fuzzy mathematics are used to estimate the membership degree of a given site to each of the 28 ($= 3 \cdot 4 \cdot 2 + 4$) possible cases; an appropriate weighting (*i.e.*, using these membership degree values) of the 28 corresponding design spectra provides a rational estimate of the site-specific response spectrum. Although the proposed method is fitted to the frame of China's earthquake regulations, it is general enough to be easily transposed to other national codes, or to more specific urban microzonation studies.

The selection of the various variables quantifying the fuzziness properties of the classification parameters is not, however, an easy task, and the methodology for that is not detailed in the text.

Chaney, Carver, Bickner, Conversano, and Lindberg, in their paper "*Seismik Risk Analysis for a Site along the Gorda Segment of the Cascadia Subduction Zone*" (**9.10**), present a very thorough evaluation of the seismic hazard at a site near Eureka in northern California. Starting from the tectonic and geological setting of the surrounding region, they identify 5 major active fault zones likely to produce significant ground motion at the site under consideration. For each of these fault zones, paleoseismic data from trenches, slip rates and historical and instrumental seismicity records lead to an estimation of the recurrence curves using the "characteristic earthquake model", and, from those curves, of both the maximum credible earthquakes (MCE) and the maximum probable earthquake (MPE) to be expected within a 100-year period. Then, given the distance between these fault zones and the site, estimates of maximum credible and maximum probable peak accelerations are provided. In both cases, it is concluded that the worst event is a local thrust event occuring just under the site, which may produce at most a 0.85 g pga (MCE: M=7.7) or, within a 100-year period (MPE: M=5.0), 0.50 g; such local events override (in terms of pga) both magnitude 8^+ events likely to occur at a distance of 50 km from the site, and magnitude around 7 events likely to occur at a distance of 20 km. In addition, trenches at the site draw the attention on the possibility of significant vertical, fault-induced *static* differential motion, which may result in shear stresses in the structure beyond those normally associated with *vibratory* strong motion. This analysis thus stresses the extreme importance of moderate size, local events (as long as pga is the design parameter); however, would other strong motion parameters such as duration, or low-frequency content, be taken into account in addition to pga, such a conclusion might be no longer valid.

To the contrary of the previous study, whose main part concerned the tectonic evaluation of major fault zones near the site, **Wong, Silva, Darragh, Stark and Wright**, focus on the estimation of site specific, realistic acceleration time histories in a *given* tectonic regime. As recent, dramatic earthquakes showed the extreme importance of surficial conditions on ground motion and damage, their paper "*Applications of the Band-Limited-White-Noise Source Model for Predicting Site-specific Strong Ground Motions*" (**9.13**), incorporates this surficial soil response through an equivalent linear approach in the now well-known BLWN (Band limited white noise) model first developped in the early 80's, making use of the random vibration theory (RVT) for estimating not only the time domain peak accelerations and velocities, but also the peak shear strains so as to iteratively adapt the soil modulus and damping. As a consequence, the four case studies presented in this paper, corresponding to sites located in central and western United States, may be considered as "state of the art", very high quality ground motion predictions, and they confirm the considerable potential of BLWN-RVT models for simple, rapid predictions of strong ground motion parameters at rock and soft sites in various tectonic regimes.

They do also show, however, the sensitivity of these predictions to some parameters which are in most cases poorly known (such as the stress drop, the frequency dependence of crustal damping, and the high frequency decay parameter κ), as well as some intrinsic limitations of the model. Among the latter, the main issue deals probably with the validity of the point source model underlying the BLWN model for sites located near large-size events: the very large pga obtained on rock sites in the epicentral area of a M 7.9 new Madrid event (1.60 g), though not impossible, contrasts with the 0.20 g observed on the Michoacan Guerrero coast in 1985. Another issue to be addressed for those models concerns the origin of the high frequency fall off of acceleration spectra (so-called f_{max}), implicitly attributed here to the near surface, *frequency independent* damping, and therefore highly variable from site to site (whereas some authors relate it to source processes, which would imply a site independence). Some of the model improvements presently under way as mentioned in the conclusion, should provide significant advancements along these directions.

