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# THE SIGNIFICANCE OF ULTRA-LIQUEFACTION AS A DISTINCT DAMAGE MECHANISM FOR LOSS MODELLING (AND FOR CONTAMINATING FIELD OBSERVATIONS OF EARTHQUAKE IMPACTS)

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**Abstract**: *Recent experience of earthquakes in New Zealand and Indonesia has highlighted the potential for liquefaction to become a principal driver of earthquake damage and loss, including at Palu of mortality. In Christchurch at least half the costs of the 2011 earthquake related to liquefaction-induced differential settlement and horizontal displacement. Before 2011, in earthquake loss modelling it was standard to treat liquefaction as a modifier of shaking-related damage levels, but in fact liquefaction drives a completely different damage mechanism. As in Christchurch, a building could be completely undamaged by shaking but still a total (100%) loss as a result of liquefaction-induced settlement. This understanding also has deep implications for how information about building damage is collected in the field. Traditionally damage has been mapped and converted into earthquake intensity metrics on the assumption there is only a single cause of damage. Inevitably past field damage data is 'contaminated' with liquefaction-related damages and this can be seen in the way that liquefaction related damage has been included within earthquake intensity scales. In the same way that we separate tsunami related damage from earthquake shaking damage from fault rupture damage, we now need a separate intensity scale for liquefaction-related damage. Field investigations of earthquake damage should start by the careful separation of liquefaction related damage levels from shaking-related damage levels.*

## The liquefaction process and preconditions

Liquefaction occurs in a loose and saturated pile of silt or sand, when, as the result of the application of a sudden force, or through vibrations, the grains pack together more tightly, reducing the porosity. The reduced volume raises the pressure of the interstitial water, forcing the particles apart. Instead of load pathways being transmitted from grain to grain, the material now behaves as a liquid and can flow. The pressure is relieved where the water can escape to the surface. However, if the liquefied layer is confined, the hydrous overpressure may drive water deeper, expanding the extent of liquefaction (Lakeland et al., 2014). Liquefaction will persist until the excess water pressures have been relieved.

While the phenomenon of liquefaction has been widely recognised for at least fifty years, the role of the phenomena in driving the economic losses from earthquake was really brought home in what happened in Christchurch, New Zealand in the earthquakes of Sept 2010 and Feb 2011.

Eastern Christchurch has a high ground-water table within 1-1.5m of the surface. The upper 10m of the delta deposits are less than 4,000 years old. Only 6500 years ago the coastline was situated to the west of the city centre.

Professor Misko Cubrinovski from the University of Canterbury (Cubrinovski, 2013), has estimated that at least half the NZ$30Bn damage from the Christchurch earthquakes can be attributed to liquefaction. He identifies 60,000 residential buildings affected by liquefaction, one third of those 'severely' while more than 8,000 had to be abandoned. Liquefaction also severely disrupted water and sewerage lifelines along with roads and bridges (Cubrinovski et al 2011).

## 'Ultra-liquefaction'

We need a word to describe the situation when liquefaction drives catastrophic outcomes. For example, when the volume of water that escapes to the surface as a result of the hydrous

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overpressures causes flooding (as in the eastern suburbs of Christchurch in February 2011). Sand silt ejecta was 50-60cm thick in places and required the removal of 400,000 tons of materials. The expulsion of 20cm of water over the top 10m of the delta sediments implies a 2% reduction in porosity.

On the outskirts of the city of Palu on the island of Sulawesi on September 28th, 2018 ultra-liquefaction created chaotic landslides that caused total destruction to houses in some neighbourhoods and is understood to have caused more fatalities than the accompanying tsunami.

'Ultra-liquefaction' can be defined as intense liquefaction leading to catastrophic surface deformation. 'Ultra-liquefaction' reflects a shallow water table, the mobilisation of liquefaction over a layer, or layers, several metres in thickness, and quite possibly, a situation in which the sediments are geologically very young and have not previously been subject to a porosity reduction of this magnitude.

**Liquefaction-related damage mechanisms**

One can identify seven forms of liquefaction-related damage:

1) Subsidence – the building sinks into the ground, disrupting services, and routes of access and egress.
2) Differential settlement –sections of the building sink to different degrees, leading to tilted floors and/or internal damage
3) Lateral displacement - the building moves sideways as a result of downslope movement on the low-friction liquefied layer, disrupting services, colliding with objects which are more deeply founded, potentially passing into land that may have different ownership, and/or that is subject to flood hazard.
4) Differential lateral displacement – sections of the building move horizontally to different degrees, leading to structural damage
5) Mass movement / landslides – downslope differential lateral displacement involving many metres of displacement, leading to catastrophic damage.
6) Air-filled pipes and tanks embedded in the ground will tend to rise to the surface in liquefied materials as well as suffer breakages from differential movements.
7) Spoilage of carpets, floors etc with water and sand – where the volume of water that escapes to the surface leads to flooding

These damage mechanisms blend into one another and can be compounded.

The nature of the damage to buildings as a result of liquefaction will then be determined by the liquefaction hazard and in particular:

- the thickness of the underlying, 'liquefiable' layers,
- the potential for porosity reduction as a result of compaction within these layers
- how these layers vary laterally
- the surface slope
- the level of shaking from the earthquake, triggering the sediment to compact

**Liquefaction is a distinct damage mechanism**

Liquefaction-related damages can be completely distinct to those damages caused by earthquake vibration.
Differential settlement and lateral displacement damages can quickly mount to the point where the building is condemned.

