Inconclusive Case Histories in Earthquake Geotechnics From Christchurch

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INCONCLUSIVE CASE HISTORIES IN EARTHQUAKE GEOTECHNICS FROM CHRISTCHURCH

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ABSTRACT

It is argued that there is still a need for further exploratory research to unravel the ultimate causes of unresolved case histories (especially those involving failures) in geotechnical earthquake engineering. Three specific examples motivated from the records of the four major seismic episodes that shook the city of Christchurch, New Zealand, in 2010 and 2011 are presented in detail. Peculiarities in these records call for an investigation of a number of plausible seismological and geotechnical contributing factors including source mechanics, forward-rupture directivity, 1Dsoil amplification, soil liquefaction, 2D basin amplification, and topographic aggravation.

1. INTRODUCTION

The study of case histories and especially the investigation of failures have always been at the heart of geotechnical engineering. A strong tradition has developed over the years in recognizing, documenting, and interpreting field observations, in order to ultimately judge the adequacy of the design methods and, most often, to propose improved theories and techniques.

In *seismic* geotechnical (as well as structural) engineering, observations of performance after a strong earthquake have largely shaped the profession and prompted scientific research. Collecting and assimilating data from case histories has even led in some cases to devising empirical charts to be readily applicable in practice. A famous example : the liquefaction chart pioneered by the late H.B. Seed[1] after recovering and compiling data from a large number of historic earthquakes with either incidents or no-incidents of liquefaction; and analyzing them using a simplified theory (essentially Newton's second law).

Every major earthquake, especially in the last 25 years, has either taught the engineering and seismological community something new, or at least reinforced the understanding of phenomena already known or suspected. Examples : Mexico 1985, Armenia 1988, Northridge 1994, Kobe 1995, Kocaeli 1999, Düzce 1999, Chi-Chi 1999, Athens 1999, Tokachi-oki 2003, Niigata-ken Chuetsu 2004, L'Aquila 2008, Chile 2009, Christchurch 2010, 2011 — just to name some of the most significant events of the last 20 years.

One of the prominent recent events that literally boosted the advance of earthquake engineering was undoubtedly the Kobe 1995 earthquake in Japan. Just a few of the significant phenomena that were unveiled (or at least elucidated) by the Kobe investigations, and some new empirical and analytical procedures that emerged from the respective case history studies are listed below, as an indication of the wealth of new findings :

- forward–rupture directivity effects on fault–normal ground motions
- interaction of emerging rupturing fault with simple structures
- occurrence of liquefaction of gravelly soils
- lateral spreading originating from soil liquefaction
- effect of various soil improvement techniques on avoiding ground failure despite extreme ground shaking
- response of quaywall retaining systems on deformable ground, undergoing large (finite) deformations
- large caisson bridge foundations acting as bulkheads against laterally–spreading ground
- pile foundations of buildings and bridges damaged by soil ("flow") displacements
- different behavior of quaywalls and breakwaters

- building and bridge damage due to pile cracking
- collapse of cut-and-cover subway station in soil (first ever in history).
- grain-crushing induced "violent" landslides.

and so on. Similarly abundant were the unprecedented phenomena in the Kocaeli and Düzce-Bolu earthquakes of 1999 in Turkey: conspicuous "fling" effects in the ground motions; large permanent rotations and toppling of otherwise undamaged buildings on mat foundations failing in bearing-capacity; collapse of a major twin tunnel; and numerous episodes of interaction of the emerging fault rupture with buildings, retaining walls, mosques, industrial facilities, high-voltage pylons.

Eleven years later than Kocaeli, in September of 2010, and again in 2011 (three times), the city of Christchurch in New Zealand suffered the effects of three (completely unexpected) earthquakes. The lessons from these events are yet to be fully comprehended, but several case histories of significant geotechnical–seismological interest await further investigation.

