The evolution of a risk-zoning system for landslide areas.

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Abstract

A system for drawing map zones to represent the risk of landslide damage to housing is described. The system is based on topographic, geologic and geomorphic mapping and is supported by stability analyses. Some comments are made on the problems of administration.

INTRODUCTION

A man's house is his greatest material possession and to lose it is a personal disaster. The publication of reliable information of the expected risk from landslide damage can sometimes prevent this loss, and should be the task of geologists in the service of governments.

Estimates of risk, made by a process such as that to be described, should be published so that land use can be designed to avoid or minimise the landslide hazard. This hazard is comparable in personal impact to that due to flood, forest fire, earthquake, or cyclone. Estimates of risk can best be presented as zones on a topographic map.

TOPOGRAPHY

The topographic map is the first input to the zoning process (fig. 1). An examination of even a 1:100 000 map, contoured as ours are at 20 m intervals, can enable the steeper areas to be recognised and marked for closer examination. At larger scales, more detailed maps, if they are available, can be used with a correspondingly closer distinction of slope classes. In the absence of detailed maps at larger scales aerial photographs used in combination with small scale maps can be used. Ideally, contoured orthophotomaps would be preferred as source material. The ultimate and essential source of information is the landscape itself.

We have developed some views on the scale of the final result, the zoning map. In Australia housing blocks are not normally smaller than 18 by 36 m and this appears on a 1:5000 map as 3.6 x 7.2 mm. At 1:10 000 blocks become difficult to distinguish and we have suffered some embarrassment from trying to use a 4 inch to one mile map (1:15840) as a base for zoning. In the absence of suitable topographic maps, we have used aerial photographs enlarged to 1:5000 and found them satisfactory.

Whatever suitable maps are chosen, slope angle classes are drawn on them. The choice of angles depends of the prevailing topography and geology and will be considered more fully in a later section. The slope classes - for instance less than 10°, 10-15°, 15-20°, and over 20° are derived from contour spacings. Suitably drawn paper templates extending over about five contour spacings can be moved round the map marking the changeovers from one class to another. We have used this method often and also a variant where perspex plates with holes cut in them having a diameter equivalent to the five-contour spacing of a given slope on a given scale are moved over the contours. Where five or more show through, a circle is drawn round the inside of the hole. A pattern of these circles outlines the area covered by the class. A method has also been used combining maps and aerial photographs. Slope angles are measured in the field by clinometer and the same slopes are used as standards for comparison on stereo-images. If suitable slopes at the limits of slope classes are chosen then the problem becomes 'is the unknown slope steeper or flatter than the measured slope?' Another approach is to construct, using the methods of Miller (1961), square-based pyramids having apparent sideslopes of predetermined angles (10, 15, 20°). These are plotted onto transparent film and viewed as a stereopair so as to form a model in space. This is laid over the photopair and direct comparisons made with the unknown slopes.

Doubtless some authorities will have computer facilities which render these simple methods inappropriate, but sophistication has no virtue of itself and the simpler, more direct, methods will give the zoner a closer knowledge of the landscape in question. The final result will be the same, a series of slope angle classes drawn on a suitable base map.

GEOLOGY

The second input is the geological map. We are fortunate in that 1:50,000 geological maps exist of most of the areas with which we chose to deal. Where these do not exist, then the zoning process will be greatly hampered and the geological mapping will have to be done as part of the geomorphic appreciation to be described later. It cannot be emphasised too strongly that the geological contribution to the process is vital and attempts to dispense with it are likely to be disastrous. Indeed, we find such a procedure difficult to imagine.

The geological map, if it does not already do so, must be interpreted in terms of rock types. Clays, weak shales and mudstones will primarily suggest themselves as slip-prone material but only field examination will confirm this.

The harder rocks must also be considered as they may often function as loads at critical places on clay slopes, and more importantly as aquifers. The recognition of the influence of surface aquifers in producing instability in adjacent soft rocks was recognised by Denness (1972) as the reservoir principle and we have found this principle to be of the utmost importance where, as in our area, fresh fractured basalt overlies soft lacustrine sediments on steep slopes.

The solid geology as indicated in most geological maps is therefore to be inspected for the presence of soft or softenable rocks and for aquifers capable of producing spring lines above steep slopes in these materials.

There is however, a considerable limitation to this simple approach. The colluvial materials on the slopes are probably critical in determining slope stability and are not usually represented on a geological map. Here a direct method has to be used, that of inspecting the slopes on each rock type in the field and determining the colluvium thickness, expected variation, and general nature. This process can be treated qualitatively at this stage but will need to be pursued in detail when the morphology is dealt with.

