Managing the dynamics of the New Zealand spatial cadastre

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Abstract

In 1995, the concept of a dynamic cadastre, based on a dynamic geodetic datum, was proposed for New Zealand to recognize that all cadastral boundaries in New Zealand are in some form of motion – relative to each other and relative to the geodetic datum which is also in motion. Subsequently New Zealand implemented a semi-dynamic geodetic datum which is accompanied by a deformation model. Later, a survey conversion project resulted in the boundaries of 70% of the land parcels in New Zealand being coordinated to survey accuracy in terms of the semi-dynamic datum. These boundaries continue to be adjusted by least squares as new cadastral survey observations and geodetic control stations are integrated into the network. However the deformation model has not, in practice, been routinely applied to cadastral boundaries. In 2010 and 2011, the Canterbury region in the South Island of New Zealand was subjected to a sequence of earthquakes that caused widespread damage and resulted in some boundaries being ruptured by up to 4 metres. A set of localized deformation models was developed to model the seismic movements. Propagating these movements through to all affected cadastral boundaries has proved to be a major undertaking which is described in this paper.

1 Introduction

Cadastral boundaries, to be useful, need to be able to be realized in the real physical world where public and private rights, restrictions and responsibilities in land apply. As an important part of the land-based property rights system, it is critical that they be well documented, managed and updated in public databases – whether digital or paper-based. We use the term “physical cadastre” here to describe the physical manifestation of boundaries in the real world. The term “spatial cadastre” is used to describe the digital or paper records that describe the shape and location of those boundaries in cadastral record systems.

Boundaries in the physical cadastre may move over time. So may the representation of these boundaries in the spatial cadastre as new survey information is accepted which indicates that the boundary coordinates are incorrect and as the spatial cadastre is reviewed and readjusted as a consequence. The mechanisms that cause, manage and record these movements are naturally related to each other (a new boundary survey may result in a new accepted position for the boundary and therefore changed coordinates) but may also operate quite independently and at different times.

New Zealand sits astride the boundary between the Australian and Pacific tectonic plates. During major earthquakes, the movements of cadastral boundaries in the physical cadastre near the fault are apparent to everyone. At other times or further from the fault, the very slow, broad-scale and inexorable deformation caused by tectonic plate movement is generally invisible to landowners but does become apparent over time to surveyors and managers of the spatial cadastral system. The dynamics in the cadastre induced by earth deformation are more obvious in New

In: S. Winter and C. Rizos (Eds.): Research@Locate'14, Canberra, Australia, 07-09 April 2014, published at http://ceur-ws.org

Zealand than in other countries such as Australia. Physical cadastral boundaries are in motion relative to other boundaries, relative to the national geodetic datum, and relative to international terrestrial reference frames.

Grant (1995) proposed the development in New Zealand of a dynamic geodetic datum which would support a system of dynamic cadastral boundaries. The most obvious driver for this model was earth deformation. It had become apparent by 1995 that the accuracy of the geodetic system could not be maintained if it was assumed that geodetic control marks were fixed in space in relation to each other or in relation to the axes of the coordinate system.

This thinking led to the implementation of a new datum for New Zealand, NZGD2000 (Grant & Pearse, 1995; Grant & Blick, 1998; Blick et al, 2003). It was implemented as a semi-dynamic datum, meaning that coordinates are defined at a reference epoch 1 January 2000, and that positions at other times are determined by applying a deformation model. The datum is aligned with ITRF96 at epoch 2000.0. Initially the deformation model was a constant horizontal velocity field defined by interpolating on a gridded representation. It was understood that over time the deformation model would be updated, both as better information about the tectonic deformation was acquired, and as events such as earthquakes introduced additional deformation components.

The deformation model handles earthquake related deformation as "patches", localized deformation models of limited spatial and temporal extent, that are added to the main secular velocity model. It was recognized (ibid) that most users of spatial data did not have the knowledge or tools to apply a deformation model, but nonetheless desired spatial data that reflected the current relative positions of data sufficiently accurately. To support these users the concept of "reverse patches" was developed, whereby the effect of earthquakes is added to the "2000.0" reference coordinates, and the patch deformation is subtracted from them to calculate coordinates before the earthquake. While this concept was developed soon after 2000, it was not until the sequence of earthquake commencing in 2010 struck the city of Christchurch and the surrounding area that there was a sufficient business driver to update the deformation model. Although there had been other major earthquakes since 2000 they only significantly affected remote, sparsely inhabited areas. In 2013 a new version of the deformation model was published including patches for eight events, four affecting the south of South Island, and four main events in the Christchurch sequence (Donnelly et al, 2014).

The cadastral system is well connected to the geodetic system and is similarly in motion resulting from earth deformation. Management of the spatial cadastre in response to deformation of boundaries in the physical cadastre, is the least well managed source of cadastral dynamics, and is the subject of this discussion.

One of the difficulties of managing a dynamic cadastre is the increasing number of customers who use the spatial cadastre in their business processes, products and services. On the one hand is the GIS community who may use it as contextual spatial data or may expressly align other datasets to it. For these customers, the dynamics of the cadastre are a nuisance – stability is often more valued by them than spatial accuracy. However on the other hand are cadastral surveyors using the cadastre in the way it was primarily intended to be used – to locate property boundaries. For these users, accuracy is more important and changes to the cadastre are expected – especially as it is surveyors who initiate those changes through the lodgement of new cadastral survey transactions.

