# 3D numerical simulation of the Site-City Interaction during the 22 February 2011 $M_W$ 6.2 Christchurch earthquake

**R. Guidotti & I. Mazzieri**
*Politecnico di Milano, Italy*

**M. Stupazzini**
*Munich RE - Geo Risk, Munich, Germany*

**P. Dagna**
*CILEA, Segrate, Milan, Italy*

**SUMMARY**
The impressive chain of catastrophic earthquakes occurred worldwide during last years, revealed the extreme fragility of modern society. Together with an inexorable urbanization growth, an increasing need of a resilient and safe society is clearly perceived and turns out to be a challenge of paramount importance. Our recent findings in 3D numerical modelling of the Christchurch earthquake allowed the evaluation of the typically multi-scale wave propagation problem in its complexity, from far-field to near-field and from near-field to soil-structure interaction effects. Considering densely populated urban environments like the Christchurch Central Business District, hints on the issues related to site-city interaction effect are given, trying to capture its characteristics that could lead to scenarios different from the free field one, and could shed light, not only on the site-effect, but also on the distribution of damage in apparently homogenous areas, features that could play a crucial social and economic role.

*Keywords: Seismic Wave propagation, Site-City interaction effect, Non-conforming approximation.*

## 1. INTRODUCTION

Even if earthquake engineering, and all the related research fields, tackle efficiently the challenge of earthquake catastrophes, the impressive chain of disastrous earthquakes occurred worldwide during last years from Chile (Maule, $M_W$ 8.8), to Japan (Tohoku $M_W$ 9.0) and New Zealand (Darfield $M_W$ 7.1, Christchurch $M_W$ 6.2), revealed the extreme fragility of modern society. Together with an inexorable urbanization growth, an increasing need of a resilient and safe society is clearly perceived and turns out to be a challenge of paramount importance. To this end, a key point is a reliable seismic risk evaluation, based on a trustable assessment of earthquake-induced damage and loss.

While the variability of strong ground motion is widely studied by many scientists both at large scale with regional models having width and depth of several kilometres, and at a small scale, considering the earthquake effect on single buildings, relatively few models have been done at the medium scale, considering the interaction between the topography and the characteristics of the soil and complex geometry of foundations and buildings of a city. In the literature it is called “Site-City interaction”. In the present contribution, thanks to new numerical advancements and non-conforming approaches, the multi-scale wave propagation problem is fully assessed referring to the 22 February 2011 $M_W$ 6.2 Christchurch earthquake, from the regional scale of the Canterbury Plains in the Southern Island of New Zealand to the urban scale of the Christchurch Central Business District (CBD) (see Fig. 1.1).

The presented case-study aims to evaluate, at the same time, the seismic response of a pounding-prone compound of buildings and the effect of a densely urbanized area in the spatial variability of strong ground motion, trying to explain the observed damage variability in apparently homogeneous areas. Looking at the variability of surface earthquake ground motion through snapshots of the velocity and displacement wave-field, it is possible to observe the active role played by the buildings cluster, in substantial agreement with the words of Trifunac (2009): “In an urban setting, a distribution of buildings will act as an extended surface source area consisting of a large number of closely spaced sources of translational and rotational motions, which will cause the warping of the half-space surface in the near-field and a seemingly random distribution of strong, high-frequency surface waves in the far field".

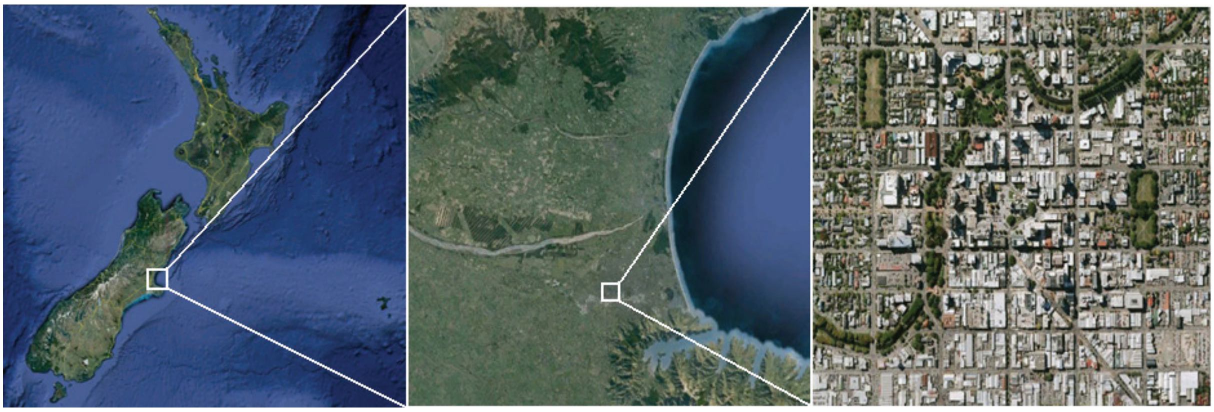

**Figure 1.1.** Multi-scale wave propagation problem studied, from the regional scale of the Canterbury Plains in the Southern Island of New Zealand up to the urban scale of the Christchurch CBD (from Google Earth).