Although it can be possible to re-level tilted buildings, this is expensive and typically only applies to low rise structures up to 3-4 stories.

We can have a situation where a building has no damage from shaking but is none-the less condemned as a total loss as a result of damage and tilting from differential settlement. A 1 in

200 tolerance can be applied by loss adjustors for the maximum acceptable tilt of the floors in a building.

A most important lesson from Christchurch is that building damages from liquefaction can be completely separate to building damages from vibrational loading. We can have a property that is completely undamaged by the shaking but is a 'total insurance loss' from the liquefaction. Away from the recent delta deposits and near-surface water table, there were many older buildings with damage caused by vibrational loading that were totally unaffected by liquefaction. Even within the area of pronounced liquefaction a building that was supported on piles driven below the deepest extent of liquefaction could avoid subsidence, although could find that the level of the ground adjacent to the building has receded.

**Different agents of earthquake damage**

Damage as a result of liquefaction reflects different damage mechanisms to damage caused by ground shaking. We should think of liquefaction as a distinct agent of damage in the same way that we consider tsunami damage or fault displacement damage as entirely distinct damage mechanisms. Just as there could be situations where a building is affected by the shaking and then goes on to be damaged by the accompanying tsunami, there will also be situations where the building is subject to immediate shaking-related damage and then goes on to suffer damage from liquefaction.

However as much as possible we should consider the different damage mechanisms separately.

This has particular significance when collecting damage data in the field after an earthquake. The tradition has been to collect information on earthquake damages independent of their cause. However, this leads to the problem that the different agents of damage then become intermixed. It would be no different to mixing damage from the tsunami with damage from the shaking. Until we can identify which buildings were hit by the tsunami we cannot isolate the tsunami damage-mechanisms.

The challenge is that while it may be fairly straightforward to identify the extent of the tsunami, the water depths and those locations where the water velocity was a primary agent of damage, it becomes more difficult to isolate where liquefaction has been a primary driver of damage. And yet in order to avoid developing a 'contaminated', mixed hazard data set of damages, this is what is required.

In performing a field survey, we first need to identify where liquefaction is a primary damage agent. We could, for example, do this through mapping evidence of building settlement or sand volcanoes. We should then collect damage data independently for those areas where liquefaction is significant and those areas where it is not.

Such separation was not undertaken in many past earthquake field investigations, which means that damage datasets mix different sources of damage. In effect vibrational damage data sets may be 'contaminated' with liquefaction-related damage datasets.

What has been learnt from Christchurch now requires a fundamental review of how information is gathered in an earthquake field investigation of property damage.

**The confusion in earthquake intensity scales**

The creation and evolution of earthquake intensity scales, going all the way back to the late 19$^{th}$ Century, was undertaken through the collection of damage data after earthquakes, but without the appreciation that earthquake-shaking and liquefaction apply distinct damage mechanisms.

We can see this confusion in the higher grades of the 1931 Modified Mercalli Intensity (MMI) Scale (Wood and Neumann, 1931) which increasingly appear to describe liquefaction related damages.

For example, at MMI VIII we find ‘sand and mud ejected in small amounts’ indicating overpressures associated with liquefaction.

At Intensity IX we find ‘well designed frame structures thrown out of plumb’, ‘buildings shifted off foundations’, ‘Ground cracked conspicuously’ ‘Underground pipes broken’, all of which, in most circumstances, suggests pronounced liquefaction.

At Intensity X there is ‘most masonry and frame structures destroyed with foundations’, ‘ground badly cracked’, ‘landslides considerable’, ‘shifted sand and mud’ all of which is plausibly liquefaction related.

At Intensity XI we have: ‘Broad fissures in ground, underground pipes completely out of service’ and ‘earth slumps and land slips in soft ground’: all likely to be the result of liquefaction.

In fact intensities VIII to XI read like a liquefaction-related damage intensity scale superimposed on an earthquake shaking intensity scale. While the earthquake shaking intensity scale, does attempt to capture stronger levels of ground shaking, the liquefaction indicators in the higher grades could simply reflect the varying proclivity of ground materials to develop liquefaction, rather than any gradation in the severity of the shaking that triggered the liquefaction.

The European Macroseismic Scale (EMS) appears to have inherited some of the same problems from the MMI scale. ‘cracks and landslides’ feature at Intensity X, whereas at intensity XI most buildings collapse. At intensity XII ‘The ground changes’ while ‘almost all structures are destroyed’. Again these could reflect intense liquefaction-related damages. In the deliberations that preceded the development of the EMS, the fourth of five considerations was: ‘the rejection of any intensity corrections for soil conditions or geomorphological effects, because detailed macroseismic observations should just be a tool for finding and elaborating such amplification effects’. This assumes the traditional paradigm: that ground deformation affects the amplification of ground motions, not reflects a different liquefaction-related damage mechanism.

We actually need two separate intensity scales, one for shaking-related damage and a separate one for liquefaction-related damages. Mixing these observations will only lead to confusion.

This problem has been appreciated when using an intensity scale for developing strong motion attenuation relations, in which an intensity-based attenuation function is derived from data only on hard rock and firm ground conditions (Gomez- Bernal et al., 2012).

However, where no assessment was made of the extent of underlying liquefaction, it is not easy to go back and revisit the separation of shaking and liquefaction related damages in past field investigations of earthquake damage. We may have to accept that such data is, in many circumstances, contaminated by liquefaction related damages.

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