2 New Zealand Cadastral System

2.1 Boundaries and plate tectonics

2.1.1 Principles of boundary definition

Survey marks play a very significant role in the definition of boundaries in New Zealand. Through common law set by precedent in court cases, an original and "undisturbed" boundary mark occupies a very high position on the hierarchy of evidence of boundary location. In the absence of such a boundary mark, survey measurements from a nearby mark (assuming it is also undisturbed) can be used to reinstate the original position of the boundary mark. The standards for cadastral survey in New Zealand require "witness marks" and permanent reference marks" to be placed in secure positions near the boundary – specifically so that they can serve this function of witnessing the boundary and allowing its reliable and accurate reinstatement in the event that boundary marks are disturbed or removed.

2.1.2 Undisturbed marks and tectonic motion

An original and undisturbed boundary mark has been taken to mean that a mark is <u>in the same position</u> as when it was driven into the ground by the surveyor that first created the new boundary. However the common law principle relying on "undisturbed" survey marks predates the present day knowledge of plate tectonics. We must now clarify what we mean by "in the same position".

In practice, the process of reinstating boundaries in New Zealand has always depends for its success on treating the slow and imperceptible movements of plate tectonics as if they were not occurring. Or to put it another way, where a boundary mark has been moved only by tectonic processes, the Courts or surveyors have (perhaps unwittingly) considered it to be “in the same position” as it was originally placed – that is, undisturbed.

As noted in Grant (1995) this allows undisturbed boundary marks to move almost perfectly in concert with the fixed assets of landowners that are firmly resting on or attached to the earth’s surface. The ownership of those assets, and the land they rest on, is thereby not affected by tectonic motion.

Of course, these marks are not in the same position in relation to the coordinate axes of the geodetic datum. Therefore coordinates of a mark, if they are to remain accurate, will necessarily change over time even though the mark is considered to be undisturbed. This led to the concept of both a dynamic datum and a dynamic cadastre (Grant 1995). It also means that accurate measurements to distant survey marks – now possible using Global Navigation Satellite Systems (GNSS) – will change over time.

2.1.3 Witness marks and earth deformation

The system of witness marks required by cadastral rules and regulations support the security of ownership because such marks are required to be within a specified distance of the boundary. This greatly reduces the risk that earth deformation will result in differential movement of witness and boundary marks. Originally, this distance restriction was intended to ensure the accuracy of measurement and boundary reinstatement given the limitations of traditional survey techniques.

More recently cadastral rules and regulations have allowed the use of Global Navigation Satellite Systems (GNSS) for cadastral survey. However a distance limitation has been retained for witnessing – not now for measurement accuracy but deliberately to minimize the risk and extent of differential movement between witness marks and the boundaries they serve to witness.

2.2 Management of the spatial cadastre

From 1996 to 2008, Land Information New Zealand developed the automated survey and title system known as Landonline. This resulted in an integrated geodetic, cadastral and land registration system with digital lodgement of structured survey and title transactions which are validated against a database populated with historical cadastral survey and land title information, and which continues to be populated with the new transactions.

2.2.1 Survey conversion project

A spatial definition of all parcels in New Zealand in the primary (ownership) layer was loaded into Landonline from the predecessor Digital Cadastral Database (DCDB). For 70% of the cadastral parcels in New Zealand, the coordinates of boundary points were then upgraded to survey accuracy. “Survey accuracy” means that the coordinates comply with the accuracy standards set in the Rules for Cadastral Survey set by the Surveyor-General).

Population of the Landonline database with accurate cadastral survey information was known as the Survey Conversion Project (Rowe, 2003). To achieve survey accuracy, the following components were required:

- An accurate geodetic datum - NZGD2000. An important attribute of NZGD2000, compared with the predecessor datum NZGD49, was that it was largely free of distortion.
- A network of geodetic control points, coordinated in terms of NZGD2000 and with all geodetic observations and coordinates brought in terms of the datum reference epoch of 2000.0 (1 January 2000).
- Extension of the geodetic network to higher density in the areas identified for survey-accurate coordinate upgrade. These “survey conversion areas” were chosen to cover the most intensive and valuable land uses – urban, peri-urban and intensive rural areas.
- Connections between geodetic control and the cadastral survey network of boundary points and marks.
- Capture of all boundary dimensions for current parcels and such other survey measurements as were necessary to provide a well-connected network (for example, connections across roads or streams).
- Least-squares adjustments of the cadastral network which allowed testing of the coordinate relative accuracies against the accuracy standards specified in the Regulations and Rules.

Those coordinates that met the accuracy standards with 95% confidence were designated as having SDC status – “Survey-accurate Digital Cadastre”. The least squares adjustment of observations also provides an estimate of the accuracy of the resultant coordinates, at least in terms of the local control used by the adjustment. The accuracy is represented by an order assigned to the coordinate.

2.2.2 Automated validation and integration of new survey transactions

For the 70% of survey-accurate parcels, this accuracy status of boundary coordinates supports the semi-automated validation of new cadastral survey transactions by least squares adjustment of the new survey information in relation to the survey accurate coordinates. For this to function effectively, the survey accurate coordinates must be maintained and improved as new survey evidence is accepted into the database.