As a result of the importance that the scientific /engineering community places on case histories, and especially on the analysis of failures, numerous publications in journals, conferences, and books have been devoted to the topic. The series of seven international conferences organized by Shamsher Prakash (from 1992 to 2013) and devoted exclusively on "Case Histories in Geotechnical Engineering" is a landmark of the world-wide interest on the subject. I also mention here the two recent books *"Geomechanics of Failures"* (one using simple fundamental analysis, and one using advanced methods) by Puzrin, Alonso, & Pinyol (2010)[2,3]; the earlier seminal publication by the late G.A. Leonards (1982)[4] on *"Investigation of Failures"* in which he made a plea for the creation of a Center for Investigating Failures; and of course, in earthquake engineering, the numerous specialty–sessions in conferences, and whole issues in Journals, devoted to case histories in geotechnical topics. Prominent in the latter category are: the Special Issue in 1996 of the Japanese Journal *Soils and Foundations*[5] presenting preliminary analyses of a vast number of failure case histories from the Kobe 1995 earthquake; and the Special Issue in 2000 of the EERI journal *Earthquake Spectra*[6] documenting and analyzing (mostly on an exploratory basis) recorded motions, failures and successes from the Kocaeli 1999 earthquake. Sometimes a single but quite unique case history has attracted the attention and the systematic efforts of numerous researchers over many years. Example: the predicament of the *Tower of Pisa* and its salvation by means of "soil extraction". (Reference is made to the comprehensive 4-volume collective publication: *"La Torre Restituta"*, sponsored by the Italian Ministry of Culture, 2005 [7] , and to a number of articles by Jamiolkovski, Burland, Vigiani.

Needless to say, the importance of analysing failures is also widely accepted in other branches of engineering as an invaluable means of improving engineering science and practice. As Petroski (1998) wrote in his book Design Paradigms: Case Histories of Error and Judgment in Engineering [8] :

> *"The concept of failure is central to the design process, and it is by thinking in terms of obviating failure that successful designs are achieved"*.

It is also worth mentioning the international fully-dedicated journal *Engineering Analysis of Failure* which covers a broad range of engineering disciplines.

2. REASONS FOR FURTHER INVESTIGATION OF SEISMIC CASE HISTORIES

Despite the past huge effort in publishing analyses of case histories in geotechnical earthquake engineering, the need for continuing the effort has not diminished. In fact, it will be argued that there are three major reasons that make such analyses even more significant today:

(a) Just in the last five years, several earthquakes around the globe have offered fascinating cases of failure, damage, and unexpected success, many of which the engineering research community has hardly touched upon as yet. Valuable lessons, some of them unique, some reinforcing prevailing paradigms, some suggesting modifications of current methods, are beginning to emerge in earthquake events such as : Niigata-ken Chuetsu (2004), Niigata-ken Chuetsu-oki (2007), Wenchuan (2008), Chile (2010), Christchurch (2010, 2011), Tohoku (2011). It is significant that such lessons be brought to light and subjected to the scrutiny of modern analysis. Of course, older events offer many cases that have not been explored yet; or are still controversial. These also belong to this category of new case histories.

(b) Re-analysis at depth of already studied (often on an exploratory basis) cases of damage and failure is essential. Why (such a re-analysis) ? (i) Because more advanced and reliable computational tools are now readily available; (ii) because the understanding of ground motions (that may have been only casually assumed in past studies) has improved substantially, allowing a realistic assessment of ground excitation; and (iii) because in past studies lack of resources might have often precluded a most thorough and complete knowledge of soil profile and properties. An additional soil investigation (e.g., using new-generation portable in-situ testing devises) would reduce the uncertainty on soil characteristics. Thus, improved modelling of problem mechanics, better definition of seismic excitation, and updated knowledge of the soil will facilitate a far more realistic assessment of the mechanics of failure than has hitherto been possible.

(c) In the last decade an unprecedented number of high-quality accelerograms have been recorded which allow the quantitative study of phenomena that have been thus far only qualitatively or theoretically known. Among others, I distinguish two examples: (i) The four recent seismic episodes that shook Christchurch, N.Z., gave about 10 or more acceleration records each (i.e., a total of about 50) on top of soil that fully or partially liquefied. Geotechnical-structural facilities next to some of the recording stations experienced ground displacement–induced distress. Scrutiny of the records with advanced effective-stress analysis methods, and assessment of the performance of the nearby facilities is certainly of significance. (ii) The 2003 Tokachi-oki, Japan, earthquake was not only recorded by hundreds of strong motion instruments, but each recording station included a pair of instruments: one on the ground surface and one at depth in rock or very stiff formation (depths ranging up to 400 m!). Evidently, such records offer a novel opportunity for studies on "soil amplification" and response of geotechnical systems (as further explained later on), let alone the potential to analyse the performance of nearby structures /foundations which were observed or monitored during the earthquake.

In the last 60 years the profession has identified and successfully faced numerous phenomena associated with the seismic performance of soils and soil-structure systems. To this end, empirical, theoretical, and experimental techniques and procedures have been developed. These procedures range from simplified analysis methods which are based on fundamentals of mechanics and soils, to sophisticated numerical methods which can be used to "realistically" model the geometry and mechanics of the problem.

