Observations on the Performance of Residential Concrete Slabs under Seismic and Soil Liquefaction Conditions

C.W Ashby
MIPENZ, CPEng. IntPE. BE. NZCE

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ABSTRACT:

The humble domestic concrete slab is a very important component in getting things right first time. Because there are so many of them, the cost of poor detailing and construction techniques have had a significant effect on the economy and wellbeing of the community running into billions of dollars worth of damage in Christchurch and causing displacement and trauma to people unnecessarily.

However many habitable houses with unreinforced cracked concrete floors are being written off unnecessarily, due to the wording of insurance policies and ignorance with respect to the reparability of such.

Unreinforced slabs are now no longer permitted for new construction of residential houses, and experience has proved the worth of waffle slabs. There is however still room for improvement if a cost effective base isolation system can be developed to protect occupants, superstructure and contents.

1 INTRODUCTION

A series of some 37 earthquakes and aftershocks greater than magnitude 5 have occurred in the 18 months since the 4th September 2010 event. On the positive side, this gives a very good opportunity to study the effects of earthquakes first hand, learn from them and develop improved construction techniques.

When I first volunteered to assist in Christchurch following the 4 September 2010 earthquake and inspected 2 groups of council flats that were write offs due to unreinforced concrete slabs, I thought at first that someone had made a mistake and left the reinforcing out.

I was absolutely astounded to learn that this was standard practice, and have concluded that this practice has cost the country and insurers billions of dollars.

Having been actively involved in the design of waffle slabs or Rib-Raft Slabs, I was also keen to see how these performed.

My prime area of interest has been the performance of residential concrete slabs under seismic conditions, particularly with respect to liquefaction and my observations are outlined in this paper.

2. GENERAL OBSERVATIONS

Foundations and floor slabs are crucial and extra effort and cost is warranted to get these right first time. If the roof or a wall is damaged it can be replaced or fixed relatively easily. However, if the foundations and floor slab are ruined chances are the house is a “write-off.”

A house is not just a building; it is someone’s home and sanctuary, their shelter, their prime asset, filled with memories and heirlooms. For their home to be written off, it can be devastating for most people.

Houses where the foundations and concrete floor are badly damaged can be very difficult to rectify because of internal partitions, services, floor coverings, etc. Houses with concrete floors in Christchurch tend to be brick veneer clad with heavy tile roofs. They are generally not economic to relocate.

While older double brick buildings pre 1931 earthquake collapsed, generally houses built in accordance with the NZ Standard for Timber-framed Buildings NZS3604 performed well, even with brick veneer and heavy tile roofs. (Noting however that with the high vertical accelerations generated in some areas heavy roof tiles were often thrown upwards and smashed on impact when they hit the roof again.) However, the Achilles heel of residential buildings in Canterbury has been foundations and slabs built in accordance with NZS 3604 on three counts;

- Under NZS3604 definitions, Liquefiable Soils constituent “Good Ground”. (Even though all PIM reports warned that the area could be subject to liquefaction, building consents were issued on the basis of the NZS3604 definition). Note that while Canterbury has now been “ring fenced” as a special case, this definition still applies to the rest of NZ and change is needed.
- NZS3604 permitted the use of unreinforced concrete slabs in residential single story buildings on “Good Ground”. (It still does, but the Department of Building and Housing has over-ridden with an amendment to the building code).
- NZS3604 permitted the use of uncompacted round river gravel under slabs. This material often rattled like marbles and settled under seismic conditions or dropped like the proverbial stone though the liquefying material underneath, leading to floors settling and internal partition walls pulling away from the floor and/or the ceiling. Use of uncompacted river gravel has since been banned.

A further factor to consider is that without satisfactory regulation or enforcement, in a competitive market, matters can tend to sink to the lowest common denominator, as responsible builders who would prefer to incorporate mesh were competing against those who did not and for the sake of $800 worth of mesh have lost work. The writer is concerned that a similar situation is developing in the North Auckland Silverdale area where the effects of shrinkage of expansive clay fills is being ignored as a cost cutting measure on a similar basis.

