6. CAUSES AND REMEDIAL MEASURES

6.1 Causes of Slope Movement

Numerous factors are cumulatively involved in slope stability. The "causes" of a landslide is commonly attributed to change in a particular factor which then triggers the landslide. Most landslides in the study area are triggered by intense rainfall, but many factors related to the natural environment and to subsequent changes by man also contribute to the instability of the slopes.

Within the study area, the dominant natural factors contributing to slope movement are:

* Steep slopes developed by stream erosion and faulting

* Deep weathering and residual soil development

* The occurrence of clay rich soils, dominated by minerals such as halloysite, montmorillonite and mica/illite, which are commonly associated with landslide-prone slopes

* Seasonal volume changes in the plastic clay soils which lower the cohesion by developing fissures and assisting water to penetrate the soil profile

* Progressive release of stored residual and overburden stress, during weathering and erosion

* Intense rainfall leading to an increase in soil moisture content and groundwater level. Hydration of clay minerals lowers cohesiveness and hence shear strength. Montmorillonite, illite and halloysite are particularly susceptible to hydration. Shear strength is also decreased by increased pore water pressure which occurs when the water table rises. Excess pore water pressure can also occur when the ground is loaded and free drainage prevented, such as in parts of the earth flow zone of active landslides where multiple failures are commonly observed. The theory of failure due to excess pore pressure is based on the Mohr-Coulomb failure criterion and the consideration of effective and total stress analyses. The detailed groundwater monitoring required or such analyses. The detailed groundwater monitoring required for such analyses was beyond the resources of the present study.

* The possibility of seismically induced landslides occurring should not be overlooked.

The <u>dominant anthropogenic factors</u> contributing to slope failure are:

* Deforestation. Rain forests are generally considered to be an effective buffer to climatic factors which may contribute to slope instability. Prandini et al (1977) reviewed the relative disadvantages and advantages of deforestation from a slope stability point of view. Deforestation is considered to have the following major disadvantages:

    a. Immediate cessation of the stabilizing effect of the forest, as a whole, on the climatic variations, with negative effects on the behaviour of soils facing new stresses

    b. Immediate cessation of interception, retention and evapotranspiration, with increases in the amount of water that reaches the ground an in infiltrating water

    c. The loss within a short time, by calcinations and erosion, of the effects of the superficial debris layer (retention, induction of underflow, slow-down of runoff), with the consequent increase in erosion and infiltration

    d a rise in the groundwater table, as a consequence of the elimination of the evapotranspiration, with possible effects on the saturation of the superficial soil, and increase in weight

    e. the loss, within a certain period of time, of the mechanical effects of the root system, eventually reducing to a great extent the induced apparent cohesion and, consequently, the shear strength of the natural mass

    Prandini et al consider the only questionable benefits of deforestation to slope stability are:

a. The relief of the load, even though this is not very significant, and its effect is present only in slopes where steepness exceeds the friction angle of the material which makes up the slope

b. The ceasing of the mechanical action of wind in tree tops, which most likely is very slightly significant, as far as the stability of slopes covered by rain forests is concerned

c. The cessation of the roots' wedge action, a doubtful effect, which apparently does not exist in rain forests, due to the root system, superficial and parallel to the slope.

Landsliding did not commence immediately after the Narracan forest was cleared. Only after sufficient time had elapsed for the root system of the forest to rot, did large landslides occur following periods of heavy rain. Local residents point out landslides on grassed slopes remote from roads, which they state occurred in the 1920's and 1930's.

Deforestation was almost certainly a dominant factor in causing these landslides which are now generally dormant and are intermediate in size between the very large fossil landslides of the Pleistocene and the recently active landslides generally associated with the more recent activities of man.

* Road and Railway Construction. Numerous landslides are attributed to road and rail cuttings in the area. This report has described many of these landslide and other are described in newspaper reports such as those includes in Appendix 2.1. The construction of roads with better grades resulted in more hillside cutting and impeded drainage, thus lowering the stability of the slopes.