Least squares adjustment is applied to all new cadastral surveys to test self-consistency of the set of new observations and also consistency with the survey-accurate coordinates in the database. This often results in changed and improved survey-accurate coordinates for existing boundary points in the neighborhood of the survey.

2.3 Changes to boundary coordinates

As well as boundary movement resulting from tectonic processes there are a number of processes that cause boundaries to move in either the physical cadastre, or the spatial cadastre, or both. For example:

- Resurvey of water boundaries may result in them moving according to the common law doctrine of accretion and erosion. This movement occurs in the physical cadastre and the new survey definition results in a change in position in the spatial cadastre.
- New survey measurements to undisturbed old boundary marks may result in the coordinates for that boundary in the spatial cadastre being corrected to the new surveyed position.
- A new survey which identifies and resolves an error or conflict in a previous survey and, as a result, reinstates that boundary position with a new mark or new recalculated boundary dimensions. The newly defined position of the reinstated boundary may result in a change in the coordinates for that boundary.
- An upgrade of geodetic control, or a new connection between geodetic control marks and the local cadastral boundaries, may result in a significant shift in coordinates for cadastral boundaries in the area.

The first three of these cases are managed as a standard process within Landonline for every new cadastral survey dataset that is approved. Following approval, the new survey measurements and vectors are integrated into the surrounding cadastral network with a specific local network adjustment.

Periodically, a need is identified in Landonline for a Wide Area Cadastral Adjustment (WACA). This may be due to upgraded geodetic control (the 4^{th} case above) (Donnelly and Palmer, 2006).

3 Categories of cadastral deformation

Section 2 above describes the standard processes applied in Land Information New Zealand for dynamic management of the physical and spatial cadastres. The spatial cadastre is adjusted many times a day as new cadastral survey datasets are lodged with the department by cadastral surveyors, approved by the department, and adjusted into the existing cadastral network by the department. In this sense, New Zealand already has a dynamic spatial cadastre even without accounting for earth deformation.

However managing the dynamics of the cadastre from earth deformation is not routine and spatial data management processes are still being developed. Earth deformation takes different forms and the appropriate spatial model for managing change varies according to the nature of the deformation. The relevant factors are:

- **Spatial variation**. The extent to which the deformation is spatially continuous or discontinuous.
- **Parcel distortion**. Another way of assessing the spatial variation is to consider whether parcel shapes are significantly distorted by the earth deformation.
- **Temporal variation**. The extent to which the deformation is on-going, continuous and linear; on-going, continuous and non-linear; or episodic and near instantaneous (discontinuous).
- **Boundaries follow ground movement**. It is not necessarily the case that deformation of the earth's surface will result in boundaries following that movement.

There are 2 principles of common law which affect the response of boundaries to ground movement. The first principle is that localized movement of the soil, such as occurs in landslips, does not result in boundary movement. The second principle is that moveable water boundaries only move if the accretion or erosion is slow and imperceptible. A sudden shift (avulsion) does not result in movement of the water boundary.

Different factors come into play with different types of ground movement. **Tectonic deformation** is the deformation resulting from the slow and steady movement of the 2 tectonic plates that New Zealand sits astride. This movement is taken up across a broad deformation zone that covers most of the country (Beavan & Haines, 2001). All boundaries in New Zealand are affected by tectonic deformation because the boundaries are in motion relative to each other. These movements are, to a large extent, modeled by the deformation model that accompanies NZGD2000.

Earthquake deformation is caused by the sudden stress release of earthquake, aftershocks and any post-seismic relaxation that follows the rupture. The impact on boundaries depends on whether the fault rupture reached the surface of the earth as well as distance from the fault rupture. Cadastral parcels that are very remote from the earthquake fault do not move significantly. Parcels that are remote may be subjected to block movement without distortion. Parcels nearer to the fault may be subjected to linear (affine) distortion. Parcel boundaries that are very close to the fault or lie across it may be bent (non-linear distortion) or even ruptured if the fault trace reaches the surface of the earth.

Indirect surface deformation may also occur where the surface layers of the earth are indirectly impacted by an earthquake. For example on steep slopes, the shaking may cause rockfalls and landslides. On relatively flat sites with soil or subsoil susceptible to liquefaction, the shaking may cause the surface to flow during the period of strong motion – buildings and other assets on the surface of the ground, as well as survey marks, may move with the flowing soil. Uplift or subsidence caused by the earthquake may also cause rivers to break their banks and follow a new flow-line to the sea. Table 1 summarizes each type of movement and the spatial model used for that movement. All of these types of movement of boundaries have been experienced in New Zealand in the last few years.

Table 1: Categories of boundary movement and spatial modeling – (Grant & Crook, 2012)

Movement Category	**Spatial variation**	**Temporal variation**	**Parcel shape distorted**	**Boundaries follow ground movement**	**Spatial model applied**
Tectonic deformation	Continuous - broad scale	Continuous - near linear	No	Yes	Datum deformation model
Earthquake - remote	Continuous - broad scale	Instantaneous + post-seismic	No	Yes	Deformation patch
Earthquake - near field	Continuous	Instantaneous + post-seismic	Near linear (affine)	Yes	Deformation patch
Earthquake - rupture zone	Discontinuous	Instantaneous + post-seismic	Non linear	Complex[1]	Interpolate across rupture, resurvey
Landslip / Rockfall	Discontinuous	Instantaneous	No	No	Not modelled
Liquefaction	Generally discontinuous	Instantaneous	Variable	Complex[2]	Not modelled
Natural boundary avulsion	Continuous but localised	Instantaneous	No	No	Not modelled

4 Canterbury Earthquakes

The Darfield earthquake of 4 September 2010 was the first in a sequence of four substantial earthquakes to impact Canterbury and Christchurch. The four major earthquakes in the sequence are outlined in Table 2 below. These four are the only earthquakes to have caused surface movements of more than 1cm (excluding highly localised movement such as that caused by liquefaction). They have therefore been the key focus of recovery and restoration activities.