## 2. SITE-CITY INTERACTION EFFECT

In this paper, the variability of the strong motion is studied at a site-city scale, a scale studied by relatively few authors, compared to the large, regional scale of alluvial basins and to the small scale of a single structure. The adopted scale seems to be the most suitable for a proper assessment of structural damages and allows a detailed study of the seismic wave propagation and amplification. Indeed, a densely urbanized area located in an alluvial basin could influence the seismic wave field, both in a passive way, as the buildings and their foundations are obstacles to the seismic wave front, and actively, acting as an extended surface source area consisting of a large number of closely spaced sources of translational and rotational motions (Trifunac 2009).

Site-effect, the phenomenon of amplification of seismic waves in a free field in an alluvial basins, has been widely studied in recent years, distinguishing stratigraphic effects due to the impedance difference between soil layers, and topographic effects, that could scatter or focus the wave field (e.g. Bouchon 1973, Bard and Bouchon 1985, Bielak et al. 1999, Paolucci 2002, Semblat 2002). The issue of the potential influence of a city on the seismic response of an alluvial basin was considered especially after the 1985 Michoacan earthquake in Mexico, where extremely high strong motion amplification were recorded in a densely urbanized area, suggesting that a cluster of buildings could modify the ground motion during an earthquake.

Early studies and applications of the so called site-city interaction are presented by Semblat et al. (2008) and mainly rely on one- or two-dimensional models. This, on one hand, simplified the understanding of this phenomenon, but, on the other hand, strongly limited the description of the mutual and simultaneous action of a cluster of buildings in the strong motion variability. It could be assessed by three-dimensional modelling of this multi-scale problem. Nevertheless, a proper model of the city and of the basin requires a remarkable computational burden that has long limited its wide applicability. Studies of Taborda (2010) and Taborda and Bielak (2011), on full three-dimensional integration of site-city interaction effects in earthquake simulations, relying on an artificial inventory of buildings, indicate that the presence of the urbanized area considerably changes the ground motion in the city and in its neighbourhood, observing significant modifications in the spatial variability of the ground motion.

## 3. NON-CONFORMING MESHING APPROACH

Numerical approaches, mainly relying on Finite Difference, Finite Element or Spectral Element methods, imply a heavy computational burden and technical resources. This, together with the intrinsic difficulties in the generation of three-dimensional unstructured hexahedral meshes, has long limited their wide applicability, as stated in the previous section. On the other side, the presented case-study, points out that the site-city interaction and its dependence on the spatial variability of the ground motion, are strongly affected by three-dimensional site effects, that cannot be neglected.

In this section we introduce a new software, namely SPEED (SPectral Elements in Elastodynamics with Discontinuous Galerkin), under development at Politecnico di Milano. Relying on "non-conforming" techniques (Mazzieri et al. 2011, Antonietti et al. 2012), like Discontinuous Galerkin Spectral Element Method, SPEED allows us to use different spectral approximation degrees as well as different mesh sizes within different sub-domains (see Fig. 3.1). Removing the constraint that element faces should have the same shape and size in the contact regions, non-conforming techniques can accommodate discontinuities not only in the mechanical parameters but also in the wave field. This is particularly useful in seismic engineering modelling of wave propagation, whenever the passage between different sub-domains (soft alluvial soil, stiff bedrock, structural elements, …) requires a sharp change of mechanical properties (in terms, i.e., of shear wave velocity and density) and therefore a sharp change in the size of the elements of the mesh.

It is then possible to adopt a high order polynomial basis on a wider mesh with a lower number of elements in the bedrock, and low order polynomial approximation on a finer and deeper refinement mesh only in specified areas. Furthermore the hexahedral elements are characterized by a better level of the quality metric, with a considerable reduction of the time needed to perform the mesh and the analysis. The possibility to nimbly vary the mesh element size and the polynomial approximation degree, with the only constraint being a proper wave propagation, offers thus the possibility to more efficiently tackle the wave propagation problem from different scales, from the far-field to the near-field, from the near-field to the site-city and soil-structure interaction effect, reducing the overall computational burden of the problem.

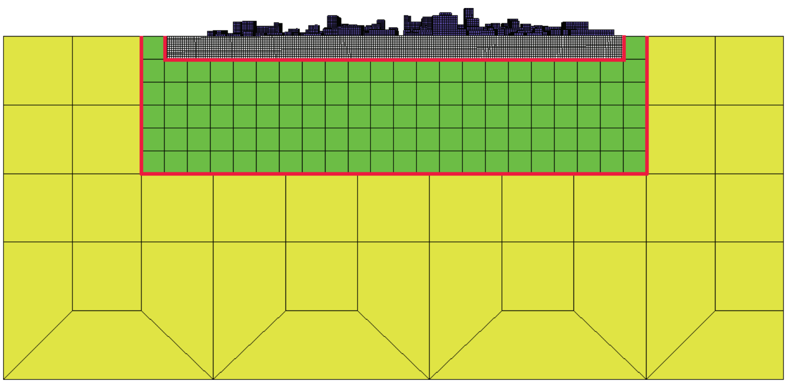

**Figure 3.1.** Sketch of the non-conforming meshing strategy: different mesh sizes are adopted within different sub-domains.