* Dams. Dams are often constructed in the small basins of internal drainage created by the anticlockwise rotation of downward and outward moving landslide material. These depressions are convenient sites for dams, but the stored water often contributes to further slope failure by increasing the pore water pressure in the soil mass. For example, both Klevans and the Dingley Dell landslides have been reactivated immediately below dams constructed in the slump/earthflow transition zone of former landslides as shown in Figure 1.3 and 4.9/4.10 respectively.

Slope failure is triggered by a change in one or more of these factors, in such a way as to increase the shear stress or lower the shear strength of the slope.

6.2 Remedial Measures

6.2.1 Methods of Approach

The control and prevention of landslide hazards at all scales of activity involves procedures in one or more of the following categories:

1. Avoid or remove the landslide problem
2. Reduce the actuating forces
3. Increase the resisting forces

In all projects it is better to avoid the landslide hazard if economically, technically, socially and legally possible. Recognition of landslide susceptibility is therefore essential in the initial planning stage of all projects.

6.2.2 Landslide Susceptibility and Hazard Evaluation in Relation to Landslide Avoidance

Landslide susceptibility is determined by examining the contribution of each factor to instability under existing and proposed changes in land use. It is necessary to assign a weighting or measure of relative importance to each factor according to the proposed land use. Numerous authors (e.g. Fabos and Caswell 1977, Shirley 1975 and Stevenson 1977) have developed methods that could be used for assessing the relative susceptibility to landsliding and showing it in map form. The methods all involve a significant degree of subjective assessment and should not be used as a substitute for detailed site investigation. Realistic evaluation of landslide risk involves geotechnical and geological study of the site conditions in relation to both existing and proposed land use. Relative landslide susceptibility maps and broad scale studies as presented here, should only be used to indicate the likelihood of landslide risk in broad terms as a basis for more detailed studies.

A landslide susceptibility map has not been attempted for this study because sufficient data is not available for all the factors which contribute to landslide occurrence and risk. It is considered preferable to use the landslide distribution map (Figure 3.4) in conjunction with the terrain map (Figure 2.4) to give a general indication of landslide hazard On site geological reconnaissance should follow to check the initial assessment. Recognition of landslide-prone areas in the planning stage of a project, allows alternative sites to be considered.

6.2.3 Removal of Landslide Material

In some cases, unstable landslide material may be partially or completely removed to increase stability. This procedure could be considered as a means of controlling minor earth flows across roads. However, it would be inappropriate for the large earth-flows in the study area where major earthworks would usually need to be carried out on private property at considerable expense.

6.2.4 Reduction of the Actuating Forces

A slope is at the limit of equilibrium when the actuating forces balance the resisting forces. In this case the factor of safety of the slope is equal to unity. The actuating forces can be reduced, and hence the factor of safety increased, by improving drainage and/or by reducing the weight of the material potentially involved in landsliding. The following techniques are suggested for the study area:

Improved surface drainage at all roadside landslides. The Shire has used this technique with some success for a number of roadside landslides. Ideally, the drainage should be improved along all sections of road in landslide pone areas. It may also be possible in some cases to interrupt surface runoff before it reaches the road easement, preferably above the slide area. Ground fissures at the head of landslides should be closed by grading or ploughing to minimize the direct entry of surface water into the landslide mass. When fissures occur within the road surface, failure may be considerably delayed by sealing the fissures with a fine bituminous mix. Techniques for the control of surface water are described by many authors, e.g. Shirley and Francis (1977), Varnes (1958), Zàruba and Mencl (1969).

Improved subsurface drainage. Subsurface drainage is often the most effective means of removing excess groundwater. It is usually expensive to install, but would be worth considering for selected landslides in the study area. Various drainage systems can be used:

1. Narrow trench drains filled with gravel aligned directly downslope, thus largely avoiding the risk of reactivating the landslide. Trench drains are sometimes connected to surface drains running across the slope above the landslide area.