3. UNREINFORCED CONCRETE SLABS

While many unreinforced slabs survived the earthquakes without notable damage where they were on good ground and not subject to liquefaction, many did not and accumulatively would have cost the country and the insurers billions of dollars and resulted in displacing people from their homes.

Unreinforced concrete floor slabs generally tended to perform badly, tearing apart principally along saw cut control joints, and with little or no resistance to differential settlement, or rupturing under liquefaction conditions.

Never the less, to some degree unreinforced concrete slabs have attracted a worse reputation than they have deserved and many good houses have been condemned to demolition because of insurance policies that undertake to 'replace as new", and perhaps a lack of understanding of repair methods available.

If an unreinforced concrete slab has cracked. The logic goes; "How do you replace a cracked unreinforced concrete floor?" To do so one must remove and then reinstate the roof, walls and services. By the time one does so it is easier and cheaper to demolish the house and rebuild.

However this logic has tended to overlook that cracked slabs can often be economically repaired.

One aspect is that unreinforced slabs were often cracked due to concrete shrinkage before the house was finished, with the crack disguised under carpet and floor coverings. While the earthquake would have exacerbated matters, the truth is that the crack was often there before the earthquake and not noticed until people got nervous and started lifting carpets and tapping tiles. In one instance observed by the writer, the tiles in the house entry foyer were cracked about 1.5mm wide. However upon lifting the tiles it was found that the crack through the underlying slab was 4.5mm wide containing 3mm of flexible latex gap filler. Thus the slab had already cracked while the house was still being built. The crack had not been repaired and the tile layer had simply laid the tiles across the crack which virtually guaranteed that the tiles would crack if there was the slightest movement.

Another aspect is that concrete shrinks. In the laboratory, concrete shrinks about 1mm per metre, but in the field resisted by surface friction with the ground below, it may only shrink $1/6^{th}$ of this amount and the concrete in equilibrium with tensile forces built up within it. When an earthquake occurs, everything is shaken and the friction between the slab and the ground is disturbed allowing the slab to shrink and the control joints and existing hairline cracks to instantly open up leading to the misunderstanding that either; the building has "spread", or the earthquake has opened a fissure under the house.

It has generally been found that the DPC Membrane under the slab is unlikely to be compromised providing the crack is less than 100mm wide. Most cracks are less than 10mm wide and therefore waterproofing should not normally be an issue.

Observations have indicated that with successive shakes the slab reaches a point of equilibrium where the cracks grow no larger. In other words the concrete has shrunk as much as it is going to. At that point the control joint has done its job and is probably best sealed solid with a 2 part epoxy or hybrid Urethane grout.

One suitable proprietary product is "Road Mender" (tm) developed for NATO to repair bombed airfields. Fine silica sand is poured down the crack as a filler and this 2 part hybrid urethane poured in which penetrated the sand binding it and deep into micro fissures of failed concrete to permanently micro-dowel repairs.

Another alternative is to maintain the control joint as a flexible joint using a backing tube of foam and a flexible filler. However this does not provide good overall diaphragm action of the slab or provide resistance against vertical shear.

Retro reinforcing of an unreinforced slab is possible. As a precaution an unreinforced concrete floor which is covered with carpet, can be retro-reinforced using stainless steel 1mm thick brace strap laid across the house and fixed to the concrete floor using concrete nails in predrilled holes. Usually the local form of construction has reinforced perimeter strip footings with D10 starters bent into the reinforced slab at 600mm centres. The idea is to well nail one end of the strap in this zone, then stretch it across the house through doorways or under internal partition walls at about 5m centres. The brace strap is kept temporarily taught by use of a temporary spring at the other end hooked onto a temporary nail protruding from the concrete.

A slow settling non-brittle adhesive can be pasted between the concrete and the brace strap and temporally weighted down as holes are drilled and nails hammered into place holding the strap to the slab, commencing at the nailed end and working towards the spring so as to keep the brace strap taught.

