Spatial maintenance of the New Zealand cadastre in response to earthquakes

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Key words: deformation, earthquake, cadastre, datum

SUMMARY

The Darfield 2010 earthquake in New Zealand caused metres of offset across surface ruptures and significant deformation over a wide area. Further movements were caused by subsequent major aftershocks although, in those cases, the fault rupture did not reach the surface. The rupture and distortion of the cadastral fabric creates challenges for the cadastral survey and geospatial communities. This distortion can be included in the deformation model that is defined for the semi-dynamic New Zealand Geodetic Datum 2000. Users of the datum have competing demands for stability, accuracy, and currency of coordinates. The challenge is to implement the distortion of the cadastre into the deformation model in a manner that best meets these demands for cadastral surveyors and the geospatial community. The proposed approach adds a "patch" to the datum deformation model that defines the deformation caused by the earthquake and updates coordinates where deformation is intense. In the region of intense deformation and boundary rupture, it is hoped that a combination of geophysical fault modeling and surface observations can be used to refine cadastral coordinates reasonably close to the fault trace.

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1. ABSTRACT

The Darfield 2010 earthquake in New Zealand caused metres of offset across surface ruptures and significant deformation over a wide area. Further movements were caused by subsequent major aftershocks although, in those cases, the fault rupture did not reach the surface. The rupture and distortion of the cadastral fabric creates challenges for the cadastral survey and geospatial communities. This distortion can be included in the deformation model that is defined for the semi-dynamic New Zealand Geodetic Datum 2000. Users of the datum have competing demands for stability, accuracy, and currency of coordinates. The challenge is to implement the distortion of the cadastre into the deformation model in a manner that best meets these demands for cadastral surveyors and the geospatial community. The proposed approach adds a "patch" to the datum deformation model that defines the deformation caused by the earthquake and updates coordinates where deformation is intense. In the region of intense deformation and boundary rupture, it is hoped that a combination of geophysical fault modelling and surface observations can be used to refine cadastral coordinates reasonably close to the fault trace.

2. BACKGROUND

The geodetic datum in New Zealand, NZGD2000, is defined as a semi-dynamic datum (Blick et al., 2003). "Semi-dynamic" means that the datum defines coordinates at a reference epoch (1^{st} January 2000), and defines a deformation model of the general tectonic movement and distortion of the land mass of New Zealand. The epoch 2000 coordinates are defined in terms of ITRF96, epoch 2000. Using the deformation model the 2000.0 coordinates of a point can transformed to the NZGD2000 coordinates of that point at any other epoch. Similarly, the deformation is used to transform observed coordinates of points back to the NZGD2000 reference epoch.

The deformation model comprises a secular component, which represents the ongoing approximately constant velocity movement and distortion of New Zealand, resulting from the relative movements at the boundary of the Australian and Pacific tectonic plates that the country straddles, and a series of "patches" to represent the deformation from specific events (to date only earthquake events), that have caused coherent regional deformation.

The secular component of the deformation is treated as constant and is only modified as new observations and improved analysis refines our understanding of it.

The non-secular component is expected to change – a new patch is generated for each event. The implementation of a patch happens some time after the event, once the affected area has been surveyed and a model of the deformation has been calculated. Blick et al (ibid) identified two main options for implementing a patch in the datum.

The more "obvious" way is what is termed a "forward" patch. The patch defines the deformation that occurs as a result of the earthquake. To calculate the coordinates of an affected point after the earthquake this deformation is added to the NZGD2000 reference coordinate, in addition to the secular component.

An alternative that has been proposed is a "reverse" patch. In this model the non-secular deformation predicted by the patch deformation model is added to the epoch 2000 coordinates of points – in effect the coordinates are patched. The NZGD2000 coordinates still do not represent the current location of points, as the secular deformation component must be added to calculate this. They also do not represent where the point actually was in 2000.0. One way of thinking of the updated coordinates is that they represent where the point would have been in 2000.0 if the earthquake had happened before that date. Conversely, if we were to pretend that the earthquake had not happened, they represent the current post-earthquake coordinates propagated back to the datum epoch of 2000.0 using the secular deformation model.

This is called a "reverse" patch because to determine coordinates of a point at time before the earthquake (for example in geodetic calculations using old observations) the deformation from the earthquake must be subtracted from the NZGD2000 coordinates. The deformation model includes a patch that applies for calculating coordinates before, rather than after, the earthquake.