Design parameters are most often specified in terms of spectral parameters (response spectrum or Fourier modulus), but an increasing number of analyses (non-linear behaviour, liquefaction, ...) require the use of time domain accelerograms. The generation of such acceleration time histories fitting a given design spectral characterization is usually done through an iterative process, where the main issue concerns the choice of the phase spectrum. **He Yang** in his paper "*A Novel Method Synthesizing Acceleration Time History with Consideration of Earthquake Environment*" (**9.26**), rightly proposes to use as a starting point in this iterative process a *real* accelerogram, chosen in a data bank so as to minimize the difference with the target spectrum. Such a method was in some way implicitely used by the authors of the previous paper (**9.13**), since they selected, for generating a time domain acceleration for a M 7.9 New Madrid earthquake, the phase spectrum of the record obtained at "La Villita" during the M 8^+ Michoacan event of 1985.

GROUND MOTION PREDICTION, SPECIFIC ASPECTS

As many structures (such as dams) are built very close to active faults, **Vallejo and Shettima** address the problem of the post-earthquake *static* residual deformations and strains in the vicinity of surficial faults. Their paper "*Fault Induced Ground Deformations and their Effect on Structures*" (**9.2**) proposes a method based on the linear elastic fracture mechanics to estimate the stresses induced near the tips of strike-slip fault segments (treated as large cracks in brittle materials), from which they derive the vertical ground deformations: uplift zones are associated with compressive stresses, and subsidence areas with tensile stresses. These simple theoretical results are shown to be in good agreement with the observed pattern of vertical displacements observed after a large earthquake (the great Kanto event, 1923) in Japan. (In that case however, the fault plane is far from being vertical - dip angle around 30° - as assumed in the model, and there might exist some dip-slip component of slip on the fault.) Such a model provides a basis for the estimation of tilting and shearing that structures (and especially long ones) might undergo.

In order to extend as much as possible the instrumental seismicity catalog for earthquake hazard estimates, **Nowroozi** presents a careful study on the "*Statistical Relations between Intensity and Magnitude of Southeastern United States Earthquakes*" (**9.4**). These relationships are derived from a catalog of 162 events covering the period 1833 - 1987 for which both epicentral intensities and body wave or Lg wave magnitudes are available (with only two events above magnitude 5.5 and intensity 8), using three different estimation methods: the least-square, major axis and reduced major axis criteria. The best method appears to be the last one (reduced major axis). The missing information (intensity or magnitude) in the whole earthquake catalog of the area (2245 events) was then obtained with these relationships, and the Gutenberg-Richter law reevaluated, suggesting a slight deficiency in magnitude around 6 (intensity 8 - 9) events, and possibly reflecting the non-completeness of the catalog...

If intraplate tectonic setting, where recurrence times are very long, desperately need such an extension of the instrumental seismicity catalog with historical macroseismic data and, whereever possible, paleoseismological studies, improvements in quantitative ground motion predictions will certainly come from high quality networks installed in seismically active areas, thus allowing the rapid gathering of numerous data. An excellent illustration of the capabilities of such a network is given in the paper "*Guerrero Accelerograph Array: Status and Selected Results*" (**9.5**), where **Anderson, Quaas, Castro, Mendez, Humphrey and Singh**, give an outline of the research already achieved and still going on with the hundreds (>600 in 5 years: 1985-1989) of data produced by this digital network, which includes studies on attenuation, site effects, scaling of spectra with magnitude, vertical to horizontal pga ratio, and rupture process of the 1985 event. The main results, in addition to the near field recordings of a M 8^+ event, are the following:

- there seems to exist an upper bound for the pga in the near field of subduction earthquakes in this region (around 0.5 - 0.6 g)
- the regional attenuation is clearly frequency dependent, in the form $1/Q = c+d/f$)
- source spectra get richer and richer in low frequencies as magnitude increases, while there is an magnitude-independent high frequency cut-off (between 10 and 25 Hz), which is attributed by the authors to near-surface attenuation.
- most of the events have a stress drop between 100 and 1000 bars, which might be indicative of a highly-stressed area, consistent with the presumed existence of a mature gap along the Guerrero coast.
- although all stations were settled on rock sites to avoid site effects, there clearly exist strong, frequency dependent local modulations (amplifications or deamplifications larger than a factor of 5) at some particular stations, which are not easy to understand (in particular by surficial weathering).
- although its mean value is clearly smaller than 1, ratio of vertical to horizontal pga values may reach high values ($>$ 1.5) at short epicentral distances, at least for moderate size events (M $<$ 5).