Table 2: Significant earthquakes in the Canterbury 2010-2011 sequence

Date and Time	**Magnitude (Richter Scale)**	**Approximate Depth (km)**	**Distance from Christchurch City Centre (km)**
4 September 2010 – 4:35	7.1	11	40
22 February 2011 – 12:51	6.2	5	7
13 June 2011 – 14:20	6.0	6	10
23 December 2011 – 15:18	6.0	6	10

[1] See section 5.5 Deep-seated movement
[2] See section 5.4 Shallow surface movement

Figure 1 – Effects of fault rupture on previously straight fence and water race. (Photo - Survus Consultants)

The Darfield earthquake was the only one to result in surface rupture. The rupture was 24km long and resulted in shearing (Figure 1) across the fault. Numerous cadastral parcels are intersected by the fault rupture as shown in Figure 2. All four earthquakes also resulted in liquefaction and lateral spreading, although this was particularly serious for the 22 February 2011 earthquake, which resulted in extensive property and land damage as well as many deaths.

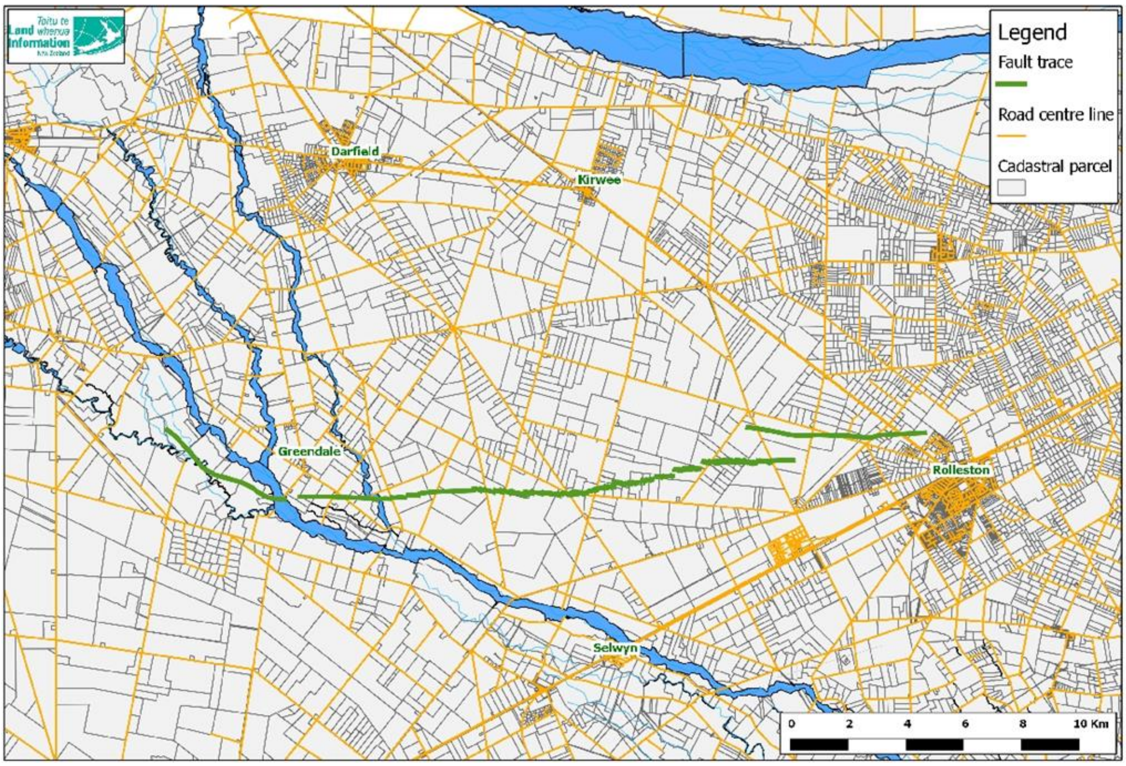

Figure 2: Darfield fault rupture overlaid with cadastral parcel fabric

5 Regulatory response to cadastral boundary movements

The legislative and regulatory responses to the sequence of earthquakes in Canterbury, New Zealand, are described in Smith et al (2011) and Grant et al (2012). Ballantyne (2004) had previously identified that there is little evidence of consistent international best practice for the re-establishment of property boundaries following earthquakes. Nickles (2009) also referred to the unsatisfactory legal position of having no legislation to deal with these situations.

5.1 Initial response under emergency legislation

Shortly after the 4 September 2010 Darfield earthquake, legislation was passed to ensure that the necessary response and recovery efforts were not impeded by legislation that had been enacted to cover less extreme circumstances. The Canterbury Earthquake Response and Recovery Act 2010[3] provided for Orders in Council to set aside any legislative provisions that were impeding the response and recovery efforts. One of the Acts specified for such flexibility was the Cadastral Survey Act 2002 which regulates the cadastral survey system in New Zealand.

