REMOTE SENSING APPLICATIONS FOR SEISMIC HAZARD ASSESSMENT

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Abstract

Remote sensing has been employed routinely in geological research to map faults and other aspects of geology. In recent years studies of earthquake risk have used remote sensing to study fault morphology, segmentation and activity. In addition to mapping geological structure satellite imagery has an important role to play in the assessment, and characterisation, of the ground. This paper illustrates the usefulness of remotely sensed data, not just to characterise faults, but also to map ground failures which provide evidence of ancient earthquakes. Using data from these sources it is possible to increase the quality of regional seismicity databases allowing better estimates of seismic hazard to be made. By combining remote sensing with a spatial database containing basic geotechnical information it becomes possible to use these technologies as a predictive tool to assess ground failure hazards.

1. Introduction

The assessment of seismic hazard requires not only the assessment of earthquake recurrence periods but also details on ground conditions. Site specific seismic hazard can be considered as a function of the probability of an earthquake occurring, the vulnerability and the cost. Therefore there are three broad components to the estimation of seismic hazard for some site or facility; estimation of the probability of earthquake recurrence, distance from the site of interest; estimating the vulnerability of the structure; and the cost of the consequences of structural failure. Table 1 shows some possible uses of remote sensing for seismic hazard assessment. The term 'remote sensing' is used here in its widest possible context.

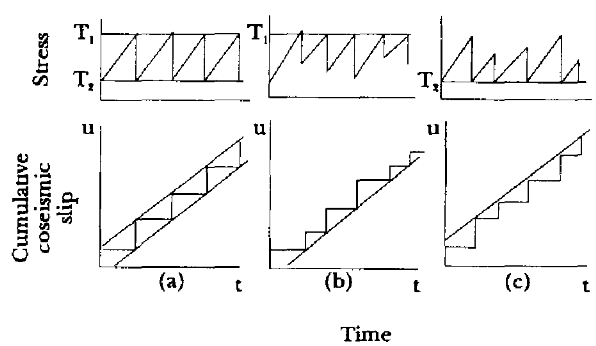


Figure 1. Three different models of earthquake recurrence (from Scholz 1990).

2. Monitoring crustal deformations

One of the principal uses of remote sensing has been the mapping of regional geological structure. Examples of this kind of study in a seismically active area can be seen in the work of Cardamone *et al* (1976). Gutmanis *et al.* (1985) used LANDSAT Thematic Mapper and Multispectral Scanner data to map faults in southern England. The ability to look at texture over a wide area, and to distinguish different lithological units, has allowed investigation of ancient and current crustal deformation.

The value of monitoring rates of crustal deformation over geological time is that it allows long term estimates of seismic hazard to be made. These estimates are based on what is believed to be a characteristic earthquake for a given fault Figure 1 illustrates different models for characteristic earthquakes. These are referred to as the linear model (a), the slip dependant model (b), and the time dependent model (c) In the linear model coseismic slip on a fault is assumed to be separated by a characteristic time period, after which a characteristic amount of displacement will occur. The slip dependent model dictates that an earthquake will occur after a given amount of deformation, therefore, assuming that the rate of crustal deformation can be defined, then it is possible to make an estimate of the period between earthquakes. However using this model it is not possible to determine the earthquake magnitude. The time dependant model assumes that an earthquake will occur after a certain period over which crustal deformation has occurred. Since the time is the assumption, which in turn controls the amount of deformation which has occurred, the magnitude of the earthquake may be estimated but when the earthquake will happen is unsure. A fuller explanation of these ideas and the assumptions inherent in them can be found in Scholz (1990).

Table 1. Some considerations in seismic hazard assessment and applicable remote sensing techniques

Component	Data required	Remote sensing applications
Earthquake Recurrence	Recorded earthquake data specifying magnitude, epicentre and depth	Teleseismic measurement of seismic waves, regional geophysics such as gravity and magnetics measurements
	Mapping of seismogenic structures	LANDSAT Thematic Mapper (TM) and Multispectral Scanner (MSS), SPOT, radar imagery, aerial photography
	Monitoring crustal deformation and strain rates	Global Positioning systems and geodetic networks and satellite imagery
	Long term seismic activity and palaeoseismological data	LANDSAT TM and MSS, SPOT, aerial photography, radar and groun penetrating radar
Vulnerability	Geology and site conditions	LANDSAT TM and MSS, SPOT, aerial photography, radar and ground penetrating radar
	Natural site period	Geophysical methods (especially seismic studies)
	Groundwater levels	Thermal imagery
	Topography	SPOT, Digital Elevation Models (DEMs)
	Location of vulnerable structures	LANDSAT TM and MSS, SPOT, aerial photography, radar
	Density of constructions	LANDSAT TM and MSS, SPOT, aerial photography, radar
Cost	Mapping and location of areas which may be affected by the failure of the primary site (e g areas which may be affected by flooding due to dam failure)	LANDSAT TM and MSS, SPOT, aerial photography, radar GIS may be particularly useful (e g estimating direction of water flow based on a digital terrain model from a dam failure)