There is no doubt that, with so abundant data, many pending questions on strong motion characteristics will receive more and more reliable answers in the near future. Similar networks should therefore be as carefully designed, installed and maintained in other seismically active parts of the world.

Papers **9.6** and **9.25** put emphasis on site effects. **Chang, Wang, Ng and Lee**, in their paper "*Subsurface Conditions in Memphis and Shelby County, Tennessee*", describe the methodology for revealing and classifying subsurface conditions in view of a better seismic zoning of large size urban areas (here about 2000 km^2). Basically, the area under consideration is divided in a number (here 2860) of equal-size cells, within which the existing soil data (mainly boring logs together with laboratory tests) are reviewed and analysed so as to result in an "average" cell-specific soil profile, used in turn for site response and liquefaction potential analysis (reported elsewhere). As emphasized by the authors, such studies face two major problems: in so large an area, the soil data coverage is highly heterogeneous because of differences in urbanisation, and selecting the cell size giving the right balance between non-sampled cells and "over-sampled" cells, is not an easy task. In addition, whichever the selected size, in heavily urbanized cells where many borings are available, the dispersion is very high (coefficients of variation between 0.2 to 0.6 in general, but sometimes higher than 1...), and the concept of "representative soil log" completely fails... The results of subsequent site response analysis must therefore be viewed mainly as a first screening of the expected effects during an earthquake, which may help the regional authorities to focus investigations on particularly sensitive sites, or to better organize rescue plans. They should in no case be used for the design of a particular structure in a particular cell.

A new clear example of site effects is presented by **Acevedo, Astroza and Monge** in their paper "*Geotechnical Units and the Damages Caused by Earthquakes in Valparaiso, Chile*" (**9.25**). Valparaiso's morphology is typical of a regression coast, including a flat sector with sand from old and modern beaches together with alluvial, colluvial, and estuarial marine sediments and artificial backfillings, surrounded by hills of folded rock: a geology-based geotechnical zoning is given. A detailed survey of the damaged structures after the 1985 event lead to the conclusion that intensity was larger in the flat sector (7.5 to 8.5) than in the hilly areas (7.25 - 7.5), as expected. The detailed examination of the intensity map within the flat sector, however, reveals a marked "pocket" of larger intensity (8.5), which could not be predicted by the geotechnical zoning, and which points toward either the need for more quantitative soil characterizations, or the possible existence of multidimensional wave propagation effects.

Again in relation with site effects, the paper "*Earthquake Damage Done at Right Angles to Epicentral Distance*" (**9.19**) by **Nasu** presents a series of qualititative damage observations (around 20) strongly suggesting an increased motion or damage in the direction perpendicular to the epicentral direction: the most recent and striking examples concern the bridge damages observed in the Loma Prieta earthquake (in the Bay Area: Embarcadero Viaduct, Cypress viaduct, Bay bridge, as well as to the south: Struve Slough bridge near Watsonville), which all correspond to "transverse" motion (with respect to source location). For each of these observations, the author makes a relationship with the fact that the local ground structure involves a soft soil layer whose thickness is varying perpendicularly to the epicentral direction, *i.e.* in the direction of increased motion (reported examples deal with many different such ground structures, such as embankments, alluvial valleys, old moats, slope deposits, inclined strata...). In addition, it seems that such directional effects appear more and more clearly as epicentral distance increases.

Although no interpretation or explanation is given for these observations, they suggest the importance of combined SH (or Love) waves with multidimensional diffraction effects inducing either their amplification or the generation of large strains (or both). They may also have important consequences as to the design of structures in some areas, leading to an increased strength in one particular direction.

