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Gomez, Christopher
Hart, Deirdre

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沿岸地震と洪水—刃物の端にある町クライストチャーチ、東京と大阪

Coastal Earthquakes and Flooding – Living on the Edge in Christchurch (NZ) Tokyo and Osaka (Jp)

ゴメスクリストファー[1,*]、ハートディードリ[2]
Christopher Gomez [1,*], Deirdre Hart [2]

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The majority of cities and megalopolis lie on sea-shores and river estuaries for the strategic position they provide. If city planners and settlers, have often taken flood hazards in consideration, more pervasive hazards like earthquake and how they interact with the late quaternary geomorphology have only recently become a concern, especially because of the increasing reliance of our contemporary societies on subterranean lifeline infrastructures. The present contribution is articulated around the hypothesis that the most recent unconsolidated sediments deposited by fluvial processes are the most likely to experience ground deformation during and after an earthquake and that those affects will in turn impact inundations from land or from the sea such as tsunamis. It also links the work to the conceptual framework of multihazards and the necessity to investigate further those complex interactions. Using GIS analysis and 2D CFD, we investigated the role of earthquakes in modifying the geometry of land in Christchurch, how it made the March 2014 flood worse, and then exported the lessons learned in Christchurch to Tokyo, Kobe, Osaka in order to understand better the present structural vulnerabilities. As the contribution is constructed as a demonstration using different examples rather than a typical scientific publication, we have used examples at different scales to show that (1) Holocene waterways on coastal low-lying land and their floodplain are particularly at risk of land-movement and increased flooding; (2) Assets of countries like Japan are concentrated for a large majorities in those areas at risk; (3) Tsunamis water flood use waterways as Troyan horses to penetrate inland and therefore the vulnerability seen in (1) further increase the vulnerability to tsunamis.

1. Introduction

1.1 Conceptual framework

In 2011, after a sequence of earthquakes shook the South Island of New Zealand, Deirdre Hart coined the term "coastal quake", explaining that coastal specificities have an impact on the surface manifestations of earthquakes (Fig. 1). Because the coast is an active edge where land systems meet the sea, the interplay of present-days and Holocene unconsolidated sediments with land and seawater, and groundwater, all contribute to a complex response to earthquakes shaking.

Those interactions take place at different scales, and as the rhythms of the different elements of the system through time are different, their interactions are meant to be changing and amplifying, or damping or at least modifying each other very differently over time and space.

Those last points still remain a vague issue for hazards and disaster risk researchers, as they still have to be addressed yet. Indeed, if research on “natural” hazards and how they meet societies and how societies fair through them, even integrating hazards and disaster as part of development, are plenty, multihazards - a natural son of pluridisciplinarity and trans-disciplinarity - is still a neglected child.

Although these concepts and ideas have become household names for both researchers and practitioners, it is at present and too often just a cover for continuing the “same old” activities. The best example supporting this point is the construction and distribution of hazard maps or vulnerability maps. In France, Japan and New Zealand that we know well enough, we are still - in 2016 - to see a single map for the local inhabitants and authorities including multiple concomitant or cascading hazards, telling them

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[1] Kobe University, Graduate School of Maritime Sciences, Laboratory of Volcanic Hazards at Sea.
[2] University of Canterbury, College of Sciences, Department of Geography, Christchurch, New Zealand
[*] christophergomez@bear.kobe-u.ac.jp

what if two volcanoes erupt together, what if a typhoon is creating flooding coming from the hills while an earthquake has just launched a tsunami on your coasts. Such event that seem rather rare to be considered may occur more often than we expect and in 2006 in Java, after a short period of quiescence, the Bantul Earthquake shook the area of Yogyakarta and Central City, and refueled the activity of Merapi Volcano that triggered further pyroclastic flows. Although the two events were far away from each other, local inhabitants shared their fear of concomitant events and the problem they were facing of "where to go". In a same manner, and also widely unreported in the International literature, it is very interesting to read the accounts that the children from primary schools of the Tohoku area gave of their tsunami experiences. Indeed, children seldom describe in details the waves or the tsunami but one element they almost all mention is the cold and the lack of preparedness for the cold.

Fig. 1 Photograph series of coastal earthquakes in Christchurch (Chch), Lyttelton, and Port-au-Prince (Haiti).