The driver for using a reverse patch is to meet the needs of most users of the geodetic system, who do not have any means of applying a deformation model, and who require coordinates that meet moderate accuracy standards in terms of the current (post-earthquake) locations of points. In particular they expect reasonable local relative accuracy – the distance or bearing calculated between two coordinates should be close to that measured between the corresponding points.

Winefield et al. (2010) discussed the implementation of a patch for the Dusky Sounds 2009 earthquake. They determined that the deformation from this earthquake did not compromise the local relative accuracy requirements of most users, so it could be implemented as a forward patch rather than a reverse patch. The same argument has applied to all earthquakes in New Zealand since the datum was established in 2000 – that is until September 2010.

The September 4 2010 magnitude 7.1 Darfield earthquake ruptured hitherto unmapped faults in the Canterbury Plains on the South Island of New Zealand, and caused displacements of several metres. This was the first of a protracted and ongoing series of earthquakes including three of magnitude 6, the most recent on 23 December 2011.

Although the subsequent earthquakes (and particularly that of February 22, 2010) were much more destructive to life and physical infrastructure, the Darfield earthquake had the largest impact on the geodetic datum and "spatial infrastructure", and it is the deformation from this earthquake that is discussed here.

The Darfield earthquake caused a 30km rupture, across which displacements of up to 5 metres were observed (Quigley et al. 2010). In addition to the direct observation of displacements across the fault rupture, the deformation caused by the earthquake was measured by reobservation of approximately 250 geodetic marks (both Global Navigation Satellite Systems - GNSS marks and precise levelled benchmarks), comparison of satellite based InSAR imagery from before and after the earthquake, and airborne LiDAR resurveys.

The geodetic observations and InSAR data have been analysed to determine a geophysical model of dislocations on rectangular fault planes (Beavan, 2012), which in turn can be used to reconstruct the surface dislocation field, using the formulae originally developed by Okada (1985). The geophysical model is unusually complex, comprising six fault planes, each of which is subdivided into many rectangular "sub-faults" to account for the variation in the slip vector across the fault plane..

Figure 1 compares the observed horizontal displacements and those determined from the geophysical model at the survey marks. Clearly there are several marks close to the fault at which the model does not reflect the observed displacement well. However beyond about 10km from the fault rupture the model fits the deformation well. The main exceptions are some points to the east (in the suburbs of Christchurch) which have been shifted (relative to the deep fault movements) as a result of local liquefaction of the near surface soil layers.

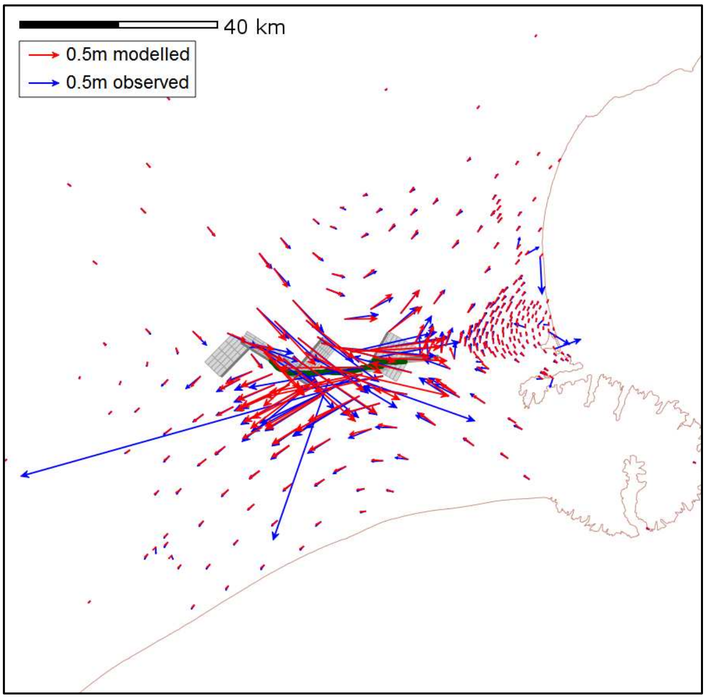

Figure 1: Observed and modelled displacements due to the Darfield earthquake. The grey rectangles are the model fault planes. The dark solid line is the surface fault trace

Clearly this earthquake has moved points to an extent that pre-earthquake coordinates of points and observations between points no longer represent their current values accurately enough for many users. In this paper we discuss the impact on two main user groups – cadastral surveyors, and maintainers of geographical information systems (GIS).

