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Landslide Recognition using LiDAR derived Digital Elevation Models-Lessons learnt from selected Australian examples

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**ABSTRACT:** The increasing use of LiDAR or airborne laser scanning (ALS) data throughout the world has facilitated widespread access to high resolution current digital elevation models (DEM). Such high resolution DEM’s have proved to be particularly useful in the recognition of landslides and erosion. This is an increasingly important issue in Australia given the publication of the recent Australian Geomechanics Society’s guidelines for landslide risk management which emphasizes the need for improved regional and local landslide inventories.

This paper presents recent examples of landslide recognition using such DEM’s from around Australia. Insight is provided into the overall landslide recognition process using remotely acquired data and how this has been enhanced using LiDAR based DEM’s and their derivative data sets.

The advantages of using LiDAR-based DEM’s are identified as compared with conventional regional derived DEM’s using photogrammetric techniques. Analytical and visualization advantages associated with the use of GIS and derivative data sets are also discussed.

The paper sets out to provide practical guidance using techniques and lessons learnt from many hours of work of detailed analysis by experienced landslide experts and comments on scope for future enhancements. In addition, limitations and downfalls are also described and recommendations made as to how this technique can best be applied to the landslide recognition process.

1 **INTRODUCTION**

The introduction of the Australian Geomechanics Society (AGS) 2007 Landslide Risk Management (LRM) Guidelines (especially AGS, 2007a; 2007b) presents strong arguments for the development of landslide inventories to assist landslide investigations and research. As such, a series of papers have been prepared by collaborating members of the AGS to discuss aspects of the overall LRM process which include this paper on landslide recognition and mapping, designing landslide databases in which such data is stored (Mazengarb et al, 2010), the application of monitored landslide performance data to aid in the assessment of landslide frequency (Flentje et al, 2010) and the use of the application of landslide inventory data into landslide susceptibility maps (Miner et al, 2010).

The visualization and interpretation of landform is a key component of any landslide inventory study and as such, the acquisition of accurate topographical information is a vital element in the overall geomorphic assessment process. Such information has traditionally been obtained through terrestrial land survey and aerial photogrammetry. However over the past 15 years the application of a new technique called Light Detection and Ranging (LiDAR) has been successfully used to generate precise and comprehensive topographical information in a wide range of environments and settings.

Essentially, LiDAR measures the distance from an airborne vehicle to the surface of the earth using the round-trip travel time of a short pulse of near infrared light (typical wavelength of 1 to
1.5 µm). Through a range of on-board instruments (including an airborne Global Positioning System and Inertial Navigation System), the elevation of the aircraft, the time of travel and the speed of light are all known and it is possible to calculate the vertical distance from the aircraft to the ground, and thus the elevation of the ground. As the LiDAR sensors are capable of receiving a vast number of return pulses every second, a dense coverage of widespread areas can be achieved in a relatively short flight time.

After the initial raw data has been collected and analyzed to differentiate ground strikes from other returns emanating from tops of trees, and buildings etc, this data can then be used to generate a digital elevation model (DEM). It is from this LiDAR-derived DEM that features such as landslides can be interpreted using techniques which are discussed in the following sections.

2 LIDAR DERIVED DIGITAL ELEVATION MODELS

2.1 How DEMs are made from LiDAR

The Digital Elevation Model (DEM) is a grid-based three-dimensional representation of terrain elevation and is a fundamental element of GIS datasets and GIS-based analyses. DEM’s can be constructed from a variety of source data (primarily contours or point data) and by using a range of techniques. Using high density airborne laser scanning (ALS) data points (subject to the considerations in the following section 2.2) allows the production of a highly accurate, contemporary DEM.

Numerous methods across many different GIS platforms can produce DEM’s. The authors have found that DEM’s generated using the ESRI ArcGIS™ 3D Analyst Triangulated Irregular Network (TIN) modeling, followed by conversion of the TIN to a raster, provides an excellent technique of DEM production. A TIN surface is generated from a series of data points (each having x, y and z values – where z is commonly elevation) producing continuous, non-overlapping triangles whereby each node represents a z value point. In contrast to TIN modeling, one alternative technique, using ESRI ArcGIS™ TOPO2RASTER tool (based on the ANUDEM program created by the Australian national University) produces a more hydrologically correct DEM, with fewer sinks.