Once the students were gathered in refuge area, they explain that the all night was extremely cold and it was impossible to sleep, pointing out that preparedness for one event should not occult the reality of this event occurring in a broader framework. Finally, another difficulty of investigating those combinations come from the fact that they can be tenuous and difficult to fathom (Gomez and Soltanzadeh, 2012).

One location where such multi-hazards has been at play and observed is the coastal area of Christchurch New Zealand (Fig. 1). With this theoretical framework in mind, we have thus investigated the geospatial framework of this issue, which can be summarize by the complex interactions of sediment, water and slope breaks (Fig. 2), all of it under the new assault of climate-change sea level rise and water cycle modifications.

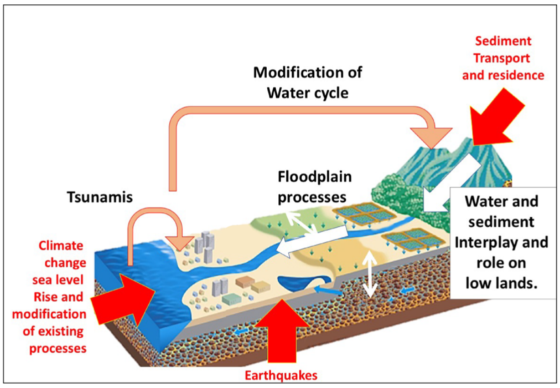

Fig. 2 Spatial framework and statement of issue.

As investigating all those elements is beyond the scope of this short contribution, the authors have chosen to focus on floods and the interactions of earthquakes with floods. This consideration seems to be essential as earthquakes modify the land geometry, reducing to null most of scenarios of flooding for tsunamis or other types of flooding.

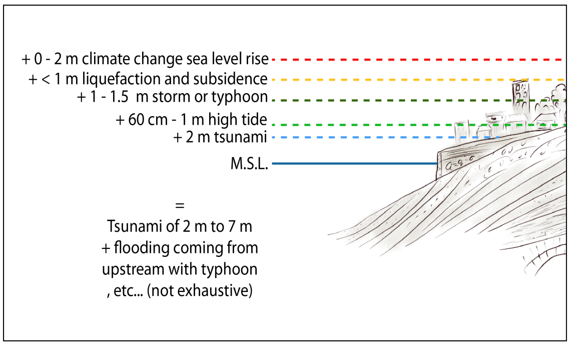

Fig. 3 Illustration of the problem of multihazards and tsunami for a hypothetical location with the same tidal condition as Kobe-city: how a tsunami of 2 m can become a 7 m coastal flood in less than 100 years.

Although tsunami simulations and tsunami inundation simulations are plenty, there is no work that has been done looking at what are the combined impacts of a tsunami with the tides and an eventually concomitant typhoon or storm, land movement due to subsidence and liquefaction and with climate change sea level rise (Fig. 3).

1.2 Study locations: Christchurch (New Zealand), Tokyo and Osaka (Japan)

For the present contribution, the authors have chosen three cities, two in Japan for the potential disaster awaiting and one in New Zealand for the lessons that could be learned from the Christchurch disaster (Fig. 4).

In Japan, two areas of concerns are Tokyo and Osaka, which are both overdue for large earthquakes and tsunamis. For the Nankai-trough earthquake and tsunami (Kobe-Osaka area) for instance, the Japanese Government estimates that about 1,45 million people could be left stranded by the event. As Tokyo and Osaka are the two economic engines of Japan, the consequences of any of the two earthquakes may lead to the worth economic downturn since WW2. In New Zealand, Christchurch City has experienced its worse historical earthquakes, in turn triggering series of issues like dominoes.

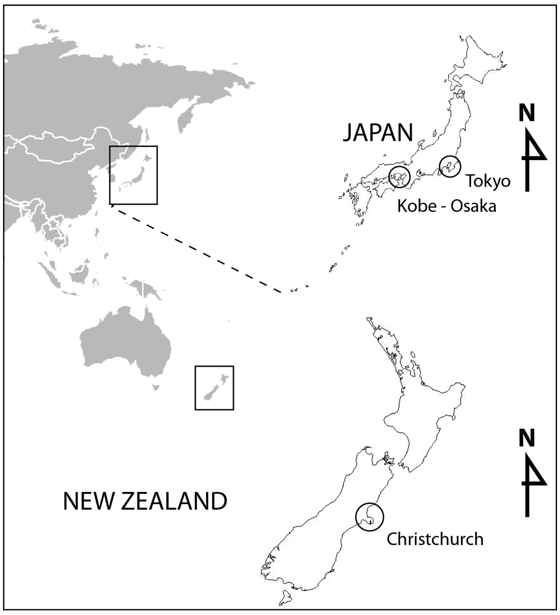

Fig.4 Map of study locations in Japan and in New Zealand.