2. Sub-horizontal drains. When used in conjunction with effect6ive surface drainage, this technique may be an appropriate, though expensive, control measure for roadside landslides in the study area. Sub-horizontal drains are drilled into the slope on a slight upwards angle and lined with 100 mm of slotted PVC tubing or similar material. Thy act effectively only when the ground is sufficiently permeable to allow drainage. The soils in the study area are predominantly plastic clays of low permeability. But free drainage often occurs through interconnected fissures and failure surfaces within the landslide material. Clay smearing on the sides of bored drains may hinder drainage. Further research on this matter and on the permeability of the soil mass is required. Shirley and Francis (1977) give practical suggestions for installing sub-horizontal drains.

3. Galleries and vertical drains tend to be expensive, but they can be effective in controlling large and/or difficult landslides.

In all cases, care should be taken to ensure that the drains do not act as a source of water when passing from saturated into unsaturated soils. The techniques will not work effectively in soils of very low permeability.

Electro-osmosis has been used successfully for controlling landslides in low permeability soils. Water travels from the anode to the cathode where it is collected and removed by drainage or pumping. It is considered an expensive technique of uncertain effectiveness that should only attempted following detail site investigation of landslides which cannot be controlled by cheaper and more conventional means.

Tree planting. The role of trees in stabilizing landslides has been examined under the discussion on deforestation in Section 6.1. Trees aid slope stability by reducing pore water pressure through evapo-transpiration, by reducing infiltration and by binding the soil at shallow depth with its root system. The Shire usually plant willows as part of their stabilization treatment of roadside landslides. It is also common practice for landowners to plant belts of cypress or pine trees in the slump zone of landslides. This technique appears to be quite successful – at least in the immediate vicinity of the trees. A good example of landslide stabilization by trees occurs at landslide no. 7 where movement on the uphill side of the road has been successfully stopped by a dense planting of trees – unfortunately, movement still continues downslope from the trees.

6.2.5 Increase in Resisting Forces

The forces resisting slope movement can be increased by constructing restraining structures and/or increasing the internal strength of the soil.

The Shire have successfully used retaining walls to stabiliz000.e earth flows on roadsides. For example, landslides no. 12 as shown below in Figure 6.1 and landslide no. 13 as shown in Figure 4.5.

Figure 6.1 – Landslide no. 12, 1978. Stabilised by wooden retaining wall. Poplar trees have been planted to aid stabilization.

It is important that effective drainage is incorporated in the remedial work and that the pile foundations of the retaining structure are founded in sound material beneath the failure zone. Poorly designed retaining structures commonly fail and may even push the failure surface deeper. A detailed site investigation should be carried out prior to designing and constructing any large retaining wall. Hutchinson (1977) lists selected references to restraining structures consisting of retaining walls, piles and soils and rock anchors. Rock and reinforced earth buttresses are also used to prevent slope movement. Each system must be adequately designed to prevent overturning and failure through or beneath the structure. The ultimate choice of restraining structure must be based on the site conditions and available finance.

The **internal strength** of the soil can be increased in a variety of ways. Methods of grouting, chemical stabilization, freezing and heating are described by Hutchinson (1977) and numerous other authors. Of these methods, chemical stabilization is the most likely one to have application in the study area. The clay soils derived from the Lower Cretaceous rocks consist predominantly of montmorillonite, which can be changed chemically by the addition of gypsum (Ca SO4 2H2O). Cation replacement occurs in which sodium ions of montmorillonite are replaced by calcium ions of gypsum. Significant increases in shear strength and permeability can result from ion exchange, but pH is unaltered. Ideally, treatment should occur along the failure surfaces of the landslide. However, top dressing of landslide susceptible pastures with gypsum may improve stability and thus help to mitigate the landslide risk. The internal strength of the soil can also be increased by reduction in groundwater as discussed in Section 6.2.4.

6.2.6 Current Shire Practice

The Shire have used a combination of control methods, consisting mainly of improved drainage, construction of retaining walls, tree planting and on-going removal of landslide material. Virtually all work has been carried out to overcome the damage and inconvenience caused following landslide events. No preventative work has been possible due to limited finance.