2.2 DEM resolution and Accuracy

The resolution at which any DEM can be produced is directly related to the average point spacing (aps) at which the raw data was collected on the ground. As an initial starting point, a useful rule of thumb suggests that if the aps= x then the DEM grid or pixel size=2x. Hengl (2006) suggests however, that a compromise may allow one to reduce this to 0.25 or 0.5 × the aps, subject to various data constraints and target variables. However, horizontal and vertical accuracies also play a significant role in setting DEM grid resolution and must also be understood and considered when producing a suitable DEM grid. As the LiDAR datasets can be quite large, it is often the case that computer resources will govern the pixel size.

LiDAR data provided by various agencies, with which the authors have been associated over the past 10 years, have readily supported DEM’s at 1, 2 or 5m resolution. For example, the 5.0m DEM in Corangamite region of Southwest Victoria, Australia has a vertical accuracy of V=+/-0.50m, a horizontal accuracy of H=+/-0.50 m and an average point spacing 2.0 pts/m.

It is important that the DEM resolution be matched with the data quality. By necessity DEM’s have generalizations built into them as a function of inaccuracies with the data and the resolution of the modelled landscape will be governed by these limitations. Hence it must be understood that LiDAR data is not perfect and includes spatial variations which rarely achieve land survey type accuracies and may not even be completely repeatable. As an example, Palamara et al (2006) report a mean absolute vertical error of 0.23 m between two ALS datasets produced for the same landscape in the Illawarra Region of NSW, Australia although much
greater errors occurred at cliffs and in steep terrain. Horizontally, accuracies were determined to be <0.5 m (pers com Flentje, 2010). The ability of ALS data to accurately represent a bare earth DEM is affected by a number of factors such as flight configuration of the survey with respect to the local topography (which may create shadow effects) and by vegetation cover. Generally, DEM resolution will determine the minimum size of a landslide feature that can be consistently interpreted. Based on the authors experience we believe the limiting threshold of landslide feature recognition is of the order of 5-10 pixels. Hengl (2006) suggests at least 4 pixels are required to represent the smallest object and at least 2 pixels to represent the narrowest.

2.3 DEM Derivatives

Whilst the DEM is often the primary output from the raw LiDAR data, GIS applications allow a number of derivative datasets to be produced from the DEM which include: terrain hill-shading, degree of slope and slope aspect, plan and profile curvature, flow accumulation, wetness and surface roughness. These derivative datasets can be extremely useful in the landslide recognition process with some limited discussion included in later sections.

3 APPLICATION OF LIDAR DEM’s TO THE LANDSLIDE RECOGNITION PROCESS

3.1 Previous techniques for Landslide recognition

A number of techniques are regularly used for the field recognition and identification of landslides. The most fundamental of these is field observation and geomorphic mapping. Traditional survey techniques are commonly used to accurately map the extents of landslides whilst remote sensing techniques can include aerial photo interpretation (usually stereoscopically), satellite imagery and more recently, Interferometric Synthetic Aperture Radar (InSAR) techniques have been used. Whatever the technique, all aim to distinguish geomorphic features which identify and distinguish the landslide within the landscape and hence the accuracy with which they can depict topographical information is critical in allowing accurate assessment of such features.

3.2 Use of LiDAR DEMs in landslide recognition

Recently, LiDAR data and the derived DEM’s have been increasingly used as a technique for landslide recognition (e.g. McKean and Roering 2004). The ability to readily detect landslide morphology is well suited to the high resolution ground models produced by LiDAR. In addition the use of the derivative data sets can also help define extents of the feature such as changes in slope aspect on an uneven hummocky disturbed surface of a landslide (i.e. variations in roughness), or abrupt slope changes at the headscarp of a slide.

However, the principal data set used in landslide recognition is the hill-shaded DEM which produces a pseudo 3-D image of the landscape. The inclination and direction of the sun provides illumination and shadowing to the landscape and can be manipulated relative to the ground surface aspect and slope to emphasize and highlight landslide features. Various aspects of landform can change and become focused depending on the sun direction and height and the process of recognition can often be an iterative one whereby identification of the feature is enhanced by a series of different views and visualizations runs.