Another limitation of the geological map is that it makes no recognition of the state of weathering of the rocks. The basalts that exist in our areas are sometimes fresh and hard, but may also be deeply weathered. Where this has occurred the whole nature of the rock changes from a strong permeable aquifer to a weak softenable clay with a consequent change in its stability potential. The effect of this process cannot be appreciated from the map but must be seen and taken to heart in the field.

The relationship between aquifers and their resulting springs and the movement of colluvium in hillcreep must also be appreciated. A weakly-issuing spring may be covered by active creep or more energetic mass movement, and this occluded spring may then be a very potent agent of instability. The blocking of the spring will cause pore pressures to rise and the material blocking it will be very suitable for failure.

All these features can be deduced from the geological map which can indicate to us the critical areas that will require special examination in the field in the next stage.

At this point it is possible to combine the slope angle classes and the geology and so eliminate those steep areas on rocks strong enough to sustain them, leaving those areas of weak rocks which because of their surface slope may contain the potential or actuality of failure.

MORPHOLOGY

The principle of the field study of mass movements must now be reviewed. Some consideration of slope classes has already been made. The angles which are used as the class limits are chosen after an examination of active failures. An inspection of several recent failures in what appears to be the same geology will generally indicate a lower limiting angle. With so many factors influencing the stability of slopes, it might be thought that the slope angle is too simple a criterion to use, but an extended area of similar materials, where several failures can be compared has, in our experience, generally indicated a lower bound to the failing slope angle. This we have called the critical angle for the prevailing geology.

Where the geology changes, the critical angle will change also. Our areas show a variety of critical angles, for example in Tertiary lake sediments 7° is taken, while on weathered basalt soils 14° is used. It would be illusory to depend too much on these exact angles but the whole process of zoning is an approach to an ideal and the establishment of critical angles is a step on the way.

The underlying geology has a strong influence on the position of changes of slope, as harder rock bands may produce steeper slopes. It has been implied that the geology is well known. This is sadly but usually untrue and most formations can show unpredictable changes in hardness. When, as we shall see, we come to the interpretation of slope profiles, each change becomes of very great concern.

Soft rock slopes subject to mass movement are poor guides to solid geology and the problems posed by hard rock bands are difficult to solve. Perhaps stratigraphic continuity can be assumed, drilling is another answer, and the pattern of mass movement is often seen more clearly from an aerial view than from the ground. Ultimately the judgement on any irregularities in slope must be reserved until further through the process. What is to be noted as this stage is that an anomaly is present.

The next stage of our geomorphic appreciation is directed to the surface drainage. The textbook examples of drainage patterns are not uncommonly seen to be represented in the field, but in mass movement areas disruption of drainage is a marked characteristic. The scale on which this occurs is often not large enough to appear significant on a 1:100 000 topographic map, but on photos or in the field it is usually obvious. Simple stream flow patterns diverted by debris tongues, ponds behind rotated blocks, and the subsequent drainage along rather than across the contours of the original slope, hillside swamps with no outlet, small valleys containing paired streams, and many other anomalies in the surface hydrology can point to movement.

Hydrological anomalies are but one of the symptoms of a disturbed slope which enable us to recognise active and fossil movement. Arcuate scarps often now vegetated or subdued by erosion, anomalous leaning or kinked trees, the universally present but ill-defined 'hummocky ground' have been exhaustively described, and Pulinowa *et al.* (1977) have given the elements an atlas of symbols so that the whole morphology may be represented.

To these natural features may be added the stretching of fences, cracks in roads, walls, and pipes, the tilting, distortion and final destruction of buildings. All must be recorded on the geomorphic map. An example from Tasmania is given in Figure 2.

It is slope complexity that ultimately leads the viewers mind to the presence of mass movement, complexity that cannot realistically be explained by any distribution of underlying solid geology or any homogenous process or erosion. It is the very anomalous nature of the surface that leads us to believe that only by this means could it have been produced.

THE AGE PROBLEM

The next question that arises is what is the age of the disturbance? It is a question of real significance because any zoning scheme must be based on the realisation that it operates in a time scale short by geological standards, but long in comparison to the occupancy of a house. A period of fifty years is a convenient yardstick, almost a lifetime, long for a house of light modern construction, long enough to see several generations of active engineering geologists and to see dramatic changes in investigation technique. It is all the more reason for zoning to be placed on a practicable and defensible methodology for it is going to influence urban land use beyond the foreseeable future.