## 4. 3D NUMERICAL MODEL OF THE CANTERBURY PLAINS

In a little more than one year, between September 2010 and December 2011 the Canterbury Plains and particularly the city of Christchurch, in the South Island of New Zealand, experienced four major earthquakes with $M_W \geq 6.0$ and a huge number of aftershocks (Gledhill et al. 2011).The most damaging and deadliest of the seismic sequence, a $M_W$ 6.2 earthquake, on 22 February 2011, struck the city and the suburbs of Christchurch, causing extensive destruction and more than 180 victims. Among the different aspects that mainly drew the attention of the scientific community on this particular event, it is worth to emphasize: (i) the extremely severe strong ground-shaking observed (Bradley and Cubrinovski, 2011), (ii) the widespread liquefaction phenomena across the city (Cubrinovski et al. 2011) and (iii) the absence of convincing evidence of the system of faults that generated the Canterbury seismic sequence, prior to the September 2010 $M_W$ 7.1 Darfield event (Green et al. 2010).

In this contribution we recall the numerical model constructed for the 22 February 2011 $M_W$ 6.2 Christchurch earthquake, presented and validated in Guidotti et al. (2011) and depicted in Fig. 4.1. The three-dimensional regional model of the Canterbury Plains combines the following features: i) a horizontally layered crustal model, with materials characterized by the mechanical properties listed in Table 4.1; ii) a simplified model for the Cretaceous-Cenozoic alluvial plain, filled with Quaternary deposits, coal, clay, limestone and sand; iii) an accurate description of the transition between the alluvial soft sediments and the rigid volcano materials, inferred from the topography of the volcano; iv) a kinematic finite fault model for the seismic source. The static model, proposed as a press release by the GNS (New Zealand Institute of Geological and Nuclear Sciences) and derived from pre-earthquake and post-earthquake geodetic data using both InSAR and GPS data, has been considered. The kinematic source model has been then obtained turning this static model into a kinematic model by assuming a rupture velocity, rise time and slip origin and making the rake constant, equal to 145°. A value $V_R$ equal to 2400 m/s is assumed as rupture velocity. The slip source time function is given by an approximate Heaviside function, with rise time $\tau$ = 0.9 s, constant across the fault plane. The kinematic source parameters adopted for the GNS model presented in Fig. 4.1 are listed in Table 4.2.

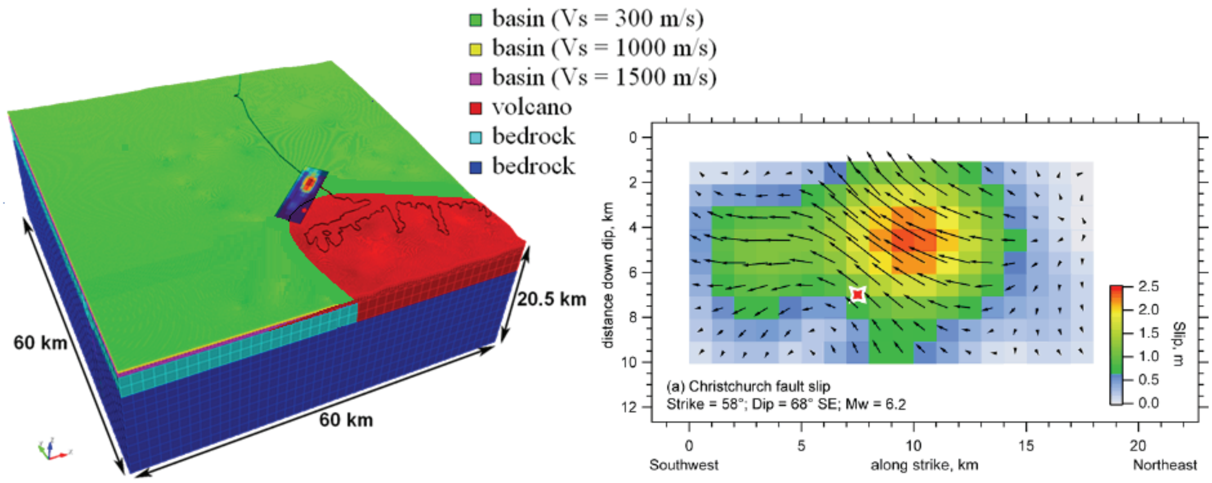


**Figure 4.1.** Three-dimensional regional model of the Canterbury Plains constructed for the 22 February 2011 $M_W$ 6.2 Christchurch earthquake (after Guidotti et al. 2011)with the kinematic seismic source model adopted.