An Order in Council[4] provided for the Surveyor-General to forego the usual requirements of consultation to make Rules (having the power of government regulations) *"specifying how the spatial extent (particularly boundaries) of Canterbury earthquake land must be defined and described"*

These interim Rules and associated guidelines (Land Information New Zealand, 2010) were made to clarify how boundaries would be deemed to have moved in different circumstances and what evidence was required of cadastral surveyors reinstating them. Following the subsequent devastating Christchurch aftershock on 22 February 2011, the emergency powers were further updated by the Canterbury Earthquake Recovery Act 2011[5].

5.2 Enduring response to boundary movements

With the interim Rules in place, an amendment to the Rules for Cadastral Survey 2010 was developed applying the normal process of full consultation. Along with some other changes, these amended Rules for Cadastral Survey 2010 generalized the regulatory response to moving boundaries. This means that the applicable standards and regulations will be in place across New Zealand for comparable future scenarios – including large slow moving landslips. The Rules (Land Information New Zealand, 2012a) and associated guidelines (Land Information New Zealand, 2012b) came into force on 1 January 2013.

5.3 Principles of reinstatement of earthquake affected boundaries

Shortly after the 4 September 2010 Darfield earthquake, concern was expressed by the public on the impact on property boundaries right across the region. The Surveyor-General established the principle that boundaries in New Zealand should continue to move in concert with movements of the bedrock. This matched the status quo for boundaries throughout the country that are affected by slow tectonic deformation.

5.4 Shallow surface movement

A complicating factor, especially within urban areas, is that a great many boundaries had been moved almost at random by the effects of soil liquefaction. In this case the common law is quite clear – where the surface layers of the land move, taking with them boundary marks, fences and other assets, the boundaries do not move.

Figure 3 – The boundary point next to the fence post has moved 2.8 metres due to lateral spreading as a result of liquefaction (Photo - Eliot Sinclair and Partners)

[3] http://www.legislation.govt.nz/act/public/2010/0114/latest/whole.html
[4] http://www.legislation.govt.nz/regulation/public/2010/0467/latest/DLM3424212.html
[5] http://www.legislation.govt.nz/act/public/2011/0012/latest/DLM3653522.html

The task of the cadastral surveyor is greatly complicated in this case by the fact that in the broad areas affected by liquefaction, all existing survey marks are subjected to highly variable movements due to liquefaction and it becomes virtually impossible for surveyors to accurately identify where that original position actually was.

5.5 Deep-seated movement

The task of reinstating boundaries affected by deep-seated movement of the bedrock is made easier by the fact that there is no applicable common law for this situation. Therefore the general principle outlined by the Surveyor-General can be followed. This has the major benefit that it leaves the assets of landowners still in their possession and on their land. This principle could be stated as: “if you owned the land before the earthquake – you still own it afterwards”.

The most complex example of this principle occurs in cases where boundary lines have been ruptured by the fault trace (see Figure 1). In this case, new angles will have been introduced to a formerly straight boundary line. This is illustrated in example D in Figure 4 (Land Information New Zealand 2012).

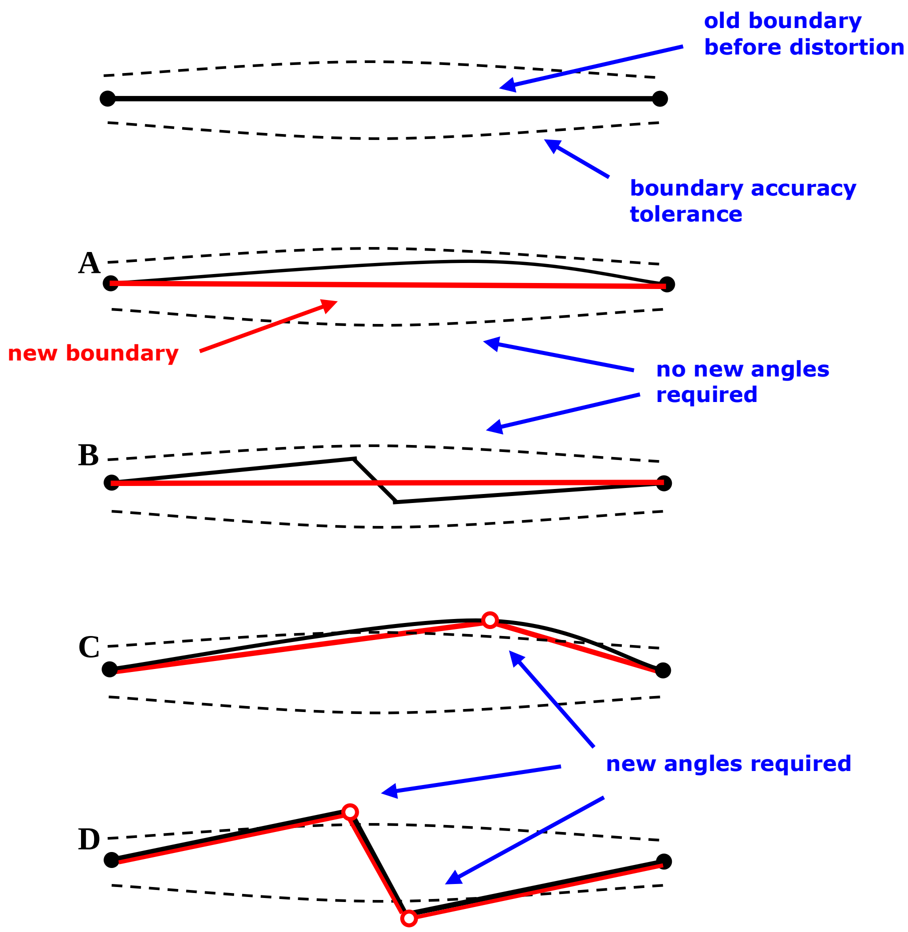

Figure 4: Boundaries affected by deep-seated distortion (Land Information New Zealand, 2012)