Since we cannot see forward, we as geologists can only look backward and, by knowing how old the disturbance is, attempt to predict how soon the mass movement cycle will be repeated. It must be admitted that at the moment measurements of this kind are usually impossible. The work of Hutchinson (in Skempton and Hutchinson, 1976) shows that in well placed cases dates can be found for old movements, but in Australia with less than 200 years of recorded history the problem is doubly difficult.

At the younger end of the scale we see active movements. These may be only days old and we can see the movements imprinted on roads, buildings and less massive structures as they occur. Here the value of photographs, measurements and descriptions is important. Today's failure will in a few years become blurred over, deliberately forgotten and surprisingly difficult to recognise. The speed at which this happens can hardly be exaggerated partly one suspects as a human reaction to disaster, but it does not offer much encouragement to the student of fossil landslides. Historical records in newspapers may provide some datings, but these failures are often difficult to locate on the ground and in any case may represent re-activations of pre-existing failures.

This problem is perhaps the most difficult part of the zoning process. Underestimation of the age of a disrupted slope may lead us into unnecessary conservatism so that even Pleistocene slope failures may be considered unsafe. We can only turn to the presently active failures and extrapolate from them.

Mass movement is part of the response of geology to climate so that climatic variation studies both in the long and in the short term are of some use. Rainfall variations are influential in controlling pore pressures in fissured clays and the monitoring of piezometers through several years has revealed some unexpected and significant behaviour in relation to landslide movements (Knights and Matthews, 1976). Rainfall records can usefully be reviewed against historical accounts, although correlations based on newspaper articles have not been very successful. Beyond rainfall records, recent advances in Holocene climatology may enable the truly fossil movements of the end of the last glacial stages to be separated out. In our case the sheer size of what we believe to have been Pleistocene failures compared with modern failures, together with the anomalous relation to what are now permeable sediments, enable us to distinguish them with some confidence.

The problem of the role of vegetation in controlling stability is still with us. It cannot really be regarded as established that vegetation invariably increases stability. It depends too much on what vegetation, what climate, and what kind of slopes are involved.

The surface features that have been described can be represented on geomorphic maps. The whole area can appear on one scale (1:5000 or 1:10000) while old and active slip areas will require more detailed maps.

At this point we have reviewed the contribution of the topographic, geomorphic and geological maps.

DETAILED STUDIES

We must now turn to the crux of the zoning problem where we see landslides in action. Working in this field where potential failures or long term stability are everyday concepts, the sight of a slope actually undergoing failure is a sobering experience. When the slope is actually failing, it is possible to say that the factor of safety is less than unity, that the many conditions for failure are satisfied, that doubts are removed and, however the process works, it is doing so here and now. A failure provides an example of the process that is of great value for it is then possible to investigate a real example, not a scenario or a potential situation.

The methodology is the same as in a regional analysis. The topography of the slide and its immediate surroundings, and the geological setting must be discovered. The materials present must be examined and sampled by drilling, and the soil parameters and water conditions determined. The changes in time in water conditions, particularly of pore pressures must be recorded. The variability of these is of particular importance in analysis.

With this sum of information we must procede to set up an analysis of the failure so that the limits of the input parameters may be found and to check for realism. Classical analysis after Bishop and Morgenstern, or for shallow slab failure, after Skempton and De Lory is known to be incapable of coping with the real world facts of progressive failure or long term stability. Many other formulations are current but none show any advantages in the real world, and stability analysis must be recognised for what it is, a simplified mathematical model of the failure process, which takes its place amongs the other intellectual techniques with the admission that its numerical appearance does not lend it any additional credibility.

Stable areas where no sign of past movements can be distinguished and dormant areas where past movement is known or suspected must also be subjected to analysis. The determination by back analysis of acceptable values of input parameters must be made as a parallel to the work in active areas. The stability of the stable areas as well as the failure of the active areas must be confirmed by analysis.

The empirical methods outlined by Stevenson (1976) have some relevance here for they enable the relative stability of an area to be estimated in relation to the analysed areas. Analysis cannot be used in a great number of locations for reasons of cost and effort, but if it can be used in the more critical places, then other similar locations can be estimated with perhaps only a minimum of groundwater information.

THE ZONING SCHEME

We have now accumulated a great deal of information on the area to be zoned, and we must now turn to the task of synthesis (fig. 3).

Zoning has always been conceived in our minds as a control on the development of dwelling houses. Any larger structures are not generally built or owned by individuals on their own financial resources, and the impact of damage is borne corporately. In most countries landslides are not an insureable risk and every possible precaution must be taken to avoid damage as the cost falls heavily on individual owners. In those countries where some corporate risk is borne, this does not relieve the cost but only spreads the impact.