But just as the clinical trials are indispensable in medicine, in (earthquake) geotechnics testing a theory against observed real (field) performance is a prerequisite to its acceptance. As Terzaghi had stated, a method, no matter how refined it may be, cannot be accepted in engineering unless it has been (repeatedly) validated against reality, i.e. through systematic comparisons of its predictions against field 'trials'. The case histories serve precisely as our full-scale natural trials.

3. EXAMPLES OF INCONCLUSIVE CASE HISTORIES

The following case histories have either not been unequivocally resolved or present difficulties in their interpretation.

3.1 Interpreting the Accelerograms of Christchurch

The city of Christchurch in New Zealand was shaken by four (at least) significant earthquakes:

- M_w 7.1, September 4, 2010
- M_w 6.3, February 22, 2011
- M_w 6.0, June 13, 2011
- M_w 5.9, December 23, 2011.

At least 10 stations recorded the three components of motion in the first two events, and 17 in the last two; these were only the stations located in Christchurch, in its port, Lyttelton, and on the southern hills. Thus, an un-precedented number of strong motion records are available.[9, 10, 11, 12] They are almost invariably true *free-field* records; most of them *must* bear the effects of soil amplification and some of them the effects of liquefaction — whether such effects can be distinguished or not. In general they are very strong for their magnitude. Fig. 1 shows a collection of some of these records and Fig. 2 their corresponding response spectra.

Interestingly, high values of peak acceleration, of the order of 0.40 g or larger, were recorded on top of layers that had clearly liquefied. We mention the CGBS, CCCC, CHHC, REHS, as four such stations where the occurrence of liquefaction was evident.[10, 12]

Several other observations which are not readily explainable in the recorded motions and their Fourier and response spectra are described below:

(a) Most of the strongest records (i.e., records of the February M 6.3 event) contain significant components in the very long period range: 2.5 – 3.5 seconds. This is seen in the form of a hump in the acceleration-response spectra, but it is much more conspicuous in the Fourier and velocity-response (SV) spectra, as shown in Fig. 3. The role of such a hump in the damage of many tall structures in the Christchurch business district (CBD) may have been decisively significant. The question is whether the hump itself is the result of soil amplification, and/or of liquefaction, and/or a product of the source mechanism as mirrored in the frequency content of the incoming seismic waves.

(b) The vertical components of the records are relatively very high. Especially for the February and June events, some of the vertical components had a peak ground acceleration exceeding 1g and in general being larger than the peak values of the two horizontal components. It is presumed that the proximity of the seismogenic faults may have played a role for some of the motions. But the CBD stations were not so close. The mechanism of faulting may have been responsible as well: a mainly-thrust rupture on a plane dipping as much as 70^o to the south. Simple kinematics would have anticipated higher vertical than horizontal components. Perplexing the interpretation is the fact that whereas the two records were on the "moving" block (the so-called "hanging-wall"), many others were located on the "stationary" bock (the "foot-wall"). One could have expected different behavior on the two blocks…Moreover, in some of the cases other phenomena may have contributed. For instance, the Heathcote Valley records of station HVSC are likely to have been influenced by the 2-D geometry of the underlying basin, as will be discussed in the sequel.

(c) The record on the port of Lyttelton, although a nearly rock record (in fact the LPCC station seems to have been installed on top of a 6 m stiff soil underlain with rock) also exhibited a small but perceptible hump in the long period range of 3 – 3.5 sec in the Fourier and SV spectra. One would be forced to believe that the hump is of a seismological (source and/or path effect), since the thin and stiff soil layer, with a fundamental period of less than about 0.1 sec could not have possibly amplified the 3 sec components. Furthermore, this hump was observed in several, if not all the seismic events, not just the strongest (for this station) February event. This remains a mystery.

Attempting to explain through wave-propagation analyses the above observations one runs onto a number of hurdles. First, the soil information is limited. Before the earthquakes essentially only qualitative information for the upper 15 m or so had been available. Subsequently, a field exploration using the Spectral Analysis of Surface Waves was conducted by Wood et al [13] and produced results in the form of V_S versus depth at many seismographic stations. This valuable information was limited down to at most 30 m below the ground surface, and was not accompanied by other soil stiffness/resistance measurements. Unfortunately, the stiff gravelly soil extends well below that depth — perhaps to 300 m or even more [114]. To give a sense of the uncertainties in soil stiffness, we mention the results for the only site with two different in-situ soil measurement: the V_S measured profile, mentioned above, and the SPT profile measured independently. The former shows a monotonically increasing stiffness with depth below the first 1 m; the latter exhibits a dramatic decrease of N values at an organic silt layer 5 – 7 m deep.