6 Deformation Models

A challenge in replicating the deformation from the Canterbury and Fiordland earthquakes to the cadastral fabric is that relatively few marks have been accurately surveyed since the earthquakes. The normal process for generating coordinates of parcel boundaries is by calculating them from surveys when the parcels are defined, but for most parcels there are no post-earthquake surveys. Instead the coordinates are recalculated by using a model that predicts the coordinate change due to the earthquakes, and applying this modeled coordinate change to the pre-earthquake coordinates of all affected parcels. This model is in the same as the NZGD2000 deformation model patch for the earthquake.

The deformation patch is calculated from surveyed coordinate changes together with other geophysical data, such as seismic data and DInSAR (Differential Interferometric Synthetic Aperture Radar) observations to construct a geophysical model of the fault mechanism causing the deformation. The geophysical model can then be used to calculate the expected deformation at any other point on the surface. In order to provide a simple and efficient means of publishing and calculating the surface deformation, a grid based representation of the surface deformation is calculated from the geophysical model.

The calculation of the patch deformation grid is detailed in Winefield et al. (2010) which uses the 2009 Dusky Sound magnitude 7.8 earthquake as an example. A much more complex model was required for the magnitude 7.1 Darfield Earthquake in 2010 (Beavan et al, 2012). However the approach in each case was very similar, and ultimately is based on equations defining the deformation due to a uniform slip on a rectangular fault plane embedded in an infinite homogenous elastic half space as formulated by Okada (1985). In order to emulate the complexity of the actual deformation, the model combines the deformation on a large number of rectangular sub-faults on each of which a different slip vector is permitted.

The initial fault model is guided by seismic evidence and surface observations which indicate the likely location of the fault plane(s). This model is then refined by numerical inversion to match the observed deformation from survey measurements and DInSAR data.

Even though the models are in some cases very complex (up to 940 separate fault planes were used to model the 4 September 2010 Darfield Earthquake) they still cannot completely represent the actual deformation.

Where the fault breaks the surface and in areas of local deformation the assumptions of elastic behavior become invalid, and the accuracy of the model deteriorates. These are also the areas the ground disturbance may require the physical cadastre to be re-established in any case, so here the model, while inaccurate, provides a useful realignment of the spatial cadastre pending its update by the resurvey and re-establishment of the physical cadastre.

Elsewhere the simplicity of the model is more acceptable, particularly since we are using surface deformation observations to calculate the model, and then using the model to calculate surface deformation where it has not been observed. To some extent the physical unreality of the model relationship between fault movement and surface deformation cancels out. In effect the geophysical model provides a mechanism for smoothing and interpolating between the observations.

7 Application of deformation models to cadastral coordinates

In practice the New Zealand spatial cadastre is embodied in Landonline, the survey and title database system maintained by Land Information New Zealand. Although the primary role of this database is to manage survey and title transactions, the spatial definition of the cadastral fabric is published from this database and is widely copied and used by the New Zealand GIS community for mapping purposes and for associating other spatially defined data with the corresponding property rights. More recently this data is also directly available to customers through web services.

The cadastral fabric is in a continuous state of change. It is updated many times a day through processing of survey transactions, for example when a parcel is subdivided. It is also spatially updated as new survey measurements, are included in the database. These are used to recompute boundary and other coordinates.

All these changes are supplied to client databases by a variety of update processes, both directly and indirectly (via intermediary spatial data service providers). Client databases in turn may use a number of bespoke processes to ensure that their own spatial data remains aligned with the cadastral fabric where this is important.

7.1 Practical considerations

The application of a reverse patch to the datum means that the published reference epoch coordinates are changed by adding the effects of earthquake deformation. The NZGD2000 reverse patch for the Canterbury and Fiordland earthquakes defines coordinate changes over an extensive area. Over much of this area though the coordinate changes are small, less than 1 cm. To reduce the impact on the spatial cadastre only changes greater than 5cm were considered. To avoid a discontinuity in the dislocation field a buffer was added around the model over which the dislocation transitioned from 5cm to zero. Even with this restriction the update still affects about 15% of the spatial data in Landonline, involving over about 500,000 parcels and about 2 million corner nodes. From an operational point of view applying a change of this magnitude proved challenging and required taking the database offline for a weekend.

For clients maintaining copies of the spatial cadastre this update is in principle no different from the day to day changes that they routinely incorporate into their databases. From a practical point of view however there are two significant differences:

- the number of features being updated is much greater than a typical incremental update, and
- the coordinate change at any location is defined a simple grid based model, unlike day to day updates which are piecemeal and not defined by any model.