Implementing the Darfield earthquake deformation into the NZGD2000 deformation model Winefield et al (ibid) presented a methodology for implementing a patch to represent the deformation from an earthquake in the NZGD2000 datum. This was developed in the context of the 2009 Dusky Sounds earthquake, and assumes that a geophysical model of the surface response to the earthquake (such as that described above) is available.

To summarise, the main factors to be determined in implementing a patch are:

- the geographical extents over which deformation must be accounted for, calculated as the area over which the modelled deformation compromises the accuracy specifications of the datum for the highest accuracy usage, such as for national geodetic adjustments. Based on New Zealand datum accuracy standards (LINZ, 2009) this is the area over which either the movement is greater than 0.02 metres or, more demandingly, the distortion is greater than 4 parts in 10^8.

- the smaller extents over which the deformation should be represented by a "reverse patch", updating NZGD2000 coordinates explicitly so that their relative accuracy requirements of the coordinates (in terms of their current positions) meet the lower accuracy needs most cadastral and geospatial users of the datum. For the New Zealand accuracy standards this is the area over which the movement is greater than 0.06m or the distortion is greater than 2 parts in 10^5.

Once these extents are determined there are additional practical decisions about how the deformation is to be represented. NZGD2000 deformation patches may be implemented using a combination of grid and triangulated networks of points at which the displacement is defined, and between which it is interpolated using a bilinear (for a grid) or linear (for a triangulated network) interpolation. These choices are guided by:

- the accuracy of the representation of the modelled deformation, which determines the spatial resolution of the representation

- the efficiency of using the patch, which encompasses the size of the data set representing the patch, and the efficiency of calculating the patch displacement at any given location.

Although the Dusky Sounds earthquake was larger than the Darfield earthquake its impact on the datum is less, as the epicentre was offshore. Over the land area of New Zealand the deformation is well modelled by an elastic response to the fault dislocation.

This is not the case for the Darfield earthquake, for which the surface deformation includes fault rupture and other local effects which are not handled by the geophysical model of deformation

None the less, the geophysical model does accurately represent deformation at distance from the epicentre as seen above, and even close to the faulting it generally represents the best information we have. In effect the geophysical model is used as a means of interpolating and smoothing the observed dislocation at specific locations, as well as incorporating information from other sources (for example InSAR) that does not explicitly measure horizontal deformation.

Applying the methodology of Winefield et al to the Darfield earthquake, we find the deformation must be modelled to a distance of approximately 200km from the epicentre (Figure 2). Over most of this area however the deformation is not of practical interest to users of the datum other than those doing geodetic adjustments combining observations from before and after the earthquake.

The area requiring a reverse patch is much smaller, extending to only about 50km from the epicentre. Over the remainder of the modelled area the deformation could be represented as either a reverse patch (updating coordinates) or a forward patch (leaving the coordinates unchanged, and incorporating this component of the deformation into the NZGD2000 deformation model).

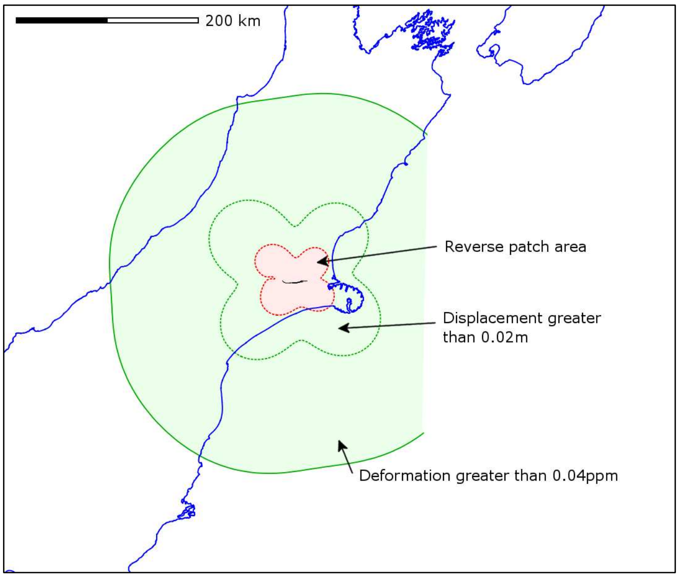

Figure 2: Extents over which the Darfield earthquake deformation needs to be modelled to support the NZGD2000 accuracy standards

Within the reverse patch area is a region close to the fault (not illustrated) in which the geophysical model fails to represent the actual deformation. The model treats the earth as a uniform elastic half space, and in the region of severe deformation close to the fault this is too simplistic to accurately predict the deformation.