A second difficulty refers to the existence of a representative rock outcrop record. The issue was explored in a very recent publication by Van Houtte et al[15]. Trying to determine which of the recording stations on stiff-soil/soft-rock stations could be used as rock-outcrop "reference" sites, they came to the conclusion that most such "rock" stations show their own local amplification effects, and therefore could not be (directly, I add) used as base motions in soil amplification studies. Nevertheless, the LPCC record in the port of Lyttelton can be de-convolved to obtain the "true" rock outcrop motion. From the results of de-convolution it is readily seen that, unsurprisingly, only the low period components of the February record are slightly reduced in the process. The 3 sec hump in the Fourier spectra remains.

However, the critical question is whether this rock motion is a good candidate to describe the base excitation of the CBD stations. For the September M_W7.1 event, both LPCC and the CBD stations (as well as HVSC) are about 20 km east of the presumed edge of the fault. So the approximate consideration of LPCC's relevance as a surrogate rock excitation may be justified. However, in the February M_W 6.3 event LPCC and the CBD stations were located on opposite sides of the seismogenic fault. Could the LPCC-deconvolved motion still be a good choice for rock motion ?

In any case, assuming that the answer is positive, several soil amplification analyses have been conducted to post-determine the ground motions in the four stations of Christchurch: CGBS, CCCC, CHHC, REHS. Two hypotheses were made for the soil profile: (i) that it only comprises the 15 – 30 m of (top) alluvial soil for which the shear velocity is available; (ii) that the above profile is underlain by about 300 m of dense soil, the velocity of which reaches progressively 700 m/s. Total-stress and effective-stress analyses — equivalent-linear and inelastic, respectively. The results are not particularly encouraging. With one single exception, the computed for the surface response spectra do not reasonably match the recorded spectra. Varying parametrically the stiffness of the stiff gravelly layer one may achieve better accord in one end of the period range, but at the expense of worsening the fit in the other end of the range.

In conclusion, the Christchurch records, many on top of repeatedly-liquefied soil, and recorded in at-least four earthquake episodes, offer a unique challenge in earthquake geotechnics. The data available so far cannot lead to convincing answers.

3.2 Heathcote-Valley Accelerograms: Seismological or 2-D Basin Effects ?

The Heathcote Valley in the southern tip of Christchurch experienced very strong shaking (recorded on HVSC) in all four events — the strongest each time of all the recorded motions, with only one exception (to be discussed below). In the February M_w6.3 earthquake, in particular, whose epicenter was located very close to the station, the peak ground accelerations in all three components exceeded 1g (two components reached even 1.5 g). These peaks were not just isolated spikes, but they had a characteristic period of about 0.3 sec. Moreover, the corresponding acceleration response spectra exhibited a distinctive $S_A \approx 2$ g plateau in the period range $0.5 < T$ (s) < 0.85, approximately, with associated peaks of $S_V \approx 220$ cm/s and $S_D \approx 30$ cm.

Remarkably, but unsurprisingly, the M_w 6.0 June event, having also originated in the "neighborhood" of HVSC, produced a peak ground acceleration of about 1.15 g, with similar frequency characteristics to those of the February records.

The valley topography suggests that basin effects may have contributed to the intensity of shaking which was recorded a mere 10–15 m from the edge of the nearly 150 m wide valley. The depth to rock at the station is about 17 m, as inferred from the surface wave measurement campaign of Wood et al [10]. Interestingly, 50 m from the seismographic station there exists an 8m-high open sub-vertical excavation in (apparently) over-consolidated clay; this has allowed a first glimpse on the nature and strength of the soil. The afore-mentioned SASW measurements[10] revealed indeed a stiff soil layer with a wave velocity of about 370 m/s, with a near-surface crust 4 m thick of 270 m/s. This is clearly a very stiff profile (elastic fundamental period of about 0.2–0.3 sec). The mountain rock outcrop shows that the (inclined) base rock is of volcanic nature.

This will be an excellent case history for assessing the importance of 2-D wave propagation effects in shallow basins, under very strong excitation.