These two features provide both a challenge and a potential solution for clients. The large number of coordinate changes may challenge maintenance processes that do not scale up to the size of this update (for example manual maintenance procedures). However clients can use the published grid based model to directly update their copy of the cadastral data. Moreover the model can be used to update their own spatial information that is aligned with the cadastre. The coordinate update model has been published in a number of formats to support clients in applying the changes.

One difficult aspect of managing a dynamic cadastre has proved to be the technical management of large-scale coordinate and parcel topology changes within a working publicly accessible database. Landonline is not a read-only public database – it has thousands of transacting professional customers. Surveyors and solicitors are lodging new datasets all the time during working hours. LINZ staff are validating and processing those transactions. The efficient operation of the land-based property market is critical to the health of New Zealand's economy so the database can only be taken offline outside normal working hours and a failed database update cannot be tolerated. The upgrade of 2 million boundary nodes on 500,000 parcels, and in a manner that did not disrupt the efficient operation of the land property market – this proved to be challenging. However a great deal has been learned and it will be easier next time.

7.2 Limitations of the deformation model

The application of a deformation model across a large part of New Zealand, cannot account for all of the evidence that a surveyor would take into account when reinstating a boundary. For example Figure 4 above illustrates situations where new angles may be introduced into boundaries that have been bent or ruptured by the fault trace. The position of these angles can only be determined by close investigation of where the bending or rupture actually occurred along the boundary line. Figure 5 also shows that even where the fault trace has reached the surface of the earth, it is not a zero-width line that can be easily modelled – it often has a complex structure and the impact on boundaries requires judgment to be applied to each boundary line if the usual accuracy standards are to be met.

Similarly, in cases of liquefaction, the deformation model provides a reasonable estimate of the movement of the bedrock. That is of some assistance to a surveyor reinstating a boundary but they will still have to assess the complex evidence provided by survey marks, boundary marks, fences and buildings, all of which may have moved almost independently as the surface or subsurface layers of the soil turned to liquid for some tens of seconds (and which have been further moved several times by successive aftershocks).

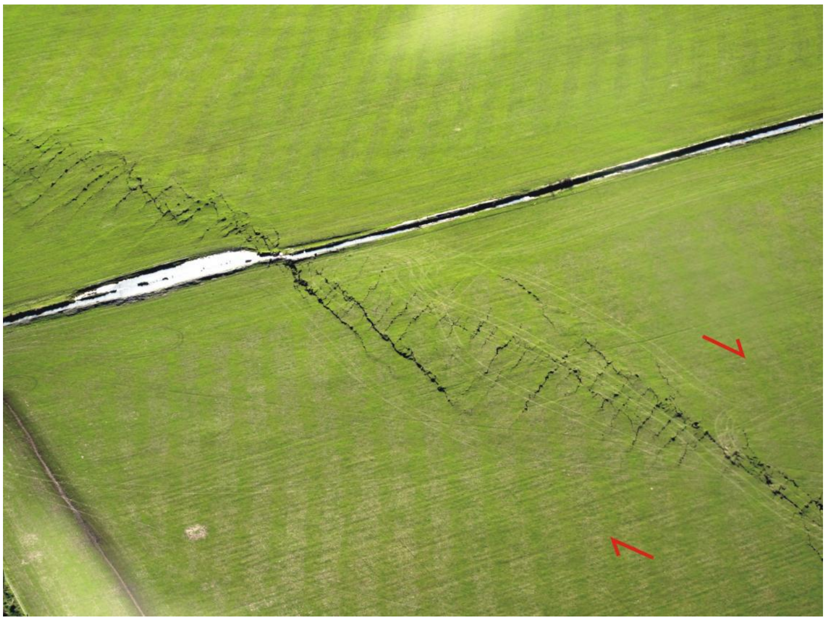

Figure 5: Greendale Fault surface rupture. Arrows indicate direction and width of displacement. Here, ~3.5 m of displacement is distributed across a zone up to 40 m wide. Photo by Richard Jongens (Quigley et al, 2010).

The deformation model therefore provides an approximation of how boundaries have moved – a much better approximation than a null model (the default model for a static cadastre) which assumes no such movement. But it cannot fully substitute for reinstatement by a licensed cadastral surveyor who is able to collect and assess local evidence of movement and apply the correct legal principles.

The ability of the model to represent the real-world changes due to the earthquakes varies across the affected area. The model has a level of uncertainty associated with it, which propagates into the coordinates calculated using it. The agreement between observed and modeled positions increases with increasing distance from the fault, and is lower where there is localised deformation caused by phenomena such as liquefaction. Based on analysis described in Donnelly et al (2014), the uncertainty of the model was used to assess whether the accuracy classification for a particular coordinate required updating, as well as the coordinates themselves.

8 Conclusions

It is apparent that cadastral boundaries physically move as a result of earth deformation and that the spatial cadastre needs to be able to respond to and model those movements. However this problem covers a complex spectrum of specialist knowledge: geophysics; geodesy; management of the spatial cadastre; and land law. The dynamics of the earth are reasonably well known, measured through geodetic techniques and modelled in solid-earth geophysics. New Zealand's geodetic datum has a deformation model associated with it to recognize the motion of "fixed" survey marks attached to the surface of the earth.

At the other end of the knowledge spectrum, land law is based on centuries of common law and precedents formed in a small number of historic court cases. Those precedent setting cases have not, to date, recognized the existence of geodynamics on the surface of the earth. The tectonic motions are slow but continuous, occur across the whole country and mostly cannot be detected by the general public. Motions resulting from earthquakes are localized, frighteningly fast, but of short duration.