In this region the only means of obtaining accurate current coordinates is by resurvey – geophysical modelling cannot reflect the complexity of the inhomogeneous, inelastic response here. The extent of this region of poor modelling obviously cannot be determined from the geophysical model - it can be estimated by analysing how well the model fits the observed data and by inference from direct observation of surface disruption and displacement.

Although further surveys are planned to obtain more detailed measurement of the deformation and its impact on the cadastre, these have been delayed due to the subsequent earthquakes, which have both complicated the deformation model, and diverted resources from these surveys to more pressing work in reconstruction and measuring their impact. The measurement of the deformation from both the Darfield earthquake in 2010, and the subsequent events in 2011 is still underway 18 months after first earthquake.

3. THE IMPACT OF DEFORMATION ON GEOSPATIAL DATA SETS

Increasingly database systems are incorporating spatial entities and applying spatial analysis. Essentially this involves using coordinates to reference physical features and to define relationships between them. The accuracy with which the coordinates reflect the current location of the features they represent is obviously degraded by tectonic deformation. The required accuracy of such systems is application dependent and very varied. A database of pizza outlets may only require an accuracy of a few tens or even hundreds of metres and can safely ignore deformation. On the other hand a database of subterranean utilities may hope for accuracies of a few decimetres or better, in which case it becomes critical to account for it.

At present few, if any, geographical information systems (GIS) support the use of a deformation model to map coordinates between different epochs. So the coordinates of spatial objects must represent their location at a specific time. In New Zealand the preferred coordinate systems are based upon the NZGD2000 datum, which references points by their location at epoch 2000.0 (in terms of ITRF96).

In principle the NZGD2000 coordinates of features are not changed by the Darfield earthquake, since the earthquake occurred after 2000. In practice however most users expect to update coordinates of features near the fault to reflect the changes from the earthquake. Indeed, in the vicinity of the faulting the pre-earthquake coordinates are not useful – the relative errors of the coordinates are too great for many uses which require accurate current coordinates.

This is the principal driver for using a “reverse patch” - to ensure that the NZGD 2000 coordinates are useful without users having to understand or apply the deformation model. “Useful” is taken to mean meeting some accuracy specification (for both absolute and relative positions) in terms of the current actual positions of the features that the coordinates represent.

However while it avoids the need to use a deformation model on a day to day basis, applying a reverse patch to a GIS data set may still be difficult to implement in GIS systems. It requires mass updating of feature coordinates. How are GIS users to apply this update in their GIS systems?

Although GIS systems do not directly support applying a reverse patch, many GIS users are accustomed to changing coordinates of features on a more local basis.

Many GIS systems are based on the spatial cadastre in the New Zealand survey and title database (Landonline) which is maintained by Land Information New Zealand (LINZ). These systems must already manage coordinate changes. Whenever a surveyor lodges a new cadastral data set into Landonline the observations in the data set are used to recalculate coordinates of points in the vicinity of the survey, and these coordinates are propagated out to users of the cadastral data. In some cases these coordinate changes may be much larger than those resulting from the earthquake deformation, particularly when new surveys encroach on areas for which the existing coordinates are based on inaccurate source data, such as areas where the database was populated by digitizing survey record sheets. LINZ is also systematically applying re-adjustments to areas of spatially inaccurate cadastral coordinates in response to user requests for improved accuracy.

So in principle updating the coordinates is not an issue for users of the cadastral data – the update will be managed by LINZ. The difference between an update due to applying a reverse patch and routine database updates is just one of scale – the reverse patch affects a much greater number of features. Often users' databases will include their own spatial data sets that need to be aligned with the cadastral base data (for example data representing underground utilities such as water reticulation). If this realignment is automated then there may be no problem with updating a much larger number of points. If users are manually realigning data this may not be practical.

Of course many New Zealand GIS data sets are not based on or linked to the cadastral data set. How are the managers of these data sets to apply spatial updates resulting from the earthquake? Generally they will not want to resurvey their entire data set. For these data sets perhaps the only practical way to update the data is to update coordinates using a deformation model.