Alternatively or as a supplement to retro reinforcing right across the building, the joint or crack can be stitched using 600mm lengths of brace strap at 1m centres at right angles across the joint of crack. If nailed at the ends and left “free” at right angles across the crack, the brace strap will stretch over say a 400mm length approximately 4mm and remain elastic drawing the joint together again when the shaking stops. The steel strap forms a frangible connection which will fail rather than causing the slab to crack elsewhere under ultimate load.

As a guide the tensile strength of the perimeter of the slab reinforced with D10’s at 600mm centres will be about 39 KN/m width. The 20 MPa concrete slab 100mm thick should have a tensile capacity of about 20KN/m width and the brace strap should have an ultimate strength of 8.8 KN, hence if placed at 1m centres the brace strap will be the weak frangible link saving the concrete in the case of overloading.

Should a foundation or slab be out of level there are under-grouting techniques such as the use of Uretek or low slump cement grout. I had previously used Uretek on a job in Auckland where differential settlement in the order of 150mm had occurred at the end of a house opening up cracks in the walls and floor and in the ceiling up to about 3mm wide. URETEK was used and the 3mm cracks closed up to a pencil line that was only visible when looked for prior to replastering.

The product is not cheap costing about $7,000 per cubic metre in place, but it is an economic solution if the only other alternative is demolition and rebuild.

The writer has however been shocked and dismayed at the conservative opposition to this product by many who have not used it or are unfamiliar with it, expecting a guarantee that if this product is used there will be no further problem within a 50 year lifetime, despite ongoing seismic activity and underlying liquefiable soils. It is not the product that is the risk but the ground. In many cases even if piling could be retrofitted (which often it cannot) it would often not solve the problem under prevailing ground conditions.

Observations indicate that the use of such grouting techniques stiffens the underlying ground locally and buildings so treated fare better than their previously less affected neighbours in subsequent events.

A paper by three Turkish authors [1] following an earthquake in Turkey in 1999 tested the effectiveness of this product in improving local soil density and reducing proneness to liquefaction or consolidation and found it to be worthwhile.

The photo below is of a previously “written off” house with cracked unreinforced concrete floors, saved from the demolition by crack repair methods and brought back to code compliance condition. In this particular case there was no liquefaction on site and floor slab levels were within new house tolerances and did not require relevelling. This is now the writer’s new residence.

4. REINFORCED CONCRETE SLABS

Reinforced slabs have historically been reinforced using 665 mesh which was made of drawn wire welded in a 6” or 150mm square grid. Because the wire was drawn in manufacture it had already been stretched past its yield point and although strong was brittle and was prone to failure across a narrow crack under seismic conditions. Further, it was often local practice to cut control joints so deep that the mesh was often cut or nicked and compromised, thereby providing no shear or tensile capacity across the control joint, rendering such slabs little better than unreinforced slabs.

However 665 mesh was better than nothing particularly if left continuous across control joints.

The writer has viewed one slab which cracked only part way across an otherwise unreinforced concrete driveway near the Darfield epicentre. A check with the metal detector revealed that the crack stopped in an otherwise unreinforced slab where a sheet of 665 mesh left over from the house had been laid at random in the drive.

As a result of the Christchurch earthquake, 665 mesh has how been phased out in favour of seismic mesh, which is commendable but perhaps not the key issue.

Larger seismic steel has not performed as well in Christchurch as anticipated possibly due to the concrete, which tends to be made with river gravel, developing isolated concentrated cracks, forcing the steel to yield at one point rather than micro cracking over a longer development length of steel which is more likely to occur where crushed aggregate has been used. With on-grade slabs there would therefore be merit in de-bonding the steel for 50mm each side of the control joint, (Denso tape wrap the steel locally, or by using crack inducers (CANZAC or similar) in a grid across the slab at about 750mm to 1m centres to induce micro cracking as used in supermarket floors.