2. Methodology

The present contribution is constructed as a conceptual statement, which does not attempt to solve one single problem at one location, as an engineer framework would, but it instead tries to present the reason why disaster risk management still has numerous shortfalls, even in the first studied component: hazards.

For this reason, the methodology is rather complex and involves field observations as well as computational solutions and demonstrations, for (a) the coastline format and characteristics and (b) the coastal waterways at three locations (1) Christchurch City in New Zealand, (2) Tokyo City in Japan and (3) Osaka-Kobe Cities in Japan.

2.1 Data creation and extraction

The dataset for Christchurch, New Zealand

Data for Tokyo:
The GIS data of West Tokyo was collected from the Tamagawa City Hall and the Setagaya City hall offices in digital format. Missing regional data were then obtained from the Geospatial Information Authority of Japan (www.gsi.go.jp)

The planform data for the period 1883 – 2012 have been constructed from the 1883 topographical map and aerial photographs over 6 different years (1947, 1974, 1979, 1984, 1989 and 2012). The 1883 topographic map or Meiji-map is a hand-drawn document that covers the present capital of Japan, and subsequently has been converted into a digital georeferenced document (). The aerial photographs have been retrieved from the free section of the database of the Geospatial Information Authority of Japan, with maximum original 400 dpi. The photographs have then been stitched together to create orthophotographs by using the Structure from Motion method for historical aerial photographs (Gomez, 2014; Gomez & Wassmer, 2015; Gomez et al., 2015).
The vertical data were generated by converting the Japanese XML format data of the GSI into grid formats from a 5 m x 5 m footprint record of Lidar data.

Data for Osaka and Kobe
For the area of Osaka-bay where both Osaka and Kobe cities are located, the same national dataset available for Tokyo was used. For the "baththub" flood evaluation, topographic data from the Geospatial Information Authority of Japan (www.gsi.go.jp) was also used.

2.2 Data Processing

Geospatial Analysis
Data visualization and data processing and digitization for diachronic analysis was performed using GIS (Geographical Information System)

technology and the open-source GIS software QGIS (www.qgis.org).

As a first approximation, the authors used a proxy of inundation potential based on topographic values, methods often referred to as the "baththub model". For this model, for each cell of the DEM the elevation in z and the elevation of the water are compared in order to determine whether or not flooding would occur.

$$\sum_{i=1}^{i=n}\sum_{j=1}^{j=m} Z_{i,j} - h_{i,j} = I_{i,j}$$

where, *i* and *j* are the location on the topographic grid, n and m the spatial maximum of i and j respectively, *Z* is the elevation of a single cell and *h* the water elevation. *I* is the inundation depth. It is not a dynamic model nor a model considering water connectivity. It nevertheless has the potential to find potential inundation zones that can be overlooked by traditional model. Indeed, as tsunami water also travels through the stormwater and the sewer system, it is most likely to create inundation in places that are not connected topographically. Such issue was observed during the 2011 Tohoku earthquake and tsunami, when manhole covers were sent flying in the air under the water pressure from the tsunami travelling towards the coast.

Nays 2D Flood model

Although Nays-2D is not a tsunami model (it was conceived as a floodplain inundation model), the authors have used it to simulate on-land progression of inundation waters to demonstrate some of the processes we could gather hint for from the topographic data.

The Nays 2-D model is a flood model for unsteady 2D depth average flow, which uses curvilinear fitted coordinates (i.e. a Cartesian grid projected over the topography). The model has been developed by Prof. Y. Shimizu from Hokkaido University and it has been widely used for academic and consulting purposes in North Japan.