Larger structures, public buildings, installations, road and rail routes all carry with them the assumption that adequate investigation has been made in the course of which the landslide risk has been recognised and minimised either by design or relocation. If the assumption is invalid then damage may result, but it will be borne by the community at large and not by an individual.

DESCRIPTIVE ZONES

In this State a two-tier zoning scheme has evolved. The lower tier is descriptive, and consists of the following classes:

I Stable ground on hard rocks.

II Stable ground on soft rocks.

III Potential landslip areas.

IV Old landslips and adjacent areas.

V Active landslips and adjacent areas.

This system attempts to represent the geological truth as far as this can be known, in terms that any reasonable person can understand. The zones are advisory, are published in easily obtainable, cheap maps and are circulated to local councils and other interested government departments.

Zone I is, in our areas, normally on dolerite, basalt or sandstone, weathering is no more than moderate, and the soil cover is not normally greater than 1.5 m. It is essentially a zone where clay failures cannot exist and slope failures of other kinds are vanishingly small under the impact of urban housing. One cannot rule out the exceptional occurrence which may be brought about by a previously unknown phenomenon or incompetent building methods.

Zone II is those areas where clay and deep soil capable of slope failure exists, but slope angles are less than the minimum observed failure slope. These areas are often subject to a swelling soil problem, but this is not directly relevant.

Zone III is those areas where both sufficient slope and failure-prone materials are present, but where no failures are known to have taken place. Presumably the groundwater conditions are not such as to bring about failure, but the possibility exists that a change in conditions caused by development could precipitate instability.

Zone IV is those areas where sufficient evidence exists of past instability to warrant an assumption of reactivation, and those areas adjacent which such reactivation could endanger.

Zone V is those areas where measureable movement is taking place and those areas which could be endangered.

In the light of the analysis that has been described boundaries must be drawn on the zone map, on the strength of the topographic, geologic, and morphologic findings and with the assistance of the stability analyses, but without reference to existing man-made structures. We have deliberately zoned a township on a base map from which all houses have been omitted so that the presence or absence of buildings will not predjudice the position of the zone lines.

The lower tier, descriptive zones are used to persuade the public of the danger and risk of the landslide hazard.

PROSCRIPTIVE ZONES

The second tier of zones is brought into use when advice is no longer enough and compulsion becomes necessary. The zones are proscriptive, and are proclaimed under the State's Local Government Act (1973).

Legal sanctions sometimes become necessary when settlements have existed before the recognition of the extent and seriousness of the landslide risk. In this case, the risk must be made plain to the owners of houses in the area so that they may be able to take prudent precautions such as the maintenance of drainage or the avoidance of deep earthworks on steep slopes, and as a warning to intending purchasers.

It may also happen that entrepreneurs have committed themselves to the construction of housing before the recognition of the risk. They will of course wish to lose as little of their investment as possible, and the zones inform them of the constraints on building.

The proscriptive zones are known as A and B landslip zones under the Act. In an 'A' zone all building is prohibited with some minor exceptions. In a 'B' zone, buildings are controlled in respect of size, siting, drainage, earthworks and the removal of trees.

The problems that arise when landslide risks are first recognised are unavoidable but we have 'taken the bull by the horns', as we believe that they will become more serious with passing time and additional development.

The relationship between the zones of the I-V scale of descriptive zones and the A and B proscriptive zones has evolved through usage, and introduces a useful degree of flexibility into the system. Originally, B, the zone where limited building could take place, was taken as equivalent to III and A as equivalent to IV and V. As the whole problem has been investigated and our confidence has increased, a partial relaxation has been made in zone IV. The term 'old landslips' has always included structures of a range of ages. The oldest of these, probably originated under different climatic conditions and are now quite stable, and so can be released for controlled building. Different parts of old structures also vary in their potential for failure. The heel area is often quite stable, while the oversteepened toe zone may still show parasitic modern failures.

Another advantage of the two-tier system of zoning is that amendments to the descriptive zones are easily introduced as they arise from detailed investigations, while proscriptive zones require a statutory process. In practice, even the first kind of amendment has not been very common, and the original descriptive zones have proved to be a good general guide.

PROBLEMS OF ADMINISTRATION

The administrative procedures have not functioned well. Little guidance can be offered in this respect as the political climate and that of public opinion, and indeed the whole physical circumstances surrounding the social impact of the landslide process are likely to be quite different in another society.