**Table 4.1.** Mechanical properties of the soil profile adopted in the numerical model depicted in Fig. 4.1.

| Layer | Depth [m] | Thickness [m] | $V_P$ [m/s] | $V_S$ [m/s] | ρ [kg/m$^3$] | Q |
|---|---|---|---|---|---|---|
| 1 | 0 - 300 | 300 | 600 | 300 | 1700 | 70 |
| 2 | 300 - 750 | 450 | 1870 | 1000 | 2000 | 100 |
| 3 | 750 - 1500 | 750 | 2800 | 1500 | 2300 | 100 |
| 4 | 0 - 5000 | 5000 | 5500 | 3175 | 2600 | 200 |
| 5 | 1500 - 5000 | 3500 | 5000 | 2890 | 2700 | 200 |
| 6 | 5000 - 20000 | 15000 | 6000 | 3465 | 2700 | 250 |

**Table 4.2.** Kinematic source parameter adopted for the simulation of the 22 February 2011 Christchurch earthquake for the GNS model depicted in Fig. 4.1.

| Hypocenter | L x W | Strike | Dip | Rake | Depth of upper points | $V_R$ | $\tau$ |
|---|---|---|---|---|---|---|---|
| -43.56°N; 172.70°E; -6.47 km | 18 x 9 km | 58° | 68° | 145° | 1 km | 2.4 km/s | 0.9 s |

Numerical simulation of seismic wave propagation within the regional model of the Canterbury Plains were performed through the high performance software package GeoELSE, designed to perform linear and non linear elastic seismic wave propagation analyses in heterogeneous media, relying on the Spectral Element formulation proposed by Faccioli et al. (1997) and exploiting in 3D its implementation in parallel computer architectures. Examples of application of GeoELSE (http://geoelse.stru.polimi.it) to seismic wave propagation studies can be found in Stupazzini et al. (2009) and Smerzini et al. (2011). The three-dimensional numerical model of the Christchurch region includes the city of Christchurch, part of the Canterbury Plains and of the Banks Peninsula, extending from the north-western Alps mountain range to the south-eastern Lyttelton-Akaroa volcanoes, covering an area of about 60x60x20 km. The 3D spatial discretization by spectral elements of the area requires, hence, the design of a large scale unstructured mesh of hexahedral elements. The mesh adopted for the numerical simulation consists of about 500,000 elements, with size ranging from a minimum of about 150 m (at the top of the alluvial basin) up to 1,500 m at bedrock. Considering a spectral degree equal to 4, the mesh is able to propagate up to about 2 Hz. The mesh creation process is performed following the schemes described in Casarotti et al. (2007), exploiting the commercial mesher CUBIT (http://cubit.sandia.gov/), state of the art software in the field of three-dimensional unstructured hexahedral decomposition, incorporating an extensive library of powerful and advanced meshing schemes.

## 5. THE CHRISTCHURCH CENTRAL BUSINESS DISTRICT: RELEVANCE OF SITE-CITY INTERACTION EFFECT IN THE SPATIAL VARIABILITY OF MOTION

In the present application, the Central Business District (CBD), social and economic heart of the city of Christchurch, characterized by a high density of tall buildings, has been modelled and set into the regional model of the Canterbury Plains, described in the previous section. The three-dimensional model of the densely urbanized area of Christchurch allows us to fully consider at a site-city scale the complexity of the strong ground motion. In this way it is possible to evaluate the seismic wave propagation on a pounding-prone compounds of buildings and, at the same time, the effect of a densely urbanized area in the spatial variability of strong ground motion, trying to explain the observed damage variability in apparently homogeneous areas. For that purpose, in this section we integrate the numerical model of the Canterbury Plains with a real inventory of buildings, namely the full set of around 150 buildings that compose the Christchurch CBD, heavily damaged by the 2011 earthquake.

### 5.1. Three-dimensional numerical model of the CBD

In Fig. 5.1, the global model is presented. Details of the meshing process can be found in Guidotti (2012). As a starting point, the real configuration of the CBD has been considered, taking information on height and floor-plan dimensions of the cluster of around 150 buildings, in an area having a dimension of about 1 km x 1 km. Also the foundations for an average depth of 10 m have been considered, and for the soil around foundations, a depth of 50 m has been taken into account. A mesh size of around 5 m leads to around 500,000 hexahedral elements in the CBD. Exploiting the non-conforming approach implemented in SPEED and discussed in Section 3, this mesh has been successively set into the numerical model described in Section 4, allowing the contact between elements having size of around 5 m on one side (CBD model) and 50 m on the other side (Canterbury Plains model).

The resulting model reaches a global number of hexahedral elements of more than one million, requiring a huge level of parallelization, performed on the Lagrange cluster located at CILEA (Consorzio Interuniversitario Lombardo per l'Elaborazione Automatica). Having the hexahedral of the CBD model size of around 5 m, a spectral approximation degree equal to 1, has been adopted in this domain. Therefore, despite adopting twice as many elements, the overall number of LGL nodes is only slightly higher than the numerical model proposed in the previous section. The main characteristics of the models and the performances of the analysis are summarized in Table 5.1. As far as the characteristics of the materials are concerned, no change has been made to the mechanical properties of the Canterbury Plains model listed in Table 4.1, with the soil around the foundations having the same characteristics of the top layer of the previous model, but with a different spectral approximation degree, equal to 1.