The hydrodynamic model resolve the equation of continuity:

$$\frac{\partial \mathrm{h}}{\partial \mathrm{t}} + \frac{\partial(\mathrm{hu})}{\partial \mathrm{x}} + \frac{\partial(\mathrm{hv})}{\partial \mathrm{y}} = \mathrm{q} + \mathrm{r}$$

and the equations of motion:

$$\frac{\partial(\mathrm{uh})}{\partial \mathrm{t}} + \frac{\partial(\mathrm{hu}^2)}{\partial \mathrm{x}} + \frac{\partial(\mathrm{huv})}{\partial \mathrm{y}} = -\mathrm{hg}.\frac{\partial \mathrm{H}}{\partial \mathrm{x}} - \frac{\tau_\mathrm{x}}{\rho} + \mathrm{D}^\mathrm{x}$$

$$\frac{\partial(\mathrm{vh})}{\partial \mathrm{t}} + \frac{\partial(\mathrm{hv}^2)}{\partial \mathrm{y}} + \frac{\partial(\mathrm{huv})}{\partial \mathrm{x}} = -\mathrm{hg}.\frac{\partial \mathrm{H}}{\partial \mathrm{y}} - \frac{\tau_\mathrm{y}}{\rho} + \mathrm{D}^\mathrm{y}$$

for which h is the water depth, t is time, u is the flow velocity in both the x and the y directions, g is the gravitational acceleration, H is the elevation of the water surface, τ_n are the shear stress in both x and y directions (directions denoted by n here), and ρ is the density of water, q is the inflow from extra culvert and r is the rainfall. The shear-stress is then described in term of velocity and roughness coefficient (Manning formula). Those basic equations in Cartesian coordinates are then transformed by the code into curvilinear equivalent (for more information, please refer to the solver manual of the Nays-2D Flood model).

3. Results

3.1 Christchurch: Water, unconsolidated sediments and earthquakes don't make a good match

Christchurch City is a low-lying city, with the majority of the land located less than 5 m from the sea-level with important fluvial corridors all within 2 m of the mean seal level (Fig. 5). It therefore appears that Christchurch is prone to river flooding, but also any advance, rise from sea water.

This setting has favored land-movement during the 2011 earthquakes, where the land dropped up to 1 m locally (Fig. 6). Figure 6 shows the topography of Christchurch as a series of outcrops with the central line of the Avon River as a spatial reference, in such a way that one can see the relation between the distance from the river and the topographic change after the earthquake as well as the relation between fluvial geomorphology and earthquake related movement. The major movement registered from the LiDAR data is the sliding of the banks (A on Fig. 6) and the vertical change in the river floodplain (B on Fig. 6).

Consequently, areas already at risk of flooding have been mostly affected and floods severity might just increase.

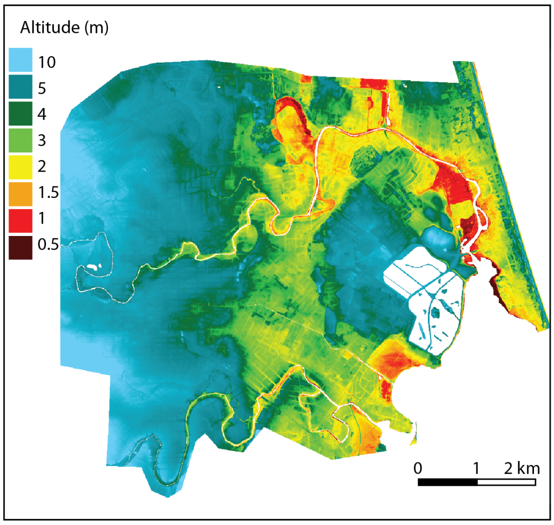

Fig. 5 LiDAR (Light Detection And Ranging) data acquired after the 2011 February earthquake sequence in Christchurch, showing low lying areas that have become further exposed to flood hazards either from river floods or from sea floods.