Briefly, the proclamation process is initiated by the geologists working on the landslide survey. They become aware of damage or the risk of damage and of the possibility of social loss. The geological and morphological circumstances are closely examined, and if time permits, some subsurface work is done, mainly to establish material properties and water conditions. A recommendation is then made by the departmental director, and is passed to the local authority (council) of the area concerned, which has the responsibility of informing all landowners that zoning has been recommended, and calling for objections.

This procedure, while appearing to be fair, causes difficulties for everyone. The local council often has the greatest difficulty in making contact with absentee landowners, and suffers the most immediate criticisms. The council also resents the loss in value of the land in its area. The landowners, endeavouring to counter technical argument, resort to emotional appeals, or attempt to find other technical opinions. This latter is a difficult and expensive course, and by the nature of the problem the local investigators, who have been involved for some years, can readily confound most investigators imported at short notice from outside. The local investigators feel keenly that their case is a good one, but are at the same time aware of their own failings, and have themselves to suffer the disapprobation of the council and the objectors.

The whole confrontation has culminated in the past in an Objectors Meeting, where objectors are able to meet the geologists. These meetings, surprisingly, are often able to calm the worst fears of some objectors, and to explain the logic of the recommendation to those affected. While not a pleasant experience for the geologists, it is an interesting and useful one, both in appreciating the effect of the investigation and in conveying difficult scientific and technical concepts to an interested and unsympathetic section of the public.

The inability of the council to identify and inform every involved landowner has proved to be the greatest stumbling block, especially when proclamations have to be made in already built-up areas. This process has taken more than two years, and in one case has had to be abandoned. A simpler and perhaps less scrupulous process may have to be adopted.

The impact of a proclamation depends on the state of development. Where little or no work has been done on the ground by the developers, and the land is still rural, the effect is simply to prevent or restrict building. In 'B' areas, where restrictions apply, some discussion takes place on the exact details of what may be built where, and how adequate stability may be achieved. These discussions are a fertile source of ideas for construction methods, and some progress has been made in using 'B' areas wisely and well.

Where a developed township is proclaimed, the main effect is on new building, which is either prohibited, resulting in open spaces being left or is again restricted. Proclaimed areas in towns are usually those where some destruction of houses has taken place and the open spaces are readily accepted, and become parks or lesser amenity areas. Proclamation in areas of damage is easily achieved as little persuasion of its necessity is required. In areas of potential instability, the whole process of conviction must be worked through and is only ever partially successful.

The loss of land value is probably the greatest complaint aimed at the zoner. His reply generally takes the form that he is merely restoring to the land the correct value that was previously overestimated in error. To the charge of arrogance in presuming to do so, he can only reply that the care he has taken is demonstrably greater than that used in the first place when 'market forces' operated. We are not aware of any systematic studies that have been made of changes of value in the market as a result of landslide zoning, although valuations for taxation purposes have been altered on an 'ad hoc'basis.

THE PURPOSES OF ZONING

This is the zoning process, but to what end?

The end is to constitute a warning to those who seek to use the land that instability is, or may be,present. If it is, let them beware. If it may be, then the use and value of the land may be protected by prudent precautions. Forewarned is forearmed.

If warnings fail, are inaccurate, or come too late, loss can result, and can be protracted and devastating both materially and spiritually for the individuals and families affected. Only those who have suffered such a disaster can appreciate the effect of it.

Landslides are unique among natural disasters in that they are uninsurable. Why this should be so may be related to their comparative rarity, their usually small area of impact, and their often slow and unspectacular behaviour. Floods, fires, earthquakes, cyclones and tsunamis, none fulfil these three conditions, and so have attracted public attention and consequent sympathy for their victims.

Landslides have been regarded as 'acts of God', a lawyers term implying a vicious unpredictability. This paper attempts to show how a system has been evolved to establish landslide zones, and so predict as far as is presently possible the risks of this disaster. The establishment of insurance should now be possible.