However, the February earthquake originated at a fault dipping to the south–southeast directly underneath the Heathcote Valley. Given the mainly-thrusting style of the rupture, this implies that HVSC is located on the hanging-wall, and may likely have been subjected to pernicious *forward rupture directivity* effects. So the question to be answered is whether the motions in HVSC were a product of 2D soil amplification, of source and directivity effects, or both; and to what extent. Note that June M_w 6.0 event had a fault also under the Heathcote Valley, although its orientation was at odds with that of the February earthquake.

A more detailed geotechnical soil exploration, a better understanding of the source mechanism(s), and a calibrated analysis are needed for explaining the "ultimate" causes of these enormous ground motions.

3.3 Amazing Accelerograms of the M_w6 June-13 Event

We have already mentioned this earthquake which occurred on a fault nearly perpendicular to the fault of the February event. Its projected trace on the ground surface passed through the hilly southeastern suburbs of Christchurch. On two of these hills accelerographs (GODS, PARS) had been installed after the February earthquake, guided by the migration of the aftershocks in that direction. To my knowledge, at least one of these hills had already suffered considerable landslides in the two earlier earthquakes.

The strongest components of each of the two accelerograms and their response spectra are shown in Fig. 4. It turns out that these (strongest) components were nearly perpendicular to the fault ! In addition to their huge peak ground accelerations (1.86 g of GODS and 0.70 g of PARS), the spectral shapes of the two motions are very similar, exhibiting a large and broad peak at 1±0.25 seconds. This similarity points at *forward rupture directivity* as one of the possible contributing factors for the size and breadth of the response spectra peaks. This however is far beyond the experience accumulated so far on the consequences of directivity, especially from earthquakes of the relatively-small magnitude (M 6) of this one. Might the hills have (also) contributed by means of their *topography* ? And in any case, what were the consequences of these extremely large ground motions ?
Clearly this is one of the most intriguing unresolved case histories from the Canterbury–Christchurch sequence of earthquakes.

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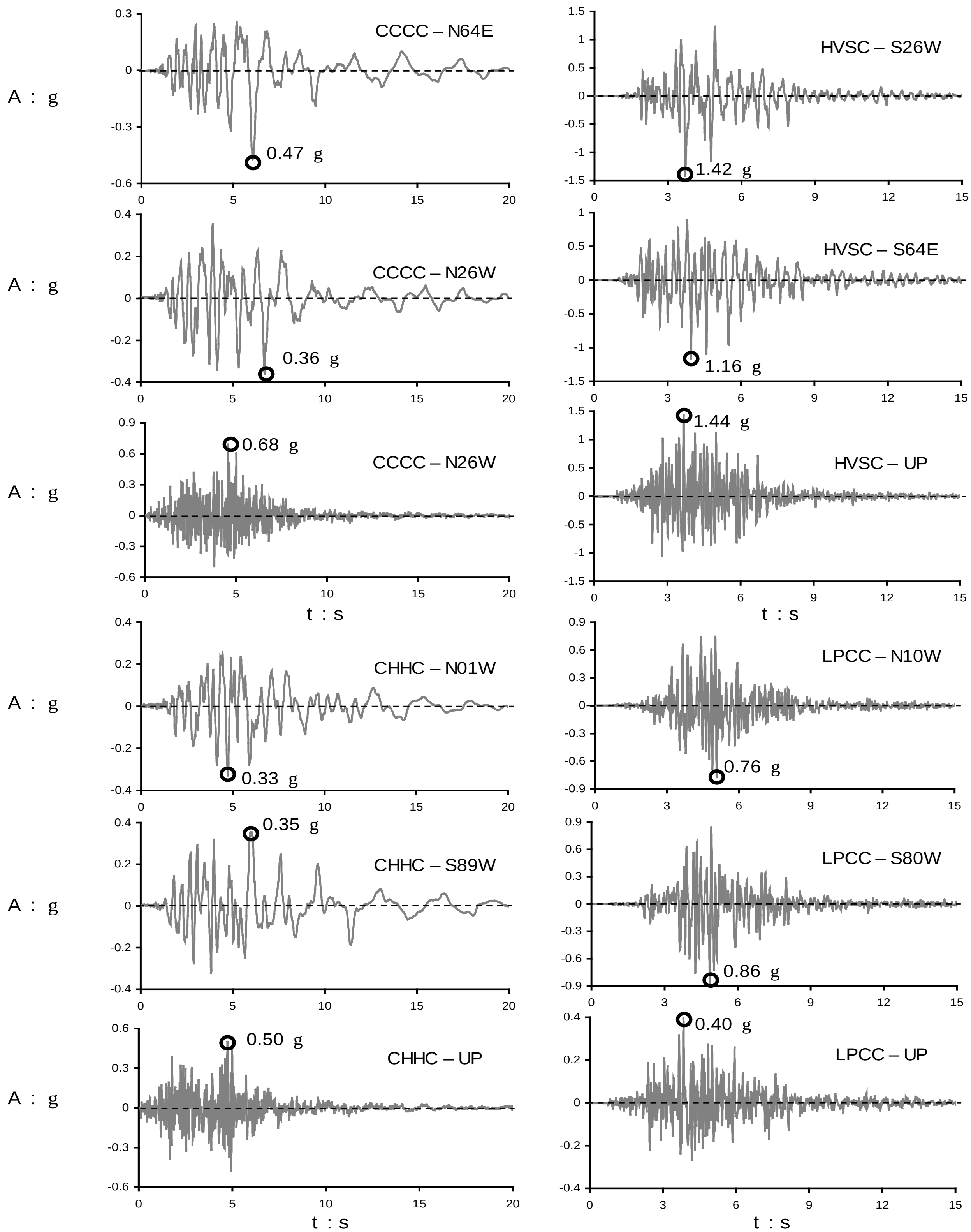