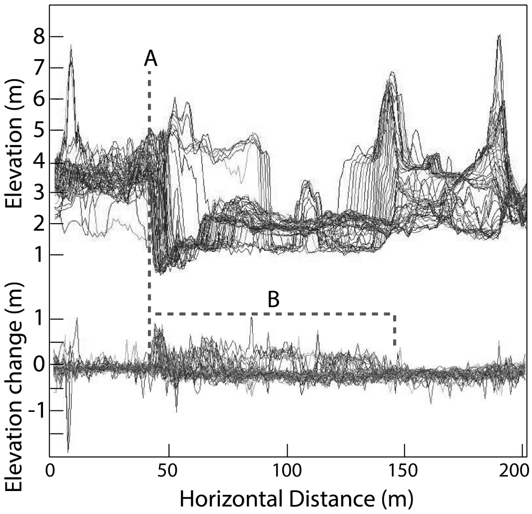

Fig. 6 The graphic at the top depicts the topography along the Avon River, the main river to the North of the map 5. The graphic at the bottom shows the variation before and after the earthquake. This variation reaches 1 m. On this graphic, positive values are subsidence while negative values show topographic rise. (A) natural bank limit and corresponding displacement showing "sliding" of the bank; (B) The area in the center corresponds to the river floodplain.

The link between spatial position and the waterways centre line is further evidenced by a progressive decrease of land movement when moving away from the river (Fig. 7). This variation seems to be more hectic close to the water, due to the relative importance to local variations.

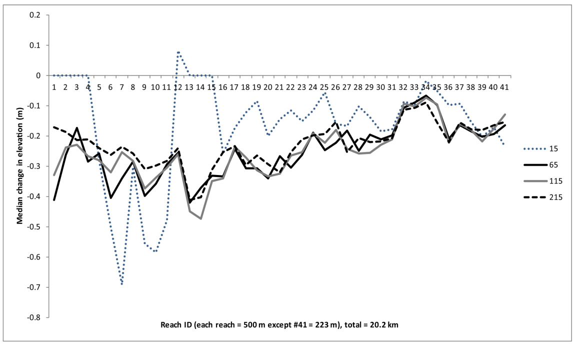

Fig. 7 Median land elevation change, by buffer of distances from the river channel, by reach of 500 m (the measures start at the estuary). This graphic shows that the land close to the Avon River channel is more prone to land movement, and more variability in the movement from one reach to another.

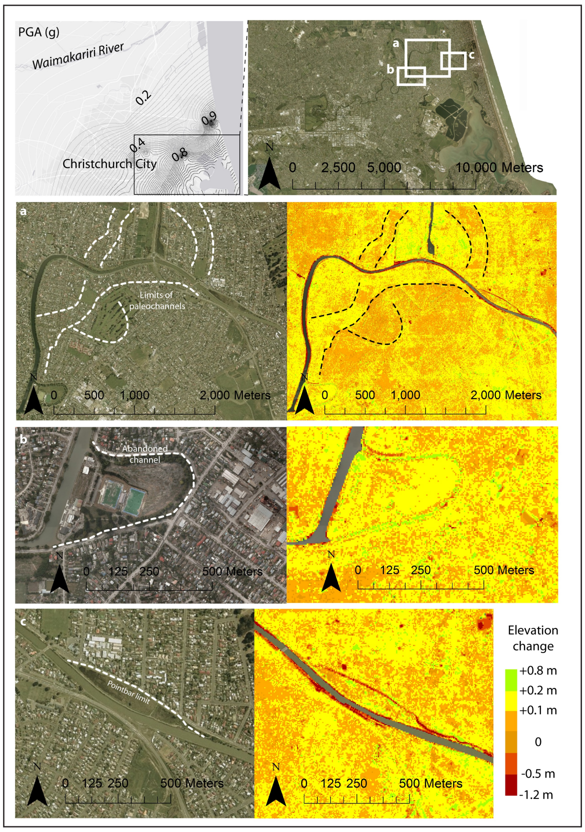

Fig. 8 The spatial distribution of maximum changes in elevation and abandoned channels and a map of the calculated Peak Ground Acceleration at the regional scale.

Mapping those measured variations with the geomorphic form, there is a direct link between fluvio-geomorphology and vertical change in elevation in Christchurch (Fig. 8). Channel banks have registered the maximum change as well as the banks of abandoned meander and oxbow lakes. As those environments are the areas where low-energy flows created the landforms, they are characterized by silt to clays saturated by water, and hence prone to movement.