Although at the moment most GIS systems do not explicitly provide tools to do this, they may provide similar functions which could be exploited for the task, (for example tools to convert data between different coordinate systems or to remove distortion in data digitized from old plans). It will require a specialist to adapt these tools for applying the deformation model to a data set.

Many GIS applications combine data from multiple sources. To ensure that spatial entities are aligned properly, users may need to be aware of which data sets have been patched, and which have not.

Ideally this would be handled by the GIS software in an analogous way to that in which coordinate systems are managed, by tracking the version of the deformation model and the epoch of the spatial definition of features in the data set. Applying a coordinate update for a reverse patch implies adopting a new version of the deformation model, since the model must now incorporate the reverse patch to predict pre-earthquake coordinates. So if GIS software tracked the deformation model version used in a data set, the users could identify which patches have been applied to the data.

In practice however, the coordinate updates from patches may be no greater than spatial updates for other reasons, such as resurveying features, and users will manage the potential misalignment of data sets from patches in the same way as misalignment from any other source.

It will not be possible to handle deformation in a consistent and reliable way in GIS data sets until the software provides a built in capability to manage deformation and deformation models in a similar way to that in which coordinate systems are currently managed. In the meantime database managers and users must rely on custom scripting to apply updates and must be aware of potential issues due to deformation when combining data sets.

4. THE IMPACT OF DEFORMATION ON THE CADASTRE

The impact of the earthquake deformation on cadastral surveying is not resolved by a simple (or even a complex) deformation model for two reasons.

- Firstly, in New Zealand cadastral definition is based primarily on physical marks. The marks are tested by remeasuring lines to other nearby marks to prove that they have not been disturbed. In the immediate vicinity of the fault this test will appear to fail. However even quite close to the fault, most points will move in a reasonably consistent manner provided there has not also been highly localised movement of the surface soil layers due to liquefaction or landslip. As most of the area around the fault rupture is rural land, the accuracy with which cadastral observations and boundary positions must be reproduced is much less than it would be in an urban area. The reverse patch area in Figure 2 is the region in which urban cadastral definition is compromised by the deformation. The region in which rural definition is compromised is much smaller.

- Secondly, cadastral boundaries are controlled by legal definition, rather than the physical location on the ground, so the impact of the deformation on the boundary definition must be assessed from a legal point of view.

There are 4 main categories of ground movement that affect cadastral boundaries from a legal perspective:

- **Continuous tectonic deformation** where the surface of the earth follows deep movement of the bedrock.

- **Earthquake rupture** where the surface of the earth generally follows deep movement of the bedrock. Where the fault trace reaches the surface, highly localised lateral and vertical movement will be evident.

- Earthquake triggered **landslides and rock-fall** leading to catastrophic land failure.

- Earthquake triggered **soil liquefaction** and consequential lateral spreading and slumping in the soil and subsoil layers.

The first two categories involve deep-seated movement which occurs in the bedrock. The surface layers generally follow the deep seated movements.

The second two categories involve shallow surface movement which occurs locally in addition to the deep seated movement.

4.1 Boundary marks (including natural boundary)

The New Zealand cadastral survey system has a hierarchy of evidence which places high evidential value on physical realisations of the legal boundary such as natural boundaries and undisturbed boundary marks.

Significantly lower evidential value is assigned to survey measurement, legal boundary dimensions on title documents or the coordinates derived from them. This numerical evidence is only valued to the extent that it can be reliably used as evidence of the original location of survey marks that have since been destroyed or disturbed.

The legal definition of cadastral boundaries does not make any formal use of coordinates, though surveyors do use coordinates within their survey software to locate marks, and coordinates are used to assist in quality control of submitted cadastral data sets.

Evidence of physical landowner occupation (for example fencing) may be relied on by a cadastral surveyor but only if it can be shown that the occupation was originally located correctly on the boundary. This depends on the judgement of a cadastral surveyor applied to a particular boundary. It therefore is not suitable for large scale spatial maintenance of cadastral boundaries.

Water boundaries that move slowly and imperceptibly are usually subject to the principles of accretion and erosion which means that the boundaries move with the wet/dry margin of the water feature. However the water margin may change suddenly (a process called avulsion), for example during a flood or as a result of diversion caused by an earthquake. In this case the legal boundary remains in the position it occupied before the avulsion took place.