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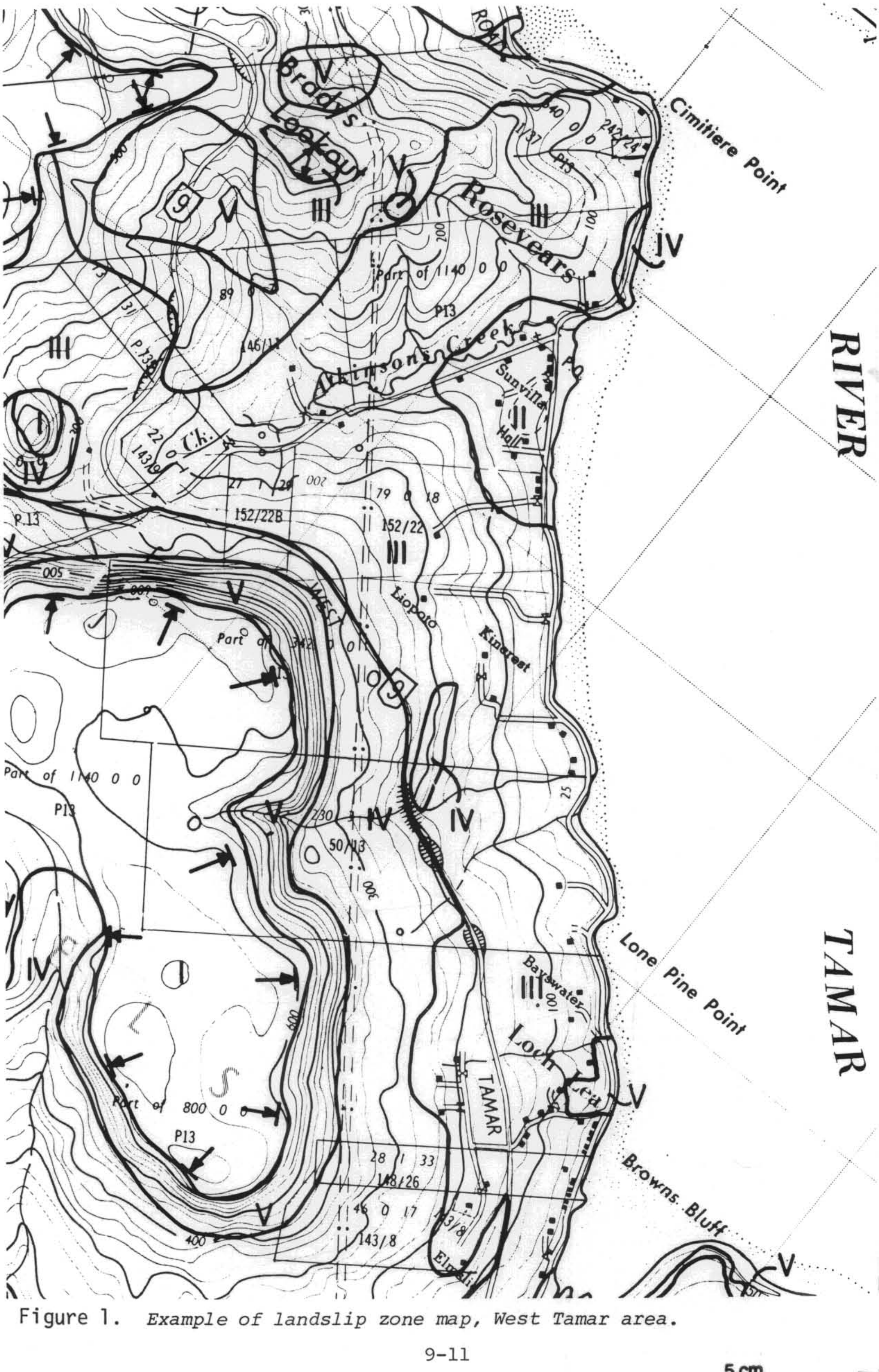