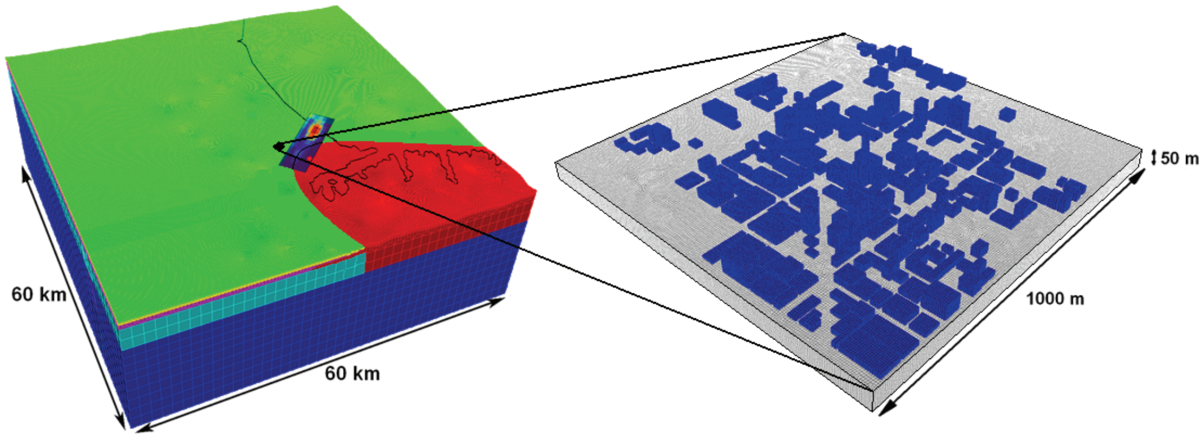


**Figure 5.1.** Global model: the three dimensional model of the Christchurch CBD has been independently meshed with element size around 5 m and set into the model of the Canterbury Plains described in Fig. 4.1.

**Table 5.1.** Size and computational time of the 3D numerical models. Data of CPU time refer to the Lagrange cluster located at CILEA.

| Model | Spectral Degree | Number of Spectral Elements | Number of LGL Nodes | Number of cores | Simulation time |
|---|---|---|---|---|---|
| Canterbury Plains | 4 | 495,385 | ~33.3 $10^6$ | 128 | ~107 h |
| Canterbury Plains + CBD | 4 + 1 | 1,043,364 | ~37.5 $10^6$ | 180 | ~450 h |

The buildings, modelled as homogeneous blocks, could be considered as shear beams, as recalled by different authors (Trifunac 2009, Taborda and Bielak 2011). Their period of vibration could be approximated in two way, as:

$$T = \frac{4h}{V_S}, \tag{5.1}$$

and, analogously, as:

$$T = \frac{N}{10}. \tag{5.2}$$

In Eqn. 5.1, $h$ and $V_S$ are the thickness and the shear velocity of the stratum, and, in Eqn. 5.2, $N$ is the number of stories of the building. Combining this relations, and being the effective height of the first mode of vibration equal to the 70% of the total height of the building ($h$ = 0.7 $H$), equal to $N$ times the interstory height $h_S$ ($H$=$N$ $h_S$), it is possible to obtain (Taborda and Bielak, 2011):

$$V_S = 28 \cdot h_S \tag{5.3}$$

Varying typical interstory height to around 4 m, in the numerical model a value of $V_S$ equal 100 m/s was adopted. A stiffer values was adopted for the foundations, equal to 400 m/s, while $V_P$ = 2.5 $V_S$ has been considered. The density of the buildings material has been considered equal to 300 kg/m$^3$, while a quality factor $Q$, equal to 10, corresponds to a critical damping ratio of 5%. These values are in agreement with values adopted by Taborda and Bielak in their 3D model and with other 2D studies (e.g. Wirgin and Bard 1996, Tsogka and Wirgin 2003).

## 5.2 Results: Peak ground values, strong motion variability and wave passage effect

In order to evaluate the role of the densely urbanized area of the CBD in the wave propagation, Fig. 5.2 shows the peak ground velocity values, retrieved along a direction across the CBD, approximately perpendicular to the wave-field directivity, namely South West-North East (SW-NE), with and without the presence of the buildings. In Fig. 5.3 a comparison between the case without city and city is presented in a comprehensive way using the map of the peak ground velocity (geometric mean of the horizontal components). It is possible to observe that the interactions and the interferences of the buildings and their foundations reduce or amplify the ground motion, considerably increasing the spatial variability of the surface response within the CBD.

Looking at the variability of surface earthquake ground motion, also through snapshots of the velocity wave-field presented in Fig. 5.4, it is possible to observe the active role played by the buildings cluster, in substantial agreement with the words of Trifunac (2009): this urban setting of buildings indeed is not merely an obstacle to the wave propagation field, but plays an active role, acting as an extended surface source area consisting of a large number of closely spaced sources of translational and rotational motions.

Some important hints about the wave passage effect on a pounding-prone compound of buildings, could be inferred looking at the snapshot of the simulated displacement of the buildings and of the wave-field, plotted in Fig. 5.5. The wave passage effect is characterized by a strong ground motion differing from point to point that produces rotational motions at the bases of the buildings that could be in counter phase. It is possible to observe, through the snapshots, the movement of the buildings, that, after few seconds, according to their different height and excitation, are effectively characterized by different movements in counter phase that could determine, in a compound of buildings, noticeable pounding effects.