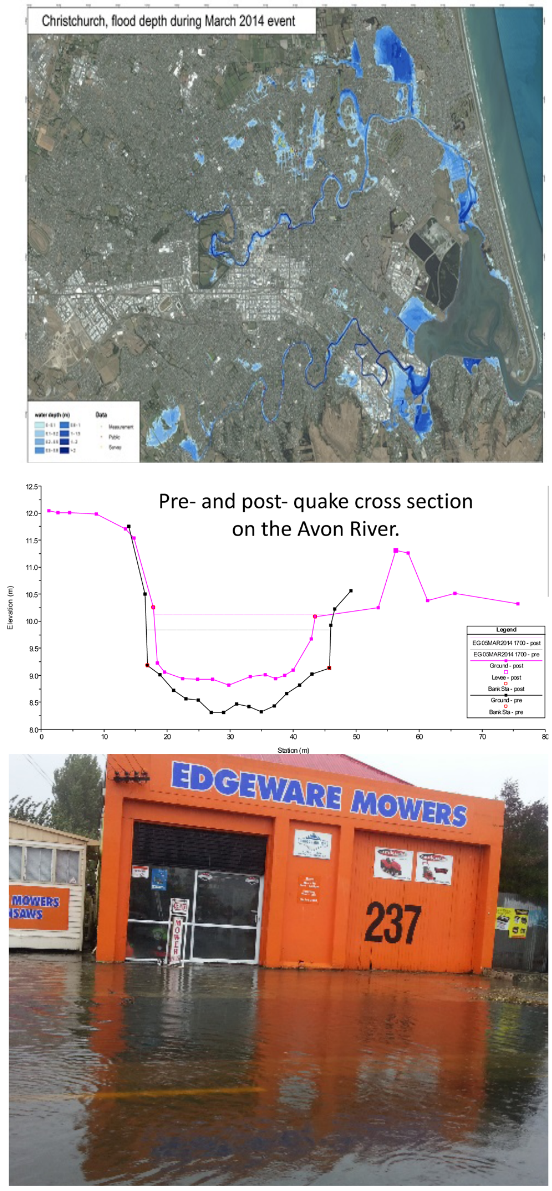

Fig. 9 Flooding, consequences of the geometry change of the Christchurch coastal area and the change in the geometry of the rivers.

As the month of March 2014 was relatively wet with 155 mm of rainfall over a month and with 55 mm of rainfall between the 3rd and the 5th of March 2014. This event triggered widespread flooding in the city (Fig. 9). However, the explanation of this flooding has to be found somewhere else. Indeed, the flooded area, correspond to the areas that have been affected by land-level change in the aftermath of the earthquake (Fig. 9) and the impact it had on the functioning of waterways.

This chain of event, earthquake + rainfall, impacted a second blow to a city in the midst of recovery from a major earthquake, putting the emphasis on how urgently mutli-hazard frameworks are needed.

3.2 Living on the edge of water: reclaim land and flooding problems.

Low-lying land made of unconsolidated sediments are very prone to liquefaction, lateral spreading and bank sliding as experienced in Christchurch. Looking at geomorphologic similarities in Tokyo and Osaka and Kobe, both Osaka and Tokyo are also coastal cities built on large Holocene coastal estuaries. They have also developed another set of vulnerable lands: reclaimed land (Fig. 10). In Tokyo, drainage or marsh-land and the reshaping of land starts as early as the Edo period (16th Century), and precise cartographic account of this evolution emerge around the mid-19th Century (Fig. 10). In less than 200 years, the coast of Tokyo has progressed of 3 km seaward, mostly through reclaimed land and the construction of artificial islands.

By comparison with the events in Christchurch, those islands are most likely to experience liquefaction and eventually lateral spreading. As Tokyo, Osaka and Kobe all concentrate a large proportion of their economic activities in those areas with for the 3 cities their port activities, city airports and "trendy" blue-edge real estate located in those areas, a combination of earthquake related movement and tsunami would be an important economic blow. In Tokyo, the density of buildings in residential areas can reach 2600 buildings per square kilometer (Fig. 11), a tsunami would not have to penetrate far inland to create important damages.

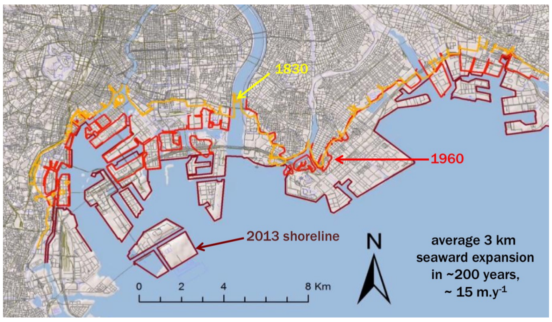

Fig. 10 Seaward movement of the coastline of Tokyo City due to reclaimed land for the period 1830-2013.