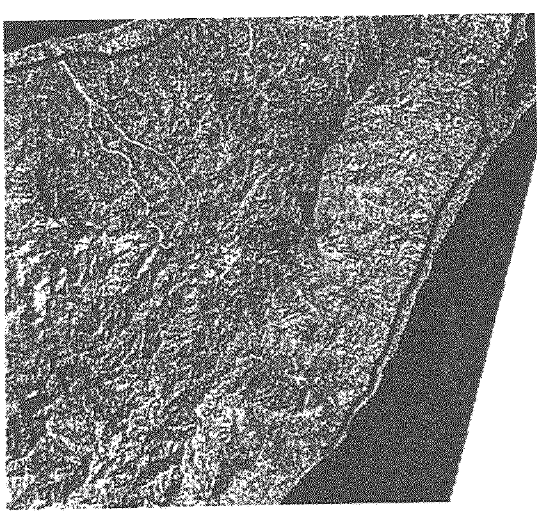
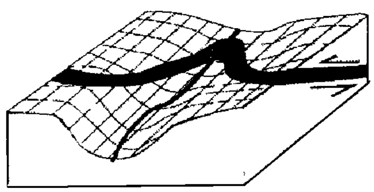


Figure 2. Satellite image of northeastern Sicily

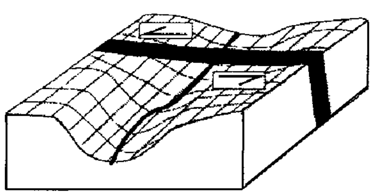
Regardless of which model is used it is clear that there is a value in monitoring neotectonic defamations and this can be achieved by remote sensing methods While aseismic (occurring without earthquake activity) and coseismic (occurring at the same time as an earthquake) crustal deformation measurements can be made by geodetic surveys and global positioning systems (GPS). The determination of longer term rates of deformation can usefully be made by remote sensing calibrated by suitable dating methods. Figure 2 shows a LANDSAT Thematic Mapper image of north-eastern Sicily. This area borders the Straits of Messina which historically has given rise to large magnitude earthquakes. Given the proximity of the major cities of Messina and Catania some estimate of seismic hazard is necessary Around the edge of the peninsula an ancient shoreline can be observed as a narrow area of flat ground highlighted by a dark line in figure 2. This shoreline can be correlated with the 25 m shoreline on the other side of the Straits of Messina which Fontes *et al.* (1987) suggest is approximately 25-28,000 years old based on ^{14}C dates. If these dates are correct then this suggests a deformation rate of approximately 1 mm/year of tectonic uplift Therefore it is clear that remote sensing provides a useful technique for locating neotectonic features which can be used as an indicator of strain rates over geological time.

Fault morphology

There is a tendency in studies which employ remote sensing to examine faults, whether they are active or not, to draw straight lines on images and interpret those as being structural in origin. In truth however, very few faults examined at outcrop are found to be straight because of the inter-relationship between topography and structure (see figure 3).



(a) Low angle dip-slip fault



(b) High angle strike-slip fault

Figure 3. The effect of surface topography on surface fault expression.

Therefore unless the fault has a very steep dip, or there is virtually no relief, then the outcrop will not appear as a straight line. Generally faults on remotely sensed data can be distinguished on the basis of.

1 Image lineations which may, or may not be, straight.
2. As a result of comminution on the fault plane and the juxtaposition of different geological units the rocks in the fault zone may show markedly different mechanical properties to those of the local area Such changes will result in differences in terrain which will be shown as a textural change on the image.
3. Major faults will also show a major change in topography which *may* be reflected in a marked change in vegetation type
4. Active faults are defined on the basis of the displacement of some recent phenomena such as housing, roads, rivers or recent sediments.
5 Active faults will often show a scatter of seismic activity on, or around, the fault trace.