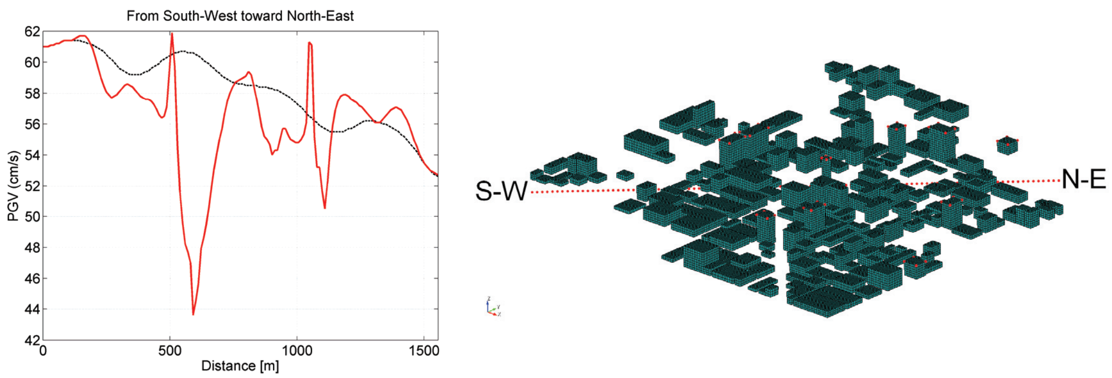


**Figure 5.2.** Peak ground velocity across the CBD along the direction SW-NE, considering (red line) or not (black line) the presence of the cluster of buildings. Distance between monitors (red dots) equal to 10 m.

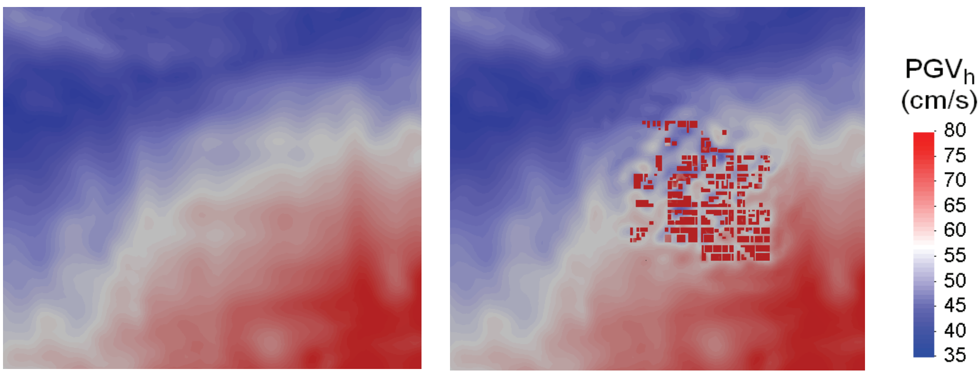


**Figure 5.3.** Spatial variability of Peak Ground Velocity (geometric mean of horizontal components) as estimated by 3D numerical simulations without and with the city.

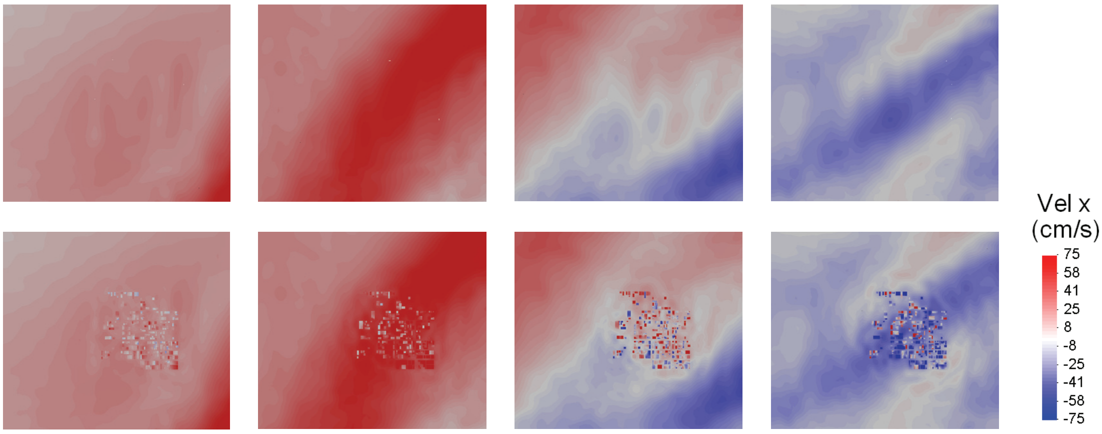


**Figure 5.4.** Snapshots (t = 5.5, 6, 6.5 and 7 s, from left to right) of the simulated velocity wave-field without the city (top) and with the city (bottom).