Finally, **Nakamura and Suetomi** are interested in the estimation of low frequency motions and strains for a safe design of (underground) lifeline facilities on soft soils. Their paper "*Prediction of Characteristics of Surface Wave for Earthquake Resistant Design*" (**9.3**) thus focus on the specific contribution of long period (T $>$ 1 s) surface waves, proposing a method to estimate the expected value of the velocity response spectra and peak ground displacement due to Love waves only. They introduce a "coefficient of influence of Love wave" $T(f)$ which represents the ratio between the response spectrum of Love waves on sedimentary sites (target), and the bedrock response spectrum (obtained by classical attenuation formulæ) multiplied by the displacement amplitude ratio between surface and bedrock (at depth) for Love waves supposed to be in their fundamental mode (obtained from classical matrix propagator methods). This coefficient is, reportedly, shown in a previous paper to be only frequency dependent, and to have a rather simple frequency dependence (basically constant and equal to 2 at long periods and zero at short periods), the parameters of which are to be estimated from statistics on actual records, and from the local geological structure (Airy phase).

From that point, rather simple algebra leads to an estimate of the peak displacements due to those Love waves, while the local geological structure allows to estimate their dispersion curve, and therefore the period of the Airy phase and the corresponding wavelength: derivation of the corresponding strains, important for lifeline facilities, is then straightforward. Comparisons of the so-predicted peak Love wave displacements with actual displacement records obtained at 2 Japanese sites show a rather good agreement. The corresponding strains are shown to be much lower than those recommended by the current Japanese regulations, mainly because those low frequency Love waves have much longer wavelengths than the S wave wavelength prescribed in the code. It is concluded that the sructures designed on the basis of the current Japanese regulations are safe against surface waves.

Such a conclusion might be discussed, however, since this paper considers only very deep sedimentary sites, and does not address the issue of intermediate period, very surficial Love waves (*i.e.*, higher modes), which may be generated locally on dipping interfaces, and, as they have much shorter wavelengths, may induce much higher strains. The proposed methodology might probably be applied with some modifications, but the statistical fit of the needed parameters is probably much more difficult at such intermediate periods.

RESERVOIR INDUCED SEISMICITY

Hetrakul, Sittipod, Tanittiraporn and Vivattananon on one side, and **Klaipongpan, Pinrode, Chakramanont and Chittrakarn** on the other, through their respective papers *Post Evaluation on Reservoir Triggered Seismicity of Khao Laem Dam*" (paper **9.20**) and "*Geological and Seismicity Evaluation of Srinagarind Dam*" (**9.21**), present investigations on two cases of earthquake phenomena associated with reservoir filling in central-western Thailand.

The Khao Laem dam is a concrete faced rockfill dam, 130 m in height, with a crest length of about 1 km; the associated reservoir has a surface area of 385 km^2 and a total capacity of 8.86 km^3. The initial impoundment started in June 1984 and by October 1985, the reservoir level was within 1 m of full pond. A single seismic station was installed in 1982, and the largest pre-impoundment event has been a 3.3 M_L earthquake occuring in 1983 within 10 kms of the dam site. A local seismic network made of 7 additional stations installed in 1984 revealed a marked increase of seismicity during the initial impoundment (Mid 84 through Mid 85), with both a much larger number of events (up to 900 per month, organized in 6 main swarms, the location of which changes with time with a clear trend to a migration away from the dam), and larger magnitudes (up to 4.5 M_L). The analysis of a number of seismicity parameters (*i.e.*, the slope of the frequency - magnitude relationship, the magnitude ratio of the largest aftershock to mainshock, and the foreshock and aftershock occurence rates), strongly suggest that this seismicity has been triggered by the impoundment, through the raising of local pore pressure and loading over pre-existing planes of weakness. In addition, the composite focal mechanisms obtained for each swarm, as well as their hypocentral distribution, are consistent with the tectonic setting of the area, characterized by two major north to northwest trending strike slip, right-lateral fault zones, and minor, younger northeast trending lineaments.

The case study on the nearby Srinagarind reservoir, though somewhat different, lead to similar conclusions. This reservoir, located about 60 km east of the former one, has a surface area of 420 km^2 and a total capacity of 17.0 km^3, and is closed by a compacted rockfill claycore type dam, 140 m in height and 610 m in length: it is therefore a likely candidate for "reservoir triggered seismicity". The initial filling started in 1977 and reached its first maximum level (3.3 m below the maximum one) in 1982. No specific seismic station was installed since the area was considered as aseismic, so that the seismicity of the area was only surveyed by the National Seismic Network of Thailand composed of 9 stations. In April 1983 however, a series of earthquakes, including a M_L 5.9 event, occurred in the upper reaches of the reservoir, about 60 kms north of dam site, and caused, in addition to minor damage as far as Bangkok, surface ruptures and sinkholes collapse in the epicentral area. 3 additional seismic stations were thus installed in the vicinity of the dam, which recorded 134 events of magnitude larger than 2.0 during the 1985-1990 period, mainly located in the area of the 1983 main shock. As for the Khao Laem dam, the earthquake parameters (b-value, mainshock / aftershock magnitude ratio, foreshock / aftershock occurrence pattern) are typical of a reservoir induced seismicity, while the consistency of the focal mechanisms with the tectonic setting suggests that the loading due to reservoir filling, together with the increase in pore pressure, allowed the stresses to reach critical values in an ***already highly stressed*** area. In addition, it appears from the 7-year observation period that the post-impoundment seismicity is not simply related with water level fluctuations.