Figure 4 shows the interpretation of a satellite image of the Wairarapa Valley in New Zealand. The valley is bounded by major tectonic structures. The image was referenced to latitude and longitude using control points derived from published maps and earthquake epicentre data were drawn from the United States Geological Survey database (from the National Earthquake Information Centre, Denver, Colorado). Using these data Murphy & Bulmer (in press), estimated return periods for large magnitude earthquakes (M≈8) of the order of 72 years. Clearly this estimate is erroneous and stems from the short time period over which the earthquake data were recorded (approximately 40 years).

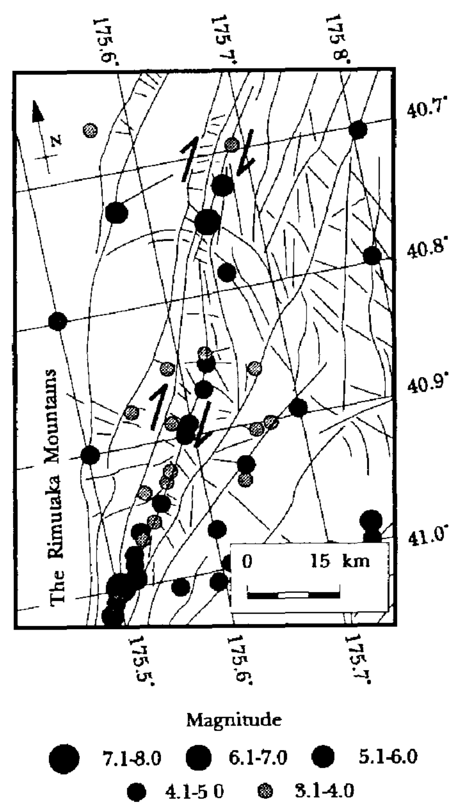


Figure 4. Faults mapped by Landsat Thematic Mapper showing seismic activity (Murphy and Bulmer in press).

Measuring fault displacement

While remote sensing is useful for measuring fault displacements over periods appropriate to geological time, monitoring on a year by year basis, is beyond the current spatial resolutions of satellite-based remote sensing

The best 'remote' method for monitoring small crustal deformations is the use of global positioning systems or geodetic measurements. Such techniques however fall into the sphere of surveying and will not be examined further in this paper.

3. Palaeoseismicity

Seismological instrumentation has only been in operation now for, at best, around 100 years. Good instrumental coverage did not come into effect until the 1960s with the establishment of the Worldwide Standardized Seismograph Network Therefore instrumental records of earthquakes do not cover return periods of large magnitude earthquakes, even, in tectonically active areas. Historical data has potential to provide information over longer time periods. However the length of this form of record is extremely variable over different regions (e.g. ~ 2000 years in southern Italy, ~ 250 years in UK, and ~ 150 years in New Zealand). Therefore it is necessary to utilize what geological evidence of earthquake shaking may exist This kind of palaeoseismological evidence is found in the form earthquake-triggered ground failure; either liquefaction, or, landslide

Liquefaction is the complete loss of shear strength in a sand, or silty sand due to earthquake shaking. Apart from the landslides which occur due to liquefaction (e g the Turnagain Heights landslide which was triggered by the 1964 Alaska earthquake) these features are usually too small to be resolved by remotely sensed methods and are dominantly found by field mapping Landslides however present a better target for the evaluation of past earthquakes. Seismically-triggered landslides can be resolved on aerial photography, and frequently, by satellite imagery Crozier (1991) used landslide evidence to calculate the magnitudes of 4 large earthquakes in the Taranaki region of New Zealand.

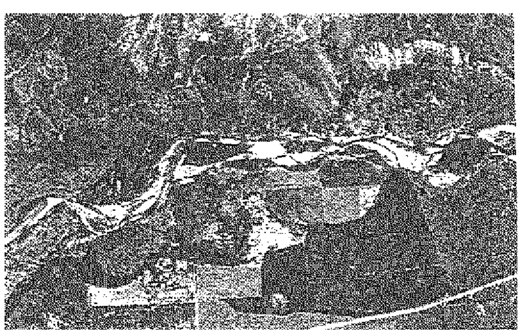


Figure 5. Aerial photograph of the Ruamahanga slide and nearby slope failures (courtesy of New Zealand Aerial Mapping).