Fig.1 : Acceleration time histories of four selected records obtained from the NGS strong motion database.

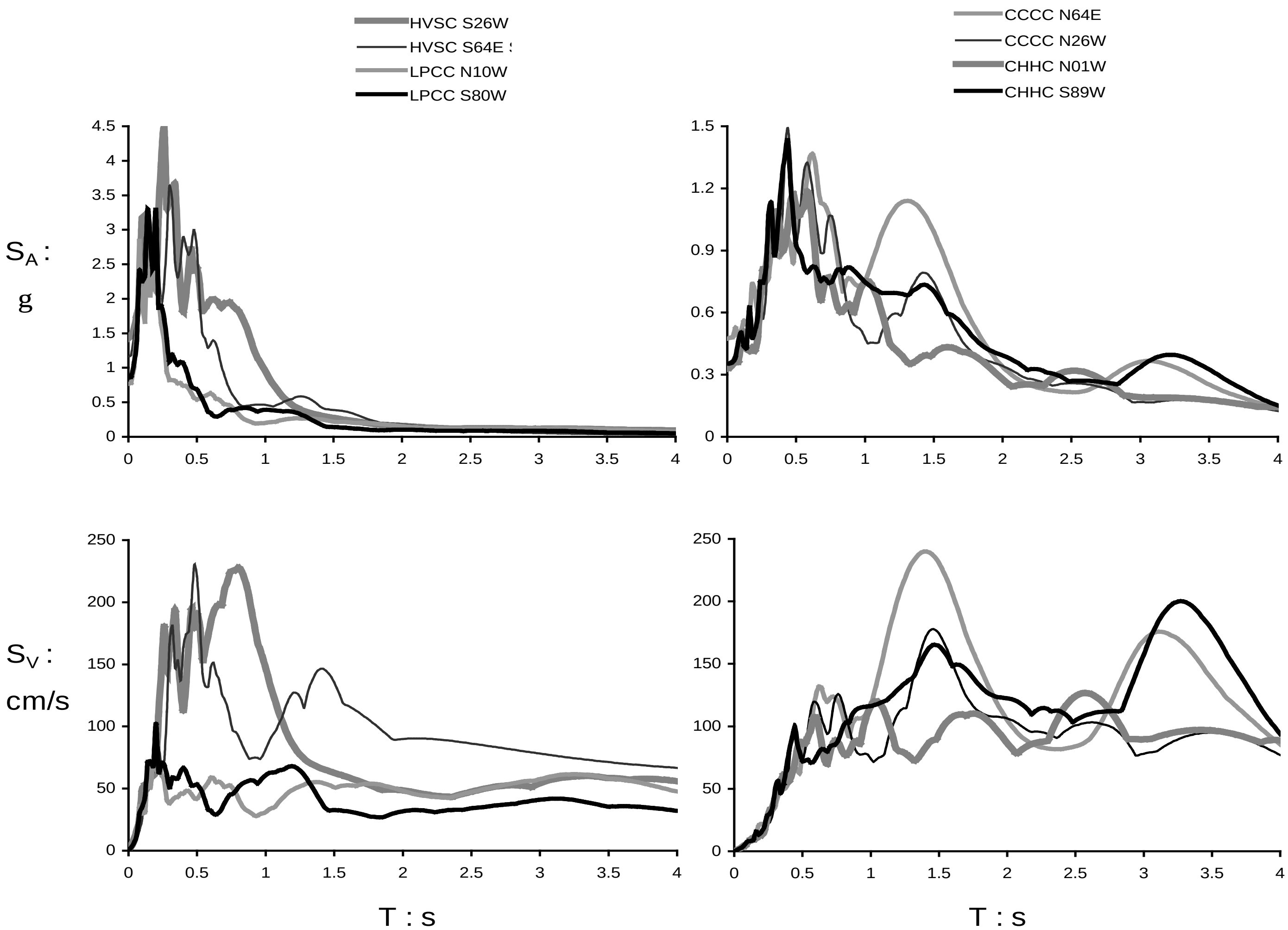

Fig. 2 : Elastic acceleration, and velocity spectra