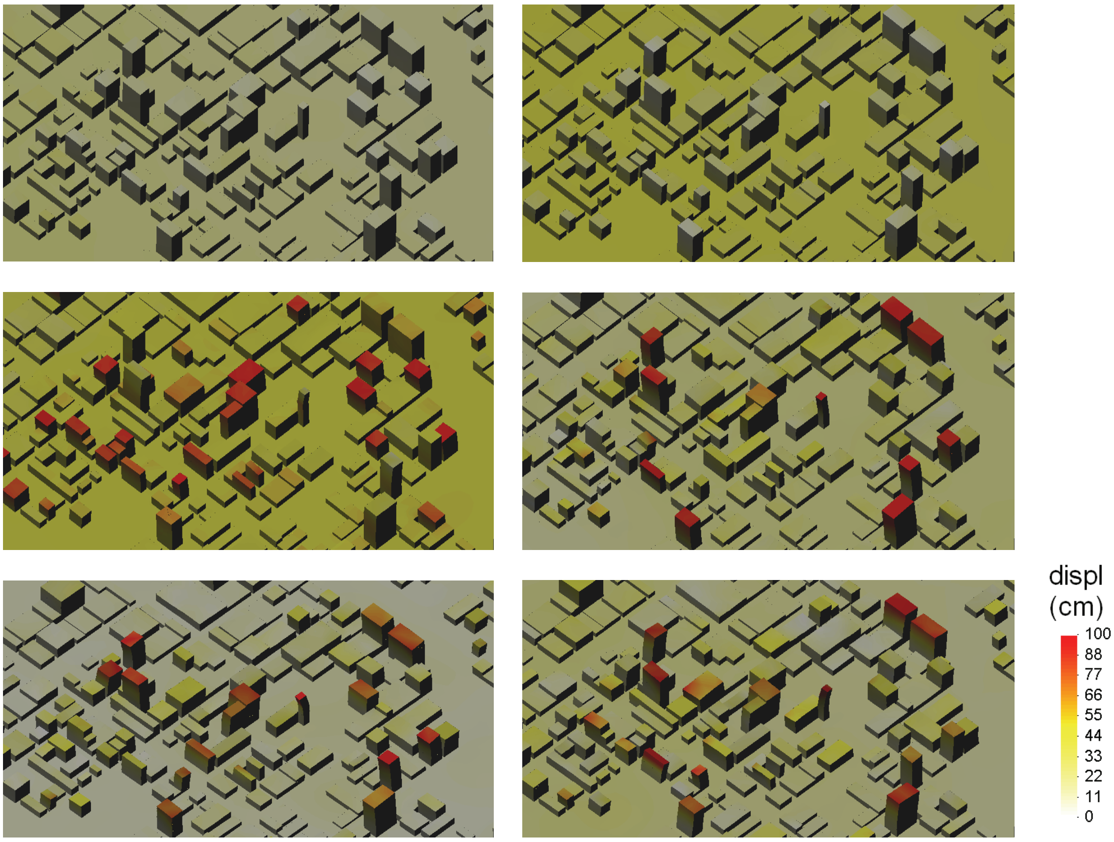


**Figure 5.5.** Snapshots (t = 5, 6, 7, 8, 9 and 10 s, from top to bottom) of the simulated displacement of the buildings of the CBD. Displacements are considered in their absolute values.

## 6. CONCLUDING REMARKS

In this contribution, the CBD, characterized by a high density of tall buildings has been modelled and set into the regional model of the Canterbury Plains, exploiting the recently developed software SPEED. The observation of the results obtained by the three-dimensional model of the densely urbanized area of Christchurch allows us to draw the following conclusions: i) The ground motion inside the city of Christchurch is considerably changed by the presence of the city, this effect is recognized with a set of monitors located through the city; ii) Looking at the spatial variability of the peak ground motion, it is evident that the cluster of buildings plays not only a passive role, but, actively as source area, consisting of a large number of closely spaced sources of translational and rotational motions; iii) The wave passage effect, characterized by a strong ground motion differing from point to point, produce translational and rotational motions at the bases that could be in counter phase and produce high level of damage in pounding-prone compounds of buildings. This can be observed through the snapshot of the displacement of building.

This model, with an element size equal to 5 m inside the city, is naturally suitable to further development, particularly considering a non-linear soil behaviour. The implementation of a model that can reliably represent the complex phenomena of liquefaction, would be of great interest to the city of Christchurch, and could significantly improve the presented results and help to explain, together with the spatial variability of the strong motion, the damage variability in apparently homogeneous areas, as observed in the Christchurch Central Business District. Notwithstanding their low probability, "Christchurch-like" seismic events are not isolated cases. They deserve special attention and form an important element in overall risk management approach. The presented case-study allowed us to draw some conclusions about the role of numerical simulations in seismic hazard assessment studies and about the future development of this topic, fostered by new advancements in numerical and computational fields.

## ACKNOWLEDGEMENT

The authors acknowledge Alberto Castellani, Roberto Paolucci, Chiara Smerzini, Paola Antonietti and Alfio Quarteroni, Politecnico di Milano, for their useful suggestions and fruitful comments. Anselm Smolka, Alexander Allmann and Martin Käser, Munich RE, and Paolo Ramieri, CILEA, are also warmly acknowledged. We deeply thank CRS4, and in particular Fabio Maggio and Luca Massidda, for the essential cooperation in the development of GeoELSE. This work has been supported by Regione Lombardia and CILEA Consortium through a LISA Initiative (Laboratory for Interdisciplinary Advanced Simulation) 2010 grant [http://lisa.cilea.it].

## REFERENCES

Antonietti, P., Mazzieri, I., Quarteroni, A. and Rapetti, F. (2012). Non-conforming high order approximations of the elastodynamics equation. *Computer Methods in Applied Mechanics and Engineering* **209-212**, 212-238.

Bard, P. Y. and Bouchon, M. (1985). The two-dimensional resonance of sediment-filled valleys. *Bulletin of the Seismological Society of America* **75:2**, 519-541.