5. WAFFLE OR "RIB-RAFT"(tm) SLABS

Waffle or Rib-raft Slabs (Firth Industries, see photo) are constructed as a deep slab typically 310mm to 385mm total thickness on top of the ground, without conventional foundations dug into the ground. The waffle slab consisting of a grid of reinforced ribs in both directions typically 100mm wide with a 300 or 400mm wide reinforced concrete perimeter beam, with a reinforced topping slab typically 85mm thick, all poured in one concrete pour, with void spaces formed typically 1.2m x 1.2m using polystyrene pods set out in a chess board fashion separated by the ribs.

Waffle slabs are typically about 17 times as strong as a conventional reinforced concrete slab and foundations while using a similar amount of concrete plus nominal additional steel. This extra strength is due to the depth of the ribs.

The other advantage of waffle slabs is that they are relatively light compared with a solid concrete slab of similar thickness. This is seen as a plus during liquefaction conditions where a heavy slab will tend to sink under its own weight.

Prior to the Canterbury earthquakes, Waffle slabs were not common in Christchurch.

However, there were sufficient to monitor performance. Between Firth Industries the supplier of Rib-raft (tm) pods, [2] and the writer approximately 28 rafts were reviewed. From investigation they all performed well structurally with no rupture or significant structural damage.

Because they were marginally more expensive than conventional slabs and recognised as being superior, they were nearly always used on potentially problematic sites. In some bad areas of liquefaction they sometimes had a tendency to tilt (the worst the writer observed was 150mm) as did other slabs on grade. They did however keep their integrity without rupture or damage and the house remained liveable and functional.

In badly hit areas failure of public infrastructure including sanitary sewer and water supply applied to all house construction types, and temporary supply of portaloos and water tankers was provided. However waffle slabs served their function and remained intact.

The following excerpt from the DBH guidance document for earthquake reconstruction- is of interest;

"An observation from the Canterbury earthquake is that there are significant advantages in people being able to remain in their homes for as long as possible after the event. This means employing building practices to limit the damage so that buildings remain habitable and ultimately gain a Green (Inspected) placard from council. Encouraging wide, stiff foundation systems such as stiff rafts (eg, waffle slab) or stiff inter-connected footings is considered to be the best way of improving performance with respect to both amenity and collapse, and thereby improving homeowners' confidence in repairing or rebuilding these locations."

Waffle slabs are cast on top of the ground rather than having foundations. However they did not tend to slide as one would imagine. In one case movement was measured relative to services after the 7.2 magnitude earthquake and found to be 5mm in one direction and 10mm in the other.

This lack of sliding is thought to be possibly due to a “Limpet” effect where atmospheric pressure bearing down on the top of the slab without the chance of air rapidly getting underneath is sufficient to hold the slab down. For whatever reason waffle slabs were not observed to slide and ground shear keys were not used.

There are advantages in casting on top of the ground as should a rupture occur directly under a building the waffle slab is free to slide rather than be pulled in half having foundations locked into the ground each side of such a rupture with conventional slabs on grade and strip footings.

Waffle slabs have enough integrity to be relevelled should such be required. It is further anticipated that it should be possible to cut if necessary and uplift, transport and relocate a waffle slab home complete with brick cladding. However where a heavy tile roof (10 tonnes) has been utilised, it would be best to replace it with a light weight roof (1.7 tonnes).

Waffle slabs if adequately reinforced (recommend DH16s in the bottoms of the ribs) and less than 25m long act as one monolithic block and do not tend to crack. This may be partially due to being built on a polythene sheet on top of the ground without foundations locking it into the ground like grader blades and not permitting the concrete to naturally shrink and take up dry shrinkage.

Historically for slabs over 25m long, a dowelled construction joint has been recommended. However, under seismic conditions this compromises the integrity of the building. With larger slabs the writer considers that it would be preferable to set up a grid of crack inducers (CANZAC or similar) across the slab under the mesh on top of the polystyrene pods at the points of contra-flexure of the topping slab spanning between ribs but in such a manner as to not compromise the edge cantilever action of the slab.