of the horizontal components of the recorded motions (5% damping).

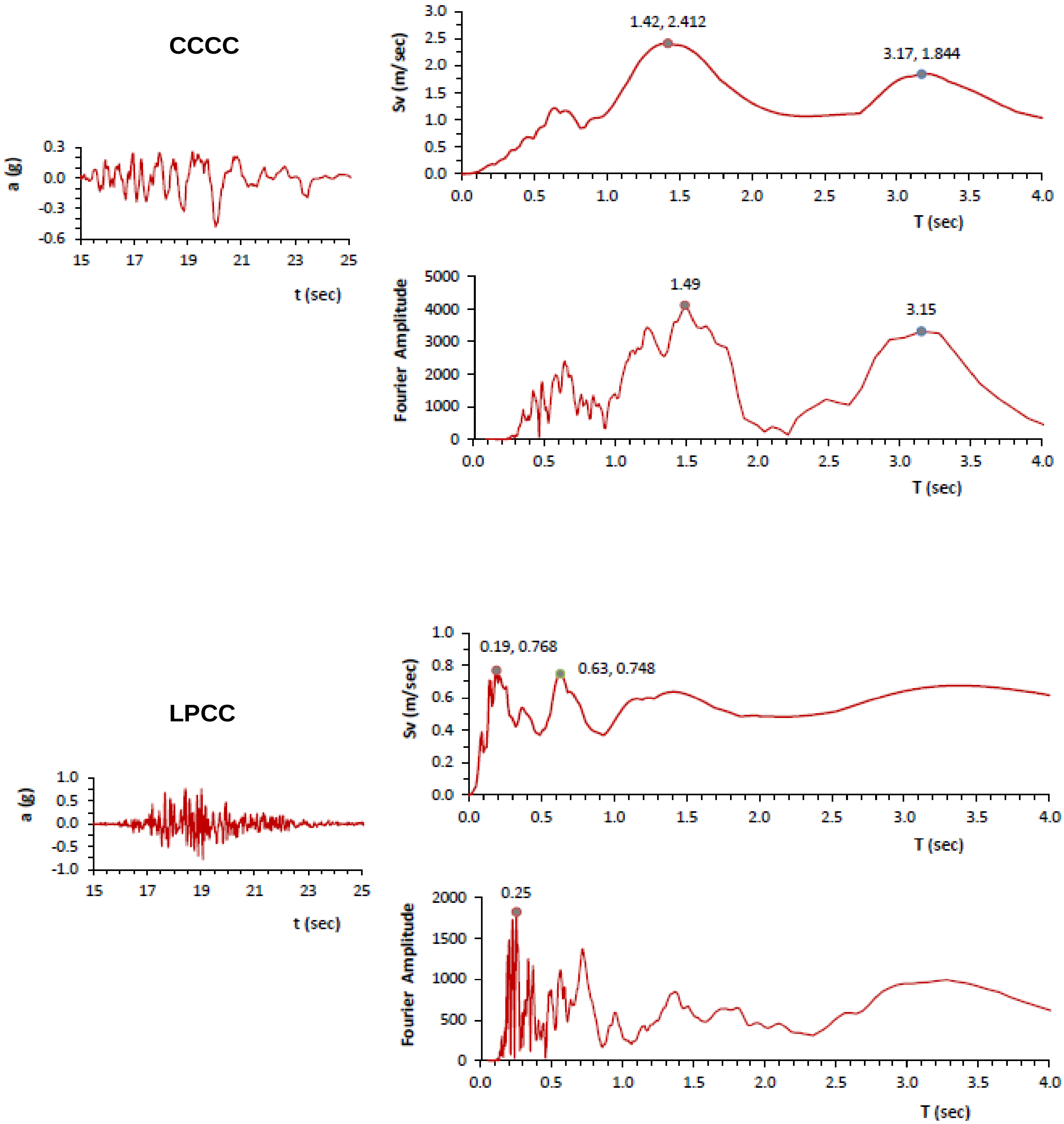

Fig. 3 : Velocity response and Fourier amplitude spectra for the CCCC and LPCC records.