Based on the authors’ recent experience using ESRI™ GIS applications, we would recommend initial assessment using sun direction from 45º, 135º, 225º and 315º with an angle of sun inclination of 45º but increasing to 70º in steep terrain. We also note that in many circumstances the illumination from a bearing of 225º causes the image to invert whereby valleys appear as ridges and vice versa. In addition shadows can be included or excluded when developing the hill-shaded models. Our experience suggests that terrain with significant relief can be obscured with shadowing and thus it is best to exclude shadowing in such landscape.
3.3 Field Calibration and Verification

Any remotely-sensed process must be recognized as having an inherent weakness of the absence of real time, in-field, direct observation. As such, the process of field calibration at the start of a LIDAR derived DEM landslide recognition program is highly recommended. This will allow the assessor to gauge landscape features in context of local geology and landform. Our experience across a number of sites around Australia, suggest what works in one area may not necessarily work in another. Hence, there is a need for early calibration through direct field observation and verification is essential to calibrate future data capture and limit misinterpretations which will still occur to some extent given data inaccuracies and limitations in the overall process. None-the-less, an annual desktop analysis of a LiDAR DEM can serve to target subsequent field-based investigations.

3.4 Benefits and Limitations of LiDAR DEM’s

A good comparison between the LiDAR and photogrammetric techniques was conducted by the US Army Corps of Engineers (USACE 2002) and highlights major differences in the technologies which makes direct comparison difficult. There is however no doubt that LiDAR has gained increasingly more acceptance in the last 10 years. Its main advantages include rapid acquisition of data over widespread areas, an ability to work in previously inaccessible environments, a capability of viewing “through” trees and vegetation, and cheaper production of DEM’s when compared with those obtained from traditional photogrammetric techniques.

Major disadvantages include initial higher costs of obtaining data, mean point spacing dictates the final DEM resolution, false sense of accuracy, processing artifacts such as trees and buildings when bare earth models are produced, challenged by very steep terrain and cliffs due to lack of clear shots. While there is open source software available to process ALS datasets, the authors prefer to use proprietary GIS software that while it is expensive to purchase, has the advantage of ready integration with other core GIS activities.

In terms of LiDAR derived DEM’s for landslide recognition work, the major advantage is the flexibility to visualize landscapes using multiple combinations of hill-shading and associated second derivative data sets. The data layers are readily integrated into standard GIS applications making the capture of new features very easy and time efficient. Comparisons over the past few years indicate landslide recognition using LiDAR derived DEM’s is up to 5 to 10 times quicker than traditional photogrametric techniques in the same landscape. The main disadvantage lies with the limiting threshold the DEM resolution places on the size of the features that can be identified. In addition other geological features such as interbedding and layering can sometimes be mistaken for instability and as such field verification is always an essential component of the process although many times may not be possible due to the expanse of areas interpreted and/or the inaccessible nature of the landscape assessed.

4 EXAMPLES

The following are a series of specific examples taken from recent landslide inventory programs within Australia which highlights both the potential and limitations of this method.

4.1 Use of aerials and LIDAR based DEM derivatives for landslide recognition

The series of images shown in Figure 1 depict a landslide located on Lake Connewarre on the Bellarine Peninsula in Victoria, Australia. The landslide was initially identified from low to moderate resolution aerial photography (later upgraded to a 35 cm high resolution aerial photograph) and confirmed by field inspection and review of a regional 1.0 m DEM. Mapping of the feature was aided by reference to both DEM derivatives including contours, degree of slope and slope aspect.
4.2 Different landslide types

Many factors such a landscape age, geology, soil type, topography and climatic conditions can significantly influence the geomorphic expression of landslides in the landscape. For example a flat plateau landscapes with depositional veneers over deeper Tertiary clay profiles at Irrewillipe near Colac in south west Victoria, (Figure 2a) has produced a smooth terrain. However the landslides tend to be very disturbed showing significant surface roughness and localized variations. Rocky terrain such as the Cretaceous Sandstones of the Otway Ranges in south west Victoria show well developed drainage patterns exploiting rock discontinuities. In this particular region the various types of landslides exist where they can be deep-seated and either translational where they develop on weak interbeds of siltstone and mudstone or rotational when they occur within previously failed materials.
4.3 Age of slide

The series of small landslides shown in Figure 3 are located within deep deposits of highly plastic Tertiary Clays on the Aire River near Princetown in the Heytesbury region of south west Victoria. The slides show distinct circular headscarps and have degraded areas of accumulation at the toe which are periodically effected by the creek at their base. Multiple events are clearly visible along the northern flank of the river with the two slides at the eastern end of the sequence displaying more crisp and well-defined features in comparison to other slides and thus reflecting their more recent occurrence. In addition, two smaller flows located within two of the central slides are also clearly more recent events than the circular slides they are situated within.