6. TILTING

Under severe liquefaction conditions buildings founded on slabs on grade can tend to tilt. However this tendency does not tend to happen on light timber framed buildings raised off the ground and founded on shallow pile foundations. Possibly part of the reason is that under liquefaction conditions ground water tends to migrate upwards. Under a house on piles it can come up and flood the subfloor area releasing local pore-water pressure. Whereas under a slab on grade water is entrapped without adequate drainage, leading to the slab acting like a “waterbed”, very sensitive to weight distribution, like a top heavy boat.

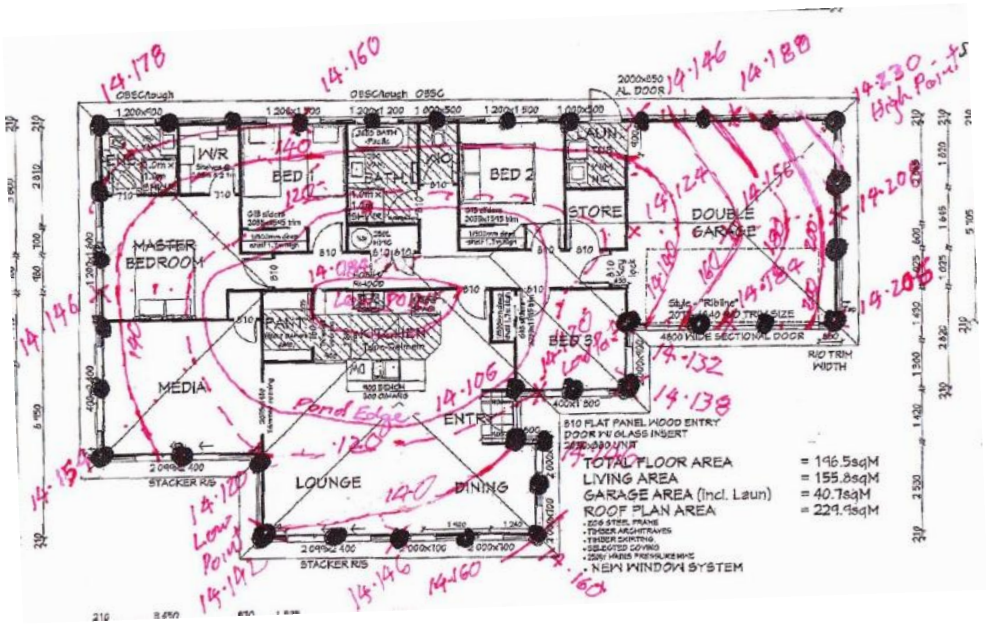
Liquefaction also does not tend to occur evenly, as evidenced during the earthquakes by liquefaction on the roads causing cars in several instances to partially sink with the front disappearing down into liquefaction and the rear wheels still on firm pavement.

The secret to overcoming the problem of tilting would be to build a reinforced earth sub-grade raft extending out beyond the foot print of the building perhaps 3m all around and of the order of 300mm to 1m thick. Like a boat this will give the structure wider beam and keep it more stable under liquefaction conditions.

7. **PILING**

Piling does work well in combination with a waffle slab flooring system usually supporting every second nodal point, where liquefiable materials are shallow and competent load bearing gravels are near surface such as at Halswell where good bearing is located at depths of typically 1 to 2m.

Piles however can be worse than useless where deep liquefiable soils are encountered such as in the eastern suburbs of Christchurch where potentially liquefiable soils are as much as 32m deep before peat is encountered, and depth to suitable gravel is uncertain. In such an area the writer has seen timber piles probably about 6m long used as friction piles, around the perimeter of an ordinary reinforced slab only (this was <u>NOT</u> a waffle slab) sink differentially of the order of 120mm. The piles then lock the structure in place preventing relevelling of the building using grouting techniques.



On the other hand on the St Andrews school site a new building was piled to an intermediate depth of 7m to competent gravel. The 22 February 2011 earthquake then occurred and the upper poorly consolidated soils liquefied and consolidated 200mm, taking adjacent and interconnected buildings, services and access down with it, leaving the new building sticking out of the ground by 200mm. Thus making the piling "cure" worse than the "disease".