ISSUES FOR DISCUSSION

Although most of the presented papers do have a geographical connotation because of the case studies they report on, they rise a few general questions that may benefit from being clearly explicited and discussed:

i) There exist significant differences in results obtained with probabilistic, general purpose zoning studies, which generaly conclude in pga values of at most a few tenths of g, and more detailed, site-specific design studies, which lead to much higher values (here up to 1.6 g for New Madrid rock sites). Where do such discrepancies come from? Is the broad seismotectonic zoning needed in general purpose studies over large areas, too broad? And therefore, what is the significance of such large size zoning studies for the design of specific structures in a specific site?

ii) In connection with the previous opposition, general purpose zoning studies generally emphasize the effects of regional, large-size events, while site-specific studies may, as is the case for the northern California site of paper 9.10, draw attention on local, moderate-size (M 5) events. Is that an artefact due to the sole use of pga as design parameter, or does it correspond to reality? Damage in San Salvador in 1986 (M=5.4, local event) or in Agadir in 1960 support the latter, at least for zones of diffuse seismicity, and for short period structures. Alternatively, strong motion duration should certainly, because of its effect on the weakening or failure mechanisms of structures, be addressed and characterized more carefully in zoning and site-specific design studies.

iii) The recent damaging earthquakes (Michoacan, 1985; Armenia, 1988; Loma Prieta, 1989) certainly renewed the interest for site effects and for microzoning studies, and almost half of the session papers do study or mention their importance. A lot of effort are - very rightly - devoted to analyse and predict the response of surficial soft soils, as witnessed by the numerous dedicated networks in various parts of the world, and the large number of participants to the blind prediction experiments carried under the joint auspices of IAEE and IASPEI. Among the questions that are arising from those data, one may mention the reported frequency dependence of damping in soft sediments, and its consequences as to the physical origin of f_{max}, as well as the actual, in situ importance of non-linear, strain dependent behaviour compared with lab measurements; in addition, Nasu's observations suggest that the variability of multidimensional diffraction effects on "dipping layers" with respect to azimutal incidence should be more carefully investigated.

Much fewer studies have been carried out, however, as regards surface topography effects, though they have been proved large to very large in a number of cases. The existence of unexplained, significant site effects on rock for some particular stations of the Guerrero array calls once again for more dedicated theoretical and instrumental investigations on this topic, which may be of critical importance in mountainous areas, as is the case of many seismic zones.

iv) The advent of high quality digital accelerograph networks, such as the Guerrero one, will no doubt bring many significant advancements as to the understanding of ground motion characteristics, and their prediction for future earthquakes. These networks, together with the dense "robust, old technology" networks now installed in various seismic parts of the world, will produce in the coming years an enormous number of strong motion data. A proper management of such a data flow in order to maximize the benefits from such networks for the whole community (*i.e.*, not limited to scientists and engineers, but including the inhabitants of seismic areas) require new data dissemination media, such as CD-ROMs, and probably also a better coordination and gathering in a few world data centers. From another point of view, all these networks generally lack appropriate geotechnical informations concerning the recording sites: for already existing networks, significant improvements will probably come more from such geotechnical investigations than from their spatial densification.

v) Finally, concerning reservoir triggered seismicity, the main question still remains unanswered: in which conditions (tectonics, hydrogeology, ...) will a "likely candidate" artificial reservoir effectively induce a significant seismicity ? How far from the reservoir, and how long after the impoundment can such induced events show up ? Responding such questions is probably highly connected with earthquake prediction problems, and seems still far out of reach.