Bielak, J., Xu, J. and Ghattas, O.(1999). Earthquake ground motion and structural response in alluvial valleys. *Journal of Geotechnical and Geoenvironmental Engineering* **125**, 413-423.

Bouchon, M. (1973). Effects of topography on surface motion. Bulletin *of the Seismological Society of America* **63**, 615-622.

Bradley, B. A. and Cubrinovski, M. (2011). Near-source strong ground motions observed in the 22 February 2011 Christchurch Earthquake. *Seismological Research Letters* **82:6**, 853-865.

Casarotti, E., Stupazzini, M., Lee, S., Komatitsch, D., Piersanti, A. and Tromp, J. (2007). CUBIT and seismic wave propagation based upon the Spectral-Element Method: An advanced unstructured mesher for complex 3D geological media. *Proceedings of the 16$^{th}$ International Meshing Roundtable*, editors M.L. Brewer and D. Marcum, Springer, New York, NY.

Cubrinovski, M., Bray, J. D., Taylor, M., Giorgini, S., Bradley, B., Wotherspoon, L. and Zupan, J. (2011). Soil Liquefaction Effects in the Central Business District during the February 2011 Christchurch Earthquake. *Seismological Research Letters* **82:6**, 893-904.

Faccioli, E., Maggio, F., Paolucci, R. and Quarteroni, A. (1997). 2D and 3D elastic wave propagation by a pseudospectral domain decomposition method. *Journal of Seismology* **1:3**, 237-251.

Gledhill, K., Ristau, J., Reyners, M., Fry, B. and Holden, C. (2011). The Darfield (Canterbury, New Zealand) $M_W$ 7.1 Earthquake of September 2010: A Preliminary Seismological Report. *Seismological Research Letters* **82:3**, 379-386.

Green, A. G., Campbell, F. M., Kaiser, A. E., Dorn, C., Carpentier, S., Doetsch, J. A., Horstmeyer, H., Nobes, D., Campbell, J., Finnemore, M., Jongens, R., Ghisetti, F., Gorman, A. R., Langridge, R. M. and McClymont, A. F. (2010). Seismic reflection images of active faults on New Zealand's South Island. *4$^{th}$ International Conference on Environmental and Engineering Geophysics*. Chengdu, China.

Guidotti, R., Stupazzini, M., Smerzini, C., Paolucci, R. and Ramieri, P. (2011). Numerical Study on the Role of Basin Geometry and Kinematic Seismic Source in 3D Ground Motion Simulation of the 22 February 2011 $M_W$ 6.2 Christchurch Earthquake. *Seismological Research Letters*, **82:6**, 767-782.

Guidotti, R. (2012). Near-field earthquake ground motion rotations and relevance on civil engineering structures. *Ph. D. Thesis*, Politecnico di Milano.

Mazzieri, I., Smerzini, C., Antonietti, P., Rapetti, F., Stupazzini, M., Paolucci, R. and Quarteroni, A. (2011). Non-conforming spectral approximations for the elastic wave equation in heterogeneous media. *Proceedings of COMPDYN 2011 - 3rd International Conference in Computational Methods in Structural Dynamics and Earthquake Engineering*. Corfu, Greece.

Paolucci, R. (2002). Amplification of earthquake ground motion by steep topographic irregularities. *Earthquake Engineering and Structural Dynamics* **31**, 1831-1853.

Semblat, J. F., Duval, A. M. and Dagla, P. (2002). Seismic site effects in a deep alluvial basins: numerical analysis by the boundary element method. *Computers and Geotechnics* **29:7**, 573-585.

Semblat, J. F., Kham, M. and Bard, P. Y. (2008). Seismic wave propagation in alluvial basins and influence of site-city interaction. *Bulletin of the Seismological Society of America* **96:6**, 2665-2678.

Smerzini, C., Paolucci, R. and Stupazzini, M. (2011). Comparison of 3D, 2D and 1D numerical approaches to predict long period earthquake ground motion in the Gubbio plain, Central Italy. *Bulletin of Earthquake Engineering* **9:6**, 2007-2029.

Stupazzini, M., Paolucci, R. and Igel, H. (2009). Near-fault earthquake ground-motion simulation in Grenoble Valley by high-performance spectral element code. *Bulletin of the Seismological Society of America* **99:1**, 286-301.

Taborda, R. (2010). Three Dimensional Nonlinear Soil and Site-City Effects in Urban Regions. *Dissertations. Paper 6*. http://repository.cmu.edu/dissertations/6.

Taborda, R. and Bielak, J. (2011). Large-Scale Earthquake Simulation: Computational Seismology and Complex Engineering Systems. *Computing in Science and Engineering* **13:4**, 14-27.

Trifunac, M. D. (2009). Review: Rotations in structural response. *Bulletin of the Seismological Society of America* **99:2B**, 968-979.

Tsogka, C. and Wirgin, A. (2003). Simulation of seismic response in an idealized city. *Soil Dynamics and Earthquake Engineering* **23:5**, 391-402.

Wirgin, A., and Bard, P. Y. (1996). Effects of buildings on the duration and amplitude of ground motion in Mexico City. *Bulletin of the Seismological Society of America* **86:3**, 914-920.