Figure 1. *Example of landslip zone map, West Tamar area.*

5 cm

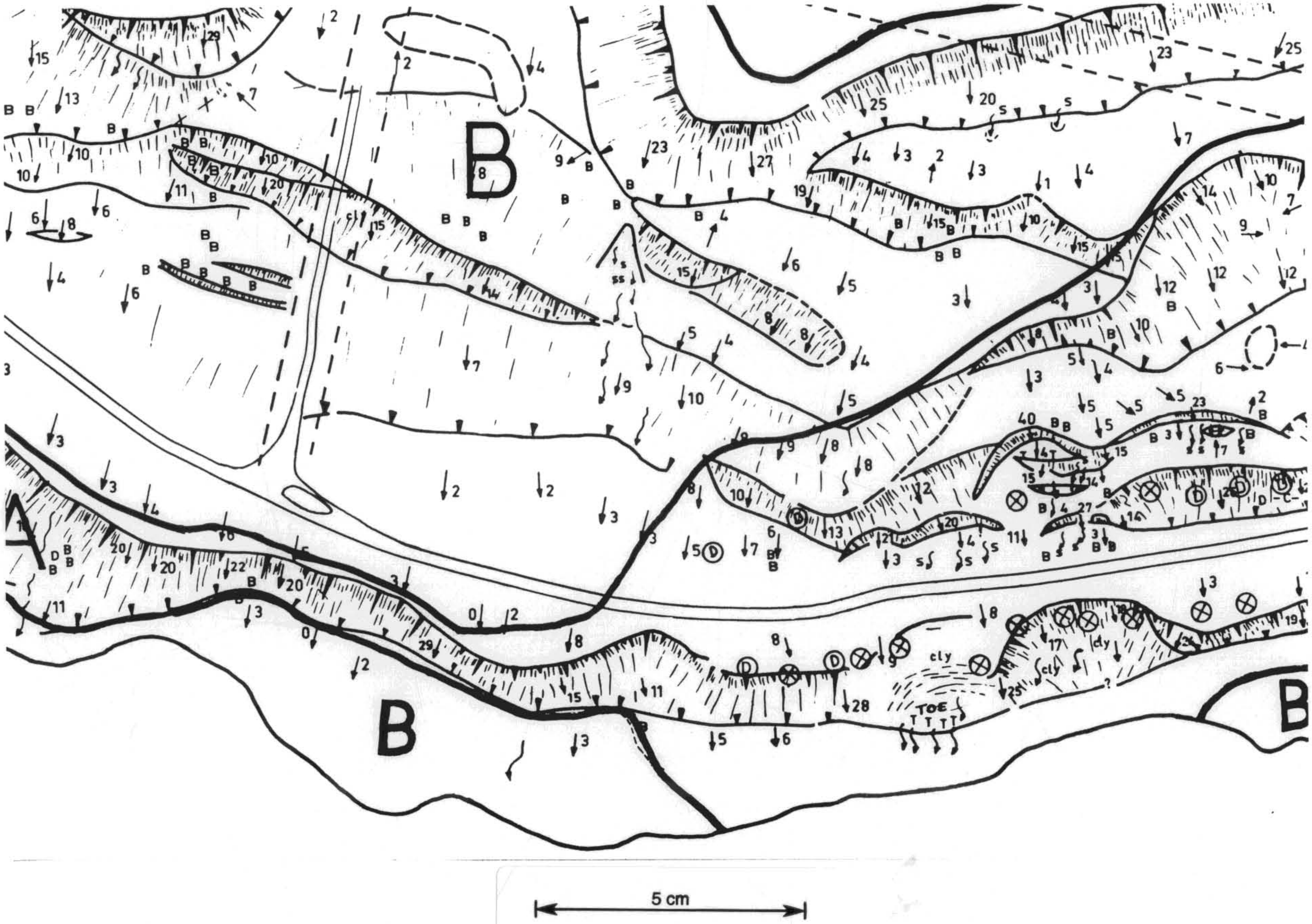
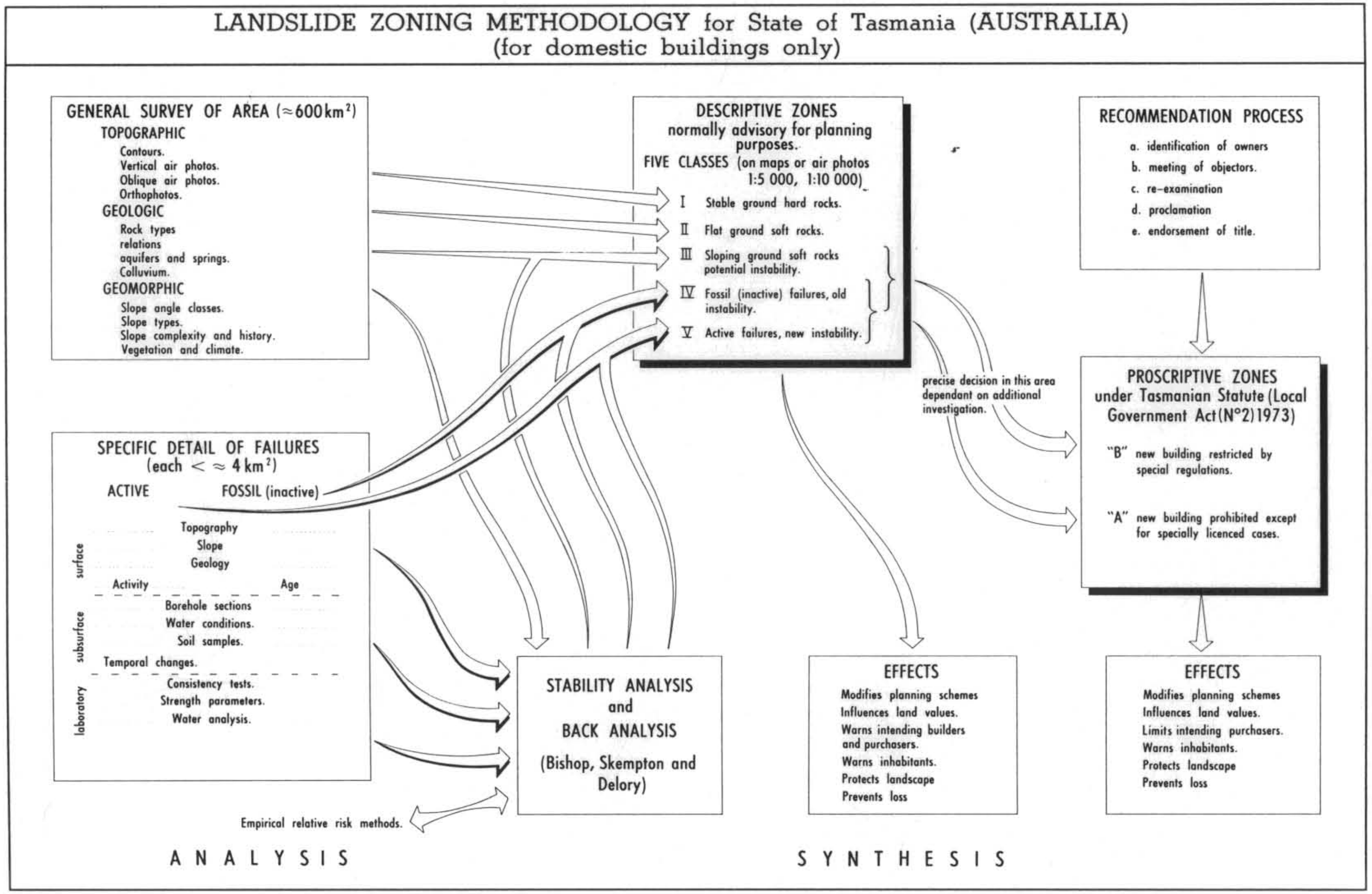