4.2 Disturbed Boundary Marks – Deep-seated Movement

The above legal principles were developed in common law before the potential impact of earthquakes and tectonic deformation was known. How does such deformation affect the definition of a mark being “disturbed” or “undisturbed” given that all of New Zealand is subject to at least continuous tectonic deformation and periodically to earthquake rupture?

The ongoing tectonic deformation of up to 50mm/year does not disturb marks in a cadastral sense, even though with modern survey equipment using Global Navigation Satellite Systems (GNSS) it is readily detectable. This is because the movements are relatively uniform within the extents of a cadastral survey – boundary dimensions and cadastral measurements are not significantly affected. The survey marks, soil and subsoil move slowly and consistently with the deforming bedrock, and the boundaries move with them.

In the New Zealand cadastre, boundary marks have been treated as undisturbed where they have retained the same relationship to the bedrock – or where we had no reason to doubt that this was the case. This system means that in the great majority of cases there is almost no disruption to landowners or cadastral surveyors resulting from continuous tectonic deformation.

Significant deformation due to earthquake rupture occurs periodically in New Zealand, typically every decade or so. The time and place of the earthquake is well known after the event. As in the case of the Darfield earthquake, the movement may be several metres and may extend over tens to hundreds of kilometres. If the fault trace reaches the surface of the earth, the rupture along the trace will be apparent to landowners and members of the public.

Away from the fault trace, the movement will not be readily apparent to the public but will be detectable to surveyors using GNSS or even conventional survey equipment.

The initial deformation from the earthquake is contributed to by post-seismic deformation over many days or months as seismic stress is relieved. The movement is initially reasonably rapid but decays over time. It may be further compounded or re-activated by major aftershocks, often on different faults and which have their own deformation pattern.

Apart from a region close to the faulting the effect on the cadastre is for the most part similar to that from ongoing deformation – the subsoil, soil, marks and legal boundaries all move consistently with the bedrock, and the effect of the deformation is not significant on cadastral measurements. On this basis a decision has been made to follow the same principle for earthquake related deformation as for ongoing secular deformation. Where it appears that the surface layers (including boundary marks) have generally followed the deep-seated rupture in the bedrock, those marks are considered to be undisturbed and the boundaries remain attached to them after the earthquake.

Closer to the fault trace this principle still applies but boundaries definitions will require recalculation due to distortion. Across the fault trace, new angles may be added to previously straight boundaries.

This principle may not fully apply in the immediate vicinity of the fault trace where highly discontinuous movement within the soil layers is also possible. For example Figure 3 shows a section of the fault trace from the Darfield earthquake. It can be seen that while the fault trace is reasonably localised, nevertheless there is a zone ranging between a few metres to tens of metres within which the deformation is highly variable and unlikely to be able to be accurately modelled.

Figure 3: A section of the Darfield earthquake fault rupture showing the complexity of the local deformation across the trace. (*GNS Science geologists Richard Jongens, Simon Cox and David Barrell)*

This local variability will often be relevant to the reinstatement of property boundaries.

4.3 Disturbed Boundary Marks – Shallow Surface Movement

Where there is evidence of movement of the surface soil and subsoil layers relative to the bedrock, boundary marks are considered to be disturbed, and no longer support the definition of boundaries. There is well established common law in New Zealand and many other countries that boundaries do not move when boundary marks are moved by landslip or similar events. This is because the marks are considered to be disturbed and no longer have any evidential value as to the location of the boundary. In these cases, the challenge for the cadastral surveyor will be to establish the original location of the boundary before the landslip occurred. Nearby survey marks that are assessed as undisturbed are used for this purpose.

In addition to the well recognized landslip and rock fall disturbance, the Canterbury earthquakes also caused extensive liquefaction, especially in the suburbs of Christchurch. Liquefaction is a phenomenon which occurs during a period of intense shaking in an earthquake. Water saturated sub-surface layers are shaken apart and behave as a liquid. Typically they break through the surface causing flooding and depositing silt. The liquefied layer also lubricates the surface layers, allowing them to move laterally. Movements associated with liquefaction can be of the order of decimetres to metres.