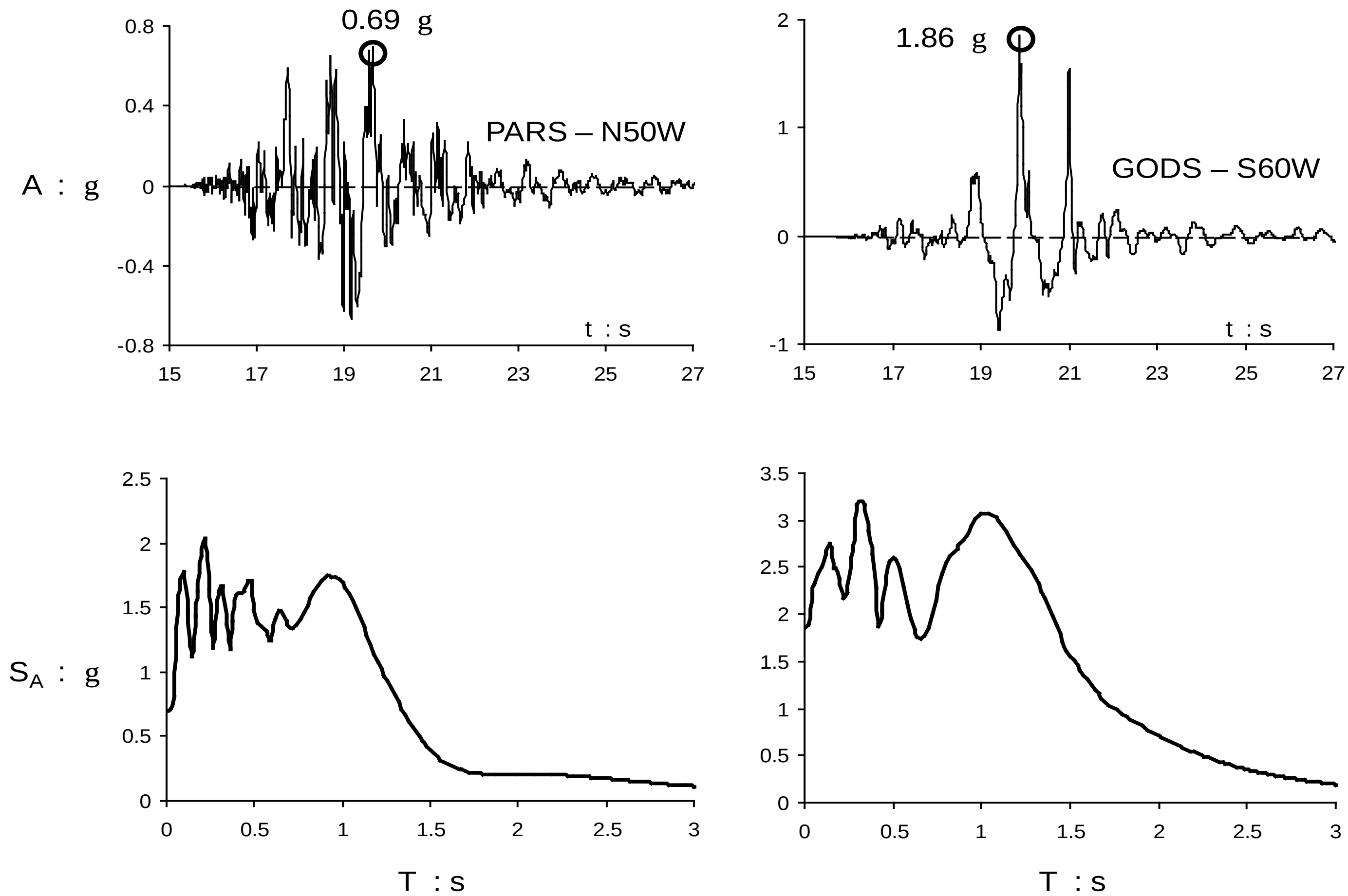

Fig. 4 : Acceleration time histories of the GODS and PARS records and their corresponding response spectra.