The cadastre must bridge the interface between the measured dynamics of the earth's surface and the relatively inflexible, slow moving and slow changing application of land law which nevertheless serves the vital function of protecting property rights in land.

New Zealand has started down the path of bridging this gap. Ballantyne (2004) recommended that principles be established and, if necessary, legislation to address the uncertain impact on property boundaries. The necessity of responding to the Canterbury earthquake sequence has taken us some way forward with the amended Rules for Cadastral Survey 2010 (Land Information New Zealand, 2012) but there is much still to learn. Grant (1995) in proposing a dynamic datum for a dynamic cadastre, anticipated that these issues may be resolved by the year 2010. That proved to be too optimistic but steps towards this goal have been made and the problem cannot be ignored for long. More research in a number of areas of geodesy, sensing of deformation, spatial management of the cadastre and land law will be required.

9 References

Ballantyne, B. (2004). *Managing the New Zealand cadastre after deformation events: applying grit to a slippery slope*. Research report prepared for LINZ.

Beavan, J., Haines, J. (2001). Contemporary horizontal velocity and strain rate fields of the Pacific-Australian plate boundary zone through New Zealand. *Journal of Geophysical Research: Solid Earth (1978–2012), 106(B1)*, 741-770.

Beavan, J., Motagh, M., Fielding, E., Donnelly, N., Collett, D. (2012). Fault slip models of the 2010-2011 Canterbury, New Zealand, earthquakes from geodetic data, and observations of post-seismic ground deformation, *N. Z. J. Geol. Geophys., Vol 55(3).*

Blick, G., Haanen, H. (2005). The Earthquake's Impact on Property Boundaries. *Proceedings, The 1855 Wairarapa Earthquake Symposium, Wellington, New Zealand.*

Blick, G., Crook, C., Grant, D., Beavan, J. (2003). Implementation of a Semi-Dynamic Datum for New Zealand, *International Association of Geodesy Symposia, 30 June – 11 July, (128), Sapporo, Japan*.

Donnelly, N., Crook, C., Amos, M., Grant, D., Ritchie, J., Roberts, C. (2014). Canterbury Earthquakes Deformation Model Accuracy. *Proceedings of Surveying and Spatial Sciences Conference (LOCATE14), 7-9 April, Canberra, Australia* (in press).

Donnelly, N., Palmer, J., (2006). Issues with maintaining spatial accuracy in a nationwide digital cadastral network. *New Zealand Surveyor 296*, 34-39.

Grant, D.B. (1995). A dynamic datum for a dynamic cadastre. *Australian Surveyor, 40(4)*, 22-28.

Grant, D.B., Pearse M. (1995). Proposal for a Dynamic National Geodetic Datum for New Zealand. *Proceedings International Union of Geodesy & Geophysics General Assembly, Boulder, Colorado, USA.*

Grant, D.B., Blick G. (1998). A new geocentric datum for New Zealand. *New Zealand Surveyor No. 288,* 40-42.

Grant, D.B., Crook, C. (2012). Spatial maintenance of the New Zealand cadastre in response to earthquakes. *Proceedings of FIG Working Week, Rome, Italy*.

Grant, D.B., Smith, M., Thompson, M. (2012). What happens to the cadastre when the earth moves: legislative and regulatory responses to the earthquakes in Canterbury, New Zealand. *Proceedings, International FIG Symposium & Commission 7 Annual Meeting, Innsbruck, Austria.*

Land Information New Zealand, Surveyor-General. (2010). *LINZG65702: Guideline for Rules for Cadastral Survey (Canterbury Earthquake) 2010.* LINZ, Wellington.

Land Information New Zealand, Surveyor-General. (2012a). *LINZS65003: Rules for Cadastral Survey 2010 (amended 1 November 2012).* LINZ, Wellington.

Land Information New Zealand, Surveyor-General. (2012b). *LINZG65704: Interim guide to the amended Rules for Cadastral Survey 2010.* LINZ, Wellington.

Nickles, W.L. (2009). Ground movement and its effect on cadastral boundaries. Chapter 8 of *Land title surveys in New Zealand.* Ed. D.F. McKay, New Zealand Institute of Surveyors.

Okada Y. (1985). Surface deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Am., 75:4,* 1135-1154.

Quigley, M., Van Dissen, R., Litchfield, N., Villamor, P., Duffy, B., Barrell, D., Noble, D. (2012). Surface rupture during the 2010 Mw 7.1 Darfield (Canterbury) earthquake: Implications for fault rupture dynamics and seismic-hazard analysis. *Geology, 40(1),* 55-58.

Rowe, G. (2003). The survey conversion project – making a survey-accurate digital cadastre a reality for New Zealand. *New Zealand Surveyor 293*, 31-38.

Smith, M., Thompson, M., Grant, D.B. (2011). Re-establishment of cadastral boundaries following the 2010-2011 Canterbury earthquakes. *Proceedings of the Spatial Sciences and Surveying Conference, Wellington, New Zealand.*

Winefield, R., Crook, C., Beavan, J. (2010). The Application of a Localised Deformation Model after an Earthquake, in *Proceedings of XXIV FIG Congress, April 11-16, Sydney, Australia*. Available at: http://www.fig.net/srl/