Figure 2.

LEGEND

12	*Slope direction and angle*
	Change in slope, downslope indicated
	Change in slope, upslope indicated
	Ridge
	Small drainage valley
	Swampy ground
•T	*Tree with downslope lean*
	Seepage
BB	*Basalt boulders*
Cly	*Clay exposed*
	Area of internal drainage
	Deformation in house or retaining wall
A ⊓	*Old adit*
	Piling
TOE	*Toe area of active landslip*
←c→	*Crack in retaining wall direction of separation indicated.*

Figure 2a. *Landslip zone map of part of the Bell Bay area.*



LANDSLIDE ZONING METHODOLOGY for State of Tasmania (AUSTRALIA)
(for domestic buildings only)
GENERAL SURVEY OF AREA (≈600 km²)
TOPOGRAPHIC
Contours.
Vertical air photos.
Oblique air photos.
Orthophotos.
GEOLOGIC
Rock types
relations
aquifers and springs.
Colluvium.
GEOMORPHIC
Slope angle classes.
Slope types.
Slope complexity and history.
Vegetation and climate.
DESCRIPTIVE ZONES
normally advisory for planning purposes.
FIVE CLASSES (on maps or air photos 1:5 000, 1:10 000)
I Stable ground hard rocks.
II Flat ground soft rocks.
III Sloping ground soft rocks potential instability.
IV Fossil (inactive) failures, old instability.
V Active failures, new instability.
RECOMMENDATION PROCESS
a. identification of owners
b. meeting of objectors.
c. re-examination
d. proclamation
e. endorsement of title.
precise decision in this area dependant on additional investigation.
PROSCRIPTIVE ZONES
under Tasmanian Statute (Local Government Act (N°2) 1973)
"B" new building restricted by special regulations.
"A" new building prohibited except for specially licenced cases.
SPECIFIC DETAIL OF FAILURES
(each < ≈ 4 km²)
ACTIVE
FOSSIL (inactive)
Topography
Slope
Geology
Activity
Age
surface
Borehole sections
Water conditions.
Soil samples.
Temporal changes.
subsurface
Consistency tests.
Strength parameters.
Water analysis.
laboratory
STABILITY ANALYSIS and BACK ANALYSIS
(Bishop, Skempton and Delory)
EFFECTS
Modifies planning schemes
Influences land values.
Warns intending builders and purchasers.
Warns inhabitants.
Protects landscape
Prevents loss
EFFECTS
Modifies planning schemes
Influences land values.
Limits intending purchasers.
Warns inhabitants.
Protects landscape
Prevents loss
Empirical relative risk methods.
ANALYSIS
SYNTHESIS

Figure 3.

5 cm