In principle the movement resulting from liquefaction is similar to that during a landslide, and common law dictates that the cadastral boundaries do not follow this movement – they stay in the their original location. However this can be complicated if the survey marks around a property all move together. In this case, they may seem to be undisturbed in relation to each other but will have come to rest in a new location. Also if all the survey marks in a broad area have been disturbed by liquefaction, or subsequently disturbed by recovery efforts, re-establishing the original boundary positions will be problematic.

While boundaries are still considered to have moved along with the deep-seated movement of the bedrock, in practice it may be difficult to quantify this where reliable nearby survey control is unavailable, and where the deformation is expected to have significantly altered observations to more distant marks. In this case, greater reliance may be placed on the geophysical fault model to predict deep movement and separate it from any localised surface movement, so that boundaries can be correctly reinstated using more distant undisturbed control.

4.4 Avulsion

The most common form of avulsion is that resulting from sudden large floods. However other events can trigger a sudden shift in the position of a water margin such as the banks of a stream.

In the case of the Darfield earthquake, the fault trace crossed a medium sized river – the Hororata River. This involved some horizontal movement but, more significantly, upthrust on one side of the fault trace and down-thrust on the other side, resulted in a new channel into which the river diverted. While the cause of this avulsion is different from the typical causes, such as flooding, the impact on the cadastre is the same. Boundaries previously defined by the river margin are not realigned to follow the new river course – instead they are considered to remain in the pre-earthquake position – to the extent that this can be determined.

5. CONCLUSIONS

Earthquake related deformation presents challenges at many levels for the New Zealand cadastral system and underlying geodetic system, in addition to the physical challenges it creates for surveyors trying to access the physical infrastructure of the system (ground marks) and to find consistent reliable control for their work.

The impact is felt both by cadastral surveyors attempting to redefine cadastral boundaries that may be distorted by the earthquake, and by the geospatial community who need to maintain the spatial integrity of their data sets to reflect the movements caused by the earthquake. Essentially then the maintenance of the cadastre needs to address two issues, which are largely independent:

- Firstly, what is the movement of the "solid bedrock" of New Zealand. This is largely answered by geophysical modelling based on comparison of observations (such as GNSS vectors and synthetic aperture radar images) from before and after the earthquake.

- Secondly, how are parcel boundaries re-established, which is particularly an issue where the surface land movement is apparently not consistent with the bedrock, or very close the fault rupture, where the bedrock has not moved coherently. Generally the existing common law provides guidance, however in areas of extensive disruption, such as those affected by liquefaction, it may be difficult to apply in practice. Here the geophysical model may be needed to re-establish boundaries correctly from more distant survey control marks.

The following table summarises the impacts of each category of deformation on the New Zealand cadastre:

Movement Category	**Spatial variation**	**Temporal variation**	**Boundaries follow movement**	**Spatial model**
Tectonic deformation	Continuous Broad scale Nearly block shift at the parcel level	Continuous secular nearly linear	Yes	Datum deformation model
Earthquake rupture (remote zone)	Continuous Broad scale Nearly block shift at the parcel level	Episodic, Near instantaneous followed by decaying post seismic movement	Yes	Deformation patch
Earthquake rupture (near zone)	Continuous Nearly linear distortion at the parcel level	Episodic, Near instantaneous followed by decaying post seismic movement	Yes	Deformation patch
Earthquake rupture (rupture zone)	Discontinuous Non-linear	Episodic, Near instantaneous followed by decaying post seismic movement	Yes but depends on survey evidence	Interpolate across rupture Reliable only after re-survey
Landslip / Rockfall	Discontinuous	Episodic, Near instantaneous	No	No specific model (datum model and patch generally applied to area)
Liquefaction	Generally discontinuous	Episodic, Near instantaneous	Generally No. May be resolved by re-survey.	No specific model (datum model and patch generally applied to area)
Natural boundary avulsion	Continuous but localised	Episodic, Near instantaneous	No	No specific model (datum model and patch generally applied to area)

The strong value placed upon physical evidence in defining cadastral boundaries in New Zealand means that the legal definition of the cadastre, upon which rights and ownership are based, is robust against all but the most extreme deformation resulting from the earthquake.

On the other hand the spatial definition of the cadastre and other features in GIS systems is not able to handle deformation well. The spatial accuracy of many GIS systems is compromised by the Darfield earthquake deformation. Although this deformation can generally be defined with good accuracy by the geophysical model there is no straightforward means of applying to spatial data, and its application will require specialist support.

6. ACKNOWLEGEMENTS

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BIOGRAPHICAL NOTES

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