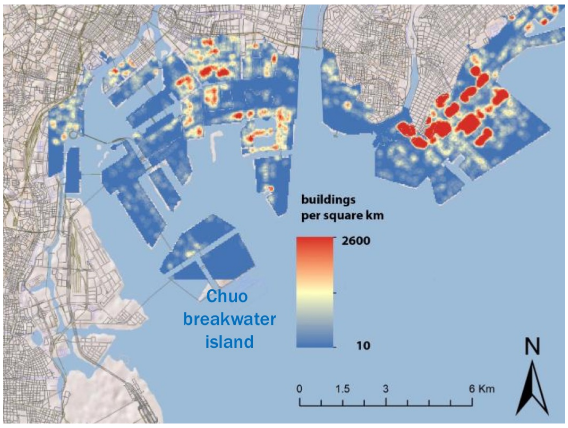

Fig. 11 A lot of people on reclaimed land. High density area, and predominantly residential. For each house, if one count 3 people on average, it is at least 7,800 people/km^2。

3.3 Tsunami inundation in Osaka-Kobe

We have seen in the previous sections that earthquakes had an immediate effect on land, bringing it to lower level through different mechanisms (liquefaction, lateral spreading, bank collapses, etc.). Within this modified "boundary condition", eventual flood water adopts unpredicted behavior because of the complex topographical changes (the reader will note that we have occulted the effects of gravity water in pipes, pipes angle change, etc., which all conduct to further flooding). This modification therefore impacts river flooding, but also flooding from the sea, as the sea-level (base-level) becomes relatively higher.

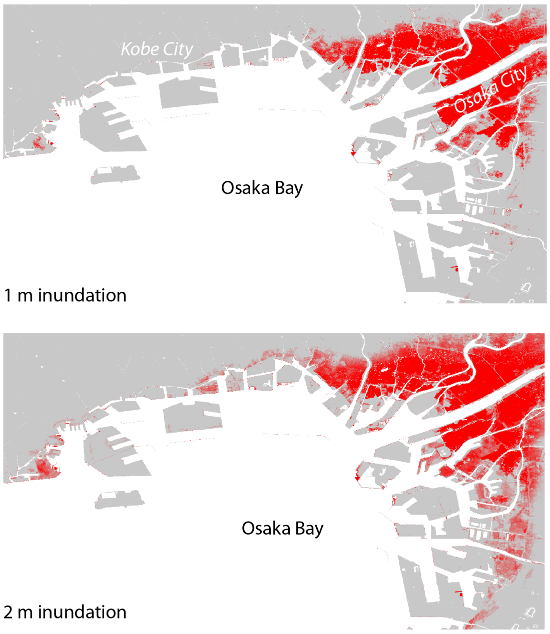

Fig. 12 Inundation map of the Osaka Bay, calculated from land elevation data.

It is therefore important to consider water level higher than the present tsunami prediction for instance.

The estuary Osaka city is built only needs a 1 m tsunami to be flooded, but the extension of floods might be more in line with the 2 m flood level if subsidence or other concomitant events occur (Fig. 12).

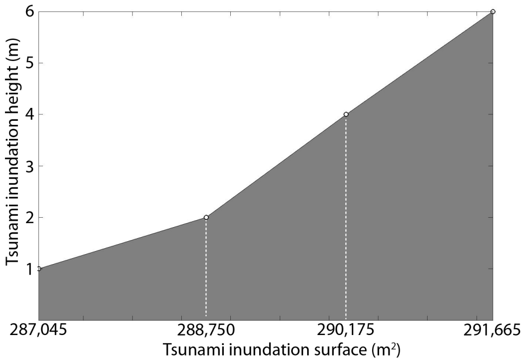

Fig. 13 Tsunami inundation surface per water height in the Osaka region.

As a 1 m inundation would concern 287,045 m^2 of land, bank failures due to the earthquakes or a tsunami itself would see very extensive flooding in Osaka City. This could be further accentuated with increased inundation heights (that can be linked to a bigger tsunami or simply the combination of other factors, such as subsidence, high tides, storms…etc.).