Christchurch central is underlain by the Riccarton gravels at a depth of 20 to 25m, but even if it were economic to pile to such depth for a house, the layer is an aquifer with its own set of problems, and differential settlement within these gravels could still occur.

Lateral flow of the ground of over 1m has been observed by the writer and under such circumstances the stresses and eccentricities induced into piles may render then worse than useless.

Piling therefore is not a silver bullet in liquefiable ground and needs to be thought about carefully. Skin friction under seismic conditions cannot be relied upon and end bearing at times can be dubious. There would be merit in providing a socket end to piles so that should differential settlement occur they would not hold the building down but would permit relevelling using a grouting method.

8. BASE ISOLATION

Although Base Isolation was practiced by the Ancient Greeks and more recently was largely developed in New Zealand by Robinson Seismic of Wellington, it unfortunately has not been as widely used in NZ as overseas.

There is only one building in the south Island using Base Isolation. The Christchurch Women's Hospital building designed by Holmes Consulting Group on the fringe of the red zone that survived intact with no damage other than a broken water pipe (possibly due to poor detailing or installation), and the hospital has been fully functional after all the large earthquakes which have struck Christchurch.

Because of the perceived cost and complexities of the system it is usually the preserve of buildings such as Parliament Buildings, Te Papa Museum and Hospitals. However, base isolation for larger buildings can save money in overall construction costs by reducing the complexities of the superstructure with a target saving of 5% of structural construction costs. Further the cost saving in disruption of service to the community etc can be 4 to 8 times the cost of preventative measures.

When one considers the damage sustained, base isolation even for residential buildings needs to be seriously considered and a cost effective solution developed.

The writer has given this matter serious thought, filed a patent and is currently working on such a solution but can say no more until it is developed. Hopefully I will be in a position to present a paper on this at the next conference.

To put Base Isolation into perspective, it can reduce the impact experienced by the structure and its occupants and contents, significantly reducing the impact by as much as 70% to 90%. Many of the older double brick buildings if they had had such a foundation would still be standing. Pallet racks would not topple, fridge doors would not fly open spilling their contents, many buildings would not have collapsed or been write offs, lives would be saved, injuries reduced, property damage minimalised, insurance premiums would be kept within reason, etc.

One however has to be aware that the natural frequency of some base isolation systems can be dangerously close to the longer critical periods induced in the Christchurch case by the deep sedimentary bowl effect under the city. There is therefore the risk that some base isolation systems could resonate making the situation worse than without them. This could largely be overcome by using a friction system as friction systems do not have a natural frequency, however some displacement after the event could occur requiring the building to be put back into place.

9. CONCLUSION

The humble domestic concrete slab is a very important component in getting things right first time. Because there are so many of them, the cost of poor detailing and construction techniques have had a significant effect on the economy and wellbeing of the community running into billions of dollars worth of damage in Christchurch and causing displacement and trauma to people unnecessarily.

Over 10,000 homes have been written off and a high percentage of these, particularly among newer homes are due to poor slab design and construction. This has been the "Achilles heel" of houses built in accordance with the New Zealand Standard NZS3604 which otherwise have generally fared well.

However many habitable houses with unreinforced cracked concrete floors are being written off unnecessarily, due to the wording of insurance policies and ignorance with respect to the reparability of such.

Unreinforced slabs are now no longer permitted for new construction of residential houses, and experience has proved the worth of waffle slabs. There is however still room for improvement with ground improvement such as grout injection for densification or soil rafts as outlined where necessary.

There is potential for a very low cost, effective base isolation system to be developed to protect occupants, the superstructure and contents. Hopefully I will be in a position to present a paper on this at the next conference.

REFERENCES;

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[2] http://www.firth.co.nz/about-firth/company-info/element-magazine/element-magazine-june-2011/eq-ribraft---a-new-and-improved-flooring-solution.aspx