Figure 3 Series of slides on the Aire River near Princetown, Victoria, Australia

Whilst some landslides can be degraded out of the landscape in a remarkably short time (tens of years depending on the geology), many are well preserved with the terrain. The use of LiDAR generated DEMs is an extremely powerful method in identifying such features. For example a slide flow which is known to have occurred in 1957 in the Razorback ranges near Picton, New South Wales, Australia, is still clearly evident in the 2.0 m DEM produced in 2009.

Figure 4a 2009 DEM (2.0 m resolution) showing landslide in Razorback Ranges near Picton, New South Wales, Australia and 4b historical photo at time of occurrence in 1957.
4.4 Effects of Geology

One significant advantage of the use of high resolution DEM’s in vegetated and forested landscapes is the removal of such obstructions to aid visual interpretation. In such cases geologic features such as bedding and layering can become apparent and in some cases may be mistaken for slope instability. Figure 5a shows an area of slope instability in a deep tertiary clay environment with clear bedding in the Heytesbury region, south west Victoria, whilst Figure 5b shows a slope with no instability but a distinct harder, more erosion resistant sandstone interbed within the Barrabool Hills near Geelong, Victoria.

Figure 5 Instability on deep deposits on banded Gellibrand Marl near Cowley’s Creek, Victoria and 5b No instability on interbedded sandstone in the Barabool Hills near Geelong, Victoria

4.5 Tree Artifacts in the DEM

Processing of the raw LiDAR data can involve a number of filtering techniques to differentiate between the various signal returns in order to produce a “bare earth” model. Whilst this process is generally very successful, some remnant signals or artifacts can be left in the topographic models which do not represent the ground surface. Commonly, artifacts from building and trees can be seen such as those shown in Figure 6 which clearly shows effects from trees. The 1.0 m DEM is from the fringe of the Otway Ranges near Johanna in far south west Victoria.

Figure 6 Tree artifacts in a 1.0m DEM near Johanna, Otway Ranges, Victoria, Australia
4.6 Impact of DEM resolution 1m versus 5m

Grid resolution has a significant effect on the visualization process with smaller grids allowing features to be interrogated at much larger scales. Recent work along the coast of the Otway Ranges in Victoria was conducted using two regional DEM’s one with 1.0 m resolution and the other with a 5.0 m resolution. Inspection and recognition of the Cape Patton landslide is clearly evident in both DEM’s but the higher resolution 1.0 m DEM allows much greater interpretation of internal features including smaller subsidiary landslides at the coast.

Figure 7a 5.0 m DEM and 7b 1.0m DEM showing the Landslide at Cape Patton, Victoria, Australia.

5 COMMENTS AND CONCLUSIONS.

The use of LiDAR-derived DEM’s and associated derivative data layers has proven an effective, economical and time efficient method for the identification and capture of landslides. The use of the LiDAR-derived DEM approach proved to be rapid and cost effective against traditional Aerial Photo Interpretation (API) allowing between 5-10 times more area to be assessed in the same time. This compares favourably with other published comparisons suggesting between 3 and 4 times more area is able to be covered using the same budgets. Whilst this method should be seen as complimenting traditional methods, it is not envisaged it would replace such methods.

A critical element to any remote observation and identification process lies in the field calibration and verification. Whilst the process is largely conducted in a GIS framework the method should not be conducted by staff that lack adequate geomorphological understanding of the landscape. Observation and assessment by experienced geo-specialists will always remain the key element in the interpretation and preparation of any landslide inventory. no matter what the technology used.

The process of producing extensive landslide inventories greatly facilitates the role of local and state governments in appropriate land use planning and decision making. To this end, the use of LiDAR-based DEM for landslide recognition should prove to be an extremely valuable tool and its ongoing use is highly recommended based on our recent experience.