3.4 Tsunami inundations on land in Fukae, Kobe-City - explaining further the issue related to waterways

Using the 2D computational fluid dynamic at the local scale, we can investigate the processes by which flooding may occur. For the present case study, we have chosen the area near the campus of Kobe University to also show that the campus was in need of serious evacuation and post-disaster community resilience reflections.

Using scenarios where the tsunami wave was 2 m, results show that wide areas on land in Fukae would be flooded (Fig. 14) although the tsunami inundation depth does not seem to exceed 1.5 m depth. This value however does not include inter-buildings acceleration nor complex liquefaction effects. Nevertheless, landward progression of the tsunami appears first from the coastal waterways, that show less flow resistance and are first inundated.

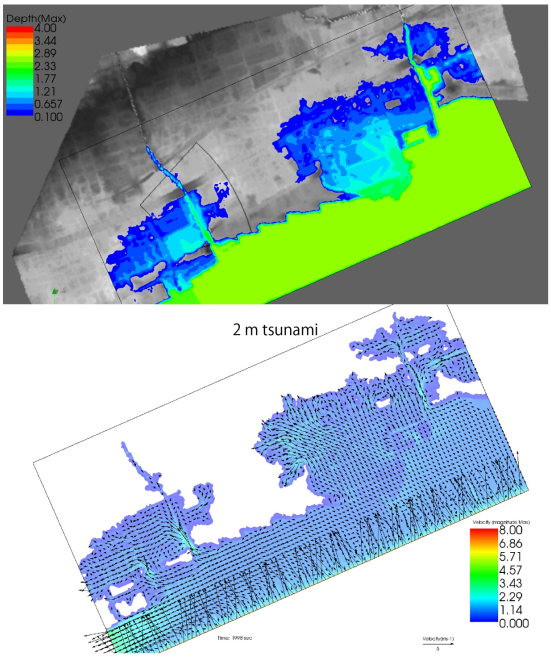

Fig. 14 Flooding simulation in the area of Fukae in Kobe-city based on the combination of a 2 m tsunami + 1 extra meter attributable to a combination or solely one of the three following components: (1) liquefaction and subsidence; (2) storm and or high tides; (3) climate change sea-level rise.

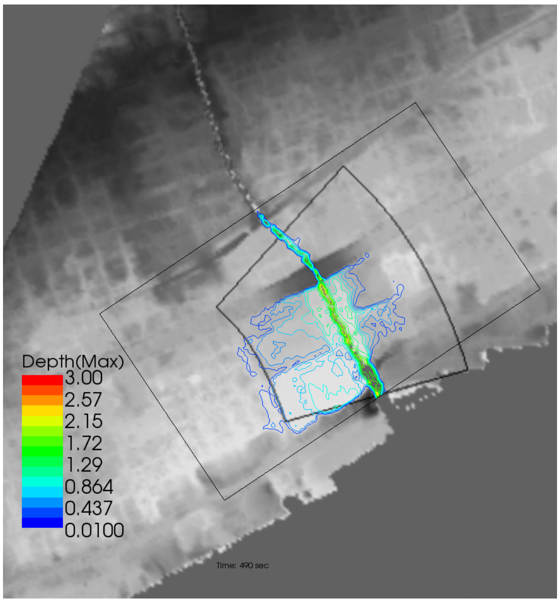

Fig. 15 Example of how flood can use waterways and propagate backwards from the coast during a tsunami.

This inundation pattern can then become a problem for evacuation as they act as Troyan horses in the city, bringing the flood first inland, before often breaching the coastline (Fig. 14 and 15).

Conclusion

The present demonstration puts the emphasis on (1) low-lying coastal areas, and more especially delta that have developed over the Quaternary and late Holocene are particularly prone to earthquake shaking and then all forms of consequent flooding. (2) Waterways and their floodplains are the most affected areas by earthquake movements, and therefore it will have an immediate effect on a co-seismic tsunami, and a delayed effect on any other flood that would occur on this new geometry.

Readers might have felt odd reading this contribution, because it has the shape of a traditional research paper, but it does not intend to be. It was more constructed as a demonstration, through different examples, of the necessity to adopt multidisciplinary approach at different scales and not by juxtaposing them, but by looking at their complex interactions.

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