Figure 5 shows an aerial photograph of a landslide triggered by the 1855 Wellington earthquake Slope failures similar to this were used by Murphy & Bulmer (in press) to enhance the length of seismic record for this section of the Wairarapa valley The location and geometry of the landslides were determined by remote sensing Once mapped it was possible to calculate an amended return period for large earthquakes (M≈8) as being in excess of 500 years.

4. Seismic hazards and Geographic Information Systems

The type of information required for the evaluation of site-specific seismic hazard is not normally collected by remotely sensed data, with the possible exception of calculating site response characteristics using geophysical surveys. The reason for this is that this process normally requires data on the distribution of soil types at depth which remote sensing cannot yield. However, much of this information can be usefully stored in a geographic information system (GIS) which can incorporate remotely sensed data.

Figure 6 shows a map of landslide hazard based on calculations from a DEM in a geographic information system. The geology, geotechnical properties of soils and estimates of the phreatic surface, were used to calculate the static factor of safety, F, (the ratio of shear strength to shear stress). Remote sensing, utilizing TM data and aerial photography, allowed a study of the area to be made in an attempt to verify the calculations from the DEM. The infinite slope model was used to calculate F. It was found that the estimates made by the geographic information system were largely correct.

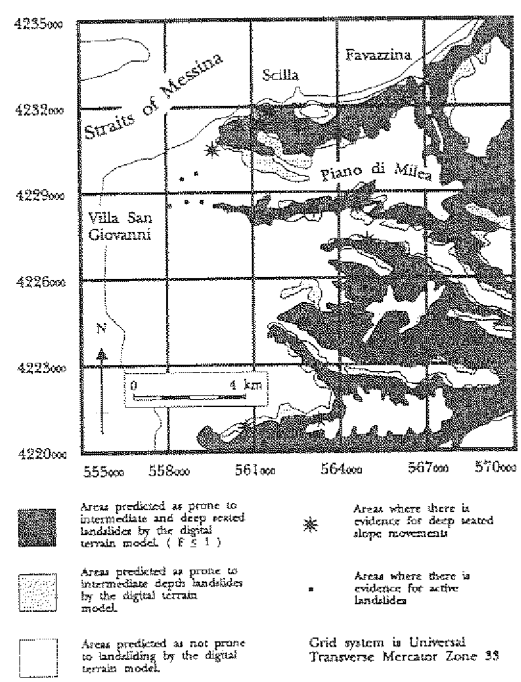


Figure 6. Map of landslide hazard based on a geographic information system.

Calculations of slope stability during earthquakes using the techniques outlined by Jibson & Keefer (1993) show large areas which were prone to failure from a large magnitude earthquake in the Straits of Messina. Descriptions by Baratta (1913) of the Straits of Messina earthquake of 28, December 1908 show that several regions suffered from seismically-triggered landslides as predicted by the model. However there were also some regions which did not show slope failure where landsliding was predicted. However, many assumptions were built into the model, and many of the datasets could have been improved to give more precise data for this form of analysis.

Other work of this kind has been carried out for seismic hazard zonation in California. Borcherdt *et al.* 1991 showed that it was possible to produce maps showing areas which were prone to amplification of seismic shaking due to soil conditions as well as liquefaction capability maps The authors drew upon published geological data which was supplemented by geophysical investigations of the sites of interest.

5. Conclusions

Clearly remote sensing has a powerful role to play in the location and mapping of the surface outcrop of active, and inactive faults. However, while many current remote sensing platforms are limited by the spatial resolution, the availability of high resolution radar imagery and high spectral and spatial resolution airborne imaging systems will mean this limitation will disappear.

GIS remains a useful technology for the assessment, mapping and presentation of seismic hazards. The facility to incorporate multiple data sets including, data derived from remote sensing, geotechnical information, historical data and earthquake source parameters allows examination of a variety of seismic hazards, and, the facility to map the extent of the impact

6. Acknowledgements

New Zealand Aerial Mapping is gratefully acknowledged for the permission to publish an extract from the aerial photograph of the Ruamahanga Slump.

7. References

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Discussion

In response to a question from Dr. C Toomer (Bristol and West HSE), Dr Murphy said that he was not familiar with atmospheric precursors to earthquakes and thought it unlikely to be a technique of much predictive value. Dr. Browitt (DES) amplified this by saying that earthquake prediction by any technique was not feasible except in a probabilistic sense He asked how landslips caused by earthquakes could be distinguished from those triggered in other ways. Dr. Murphy said that one needed to prove that the landslip could not have occurred under ambient conditions without seismic accelerations.