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BUILDING IN AREAS OF LANDSLIP, SUBSIDENCE & ROCKFALL

[including hillside building guidelines]

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ABSTRACT

Landslips, subsidences & rockfalls pose a significant hazard and risk to development / persons in areas subject to such hazard; as such, where planning authorities have an Environmental Planning Instrument with associated “hazard map”, this map & the associated “risk assessment” is used to assist in the evaluation of a particular development. This paper describes some of the risks associated with residential and low rise building works in areas identified as having a landslip, subsidence or rockfall hazard [including cliff lines & coastal cliffs] and provides some guidelines on preferred methods of building in such areas. The paper also discusses some of the practical issues relating to the planning & approval processes.

The guidelines provided are based on over 70 years of combined experience with slope stability & subsidence issues in relation to building & engineering construction.

1 INTRODUCTION

When settlement moves from the plains into hillside areas to avoid the dangers of flood and uninteresting landscape, the development has moved into a different danger zone, that of landslip and rockfall. Also, with the advent of man's use of mineral resources and underground mining, many desirable areas are now subject to a “man induced” hazard, that of "mine subsidence" in addition to natural ground subsidence problems.

These hazards are also often intensified by the clearing of native vegetation, or by the desire to build close to steep cliffs to take advantage of the "view" [e.g. by building near the top of a coastal cliff headland]. In addition, the clearing of vegetation for pastoral, residential, or other use, can seriously disturb the natural equilibrium which has developed over time by tectonics, climate and vegetation. Consequently, human activity is now a major contributor to environmental change and increased landslip and rockfall hazard. It is therefore important that development works now be carried out in such a way that the risks are both recognised and reduced [or even eliminated] by appropriate control / planning measures.

Whilst many professional societies have encouraged the development of prudent building practice in areas of landslip, subsidence and rockfall, the diversity of technical opinion has so far precluded [in Australia] the development of specific guidelines for implementation by the practising engineer. As such, it is the intent of this paper to contribute some guidelines that have been found successful within the eastern seaboard of Australia. The guidelines are however not pre-emptive rules as it is envisaged that in the longer term the professional bodies will develop more comprehensive guidelines with a broad technical consensus.

The need for such guidelines is also apparent as in some countries up to 20,000 deaths have been recorded from a single landslip event; even in Australia where the landform has generally low relief, there have been fatalities (viz: 19 at Thredbo (George, 1997). Further, as the financial losses from landslip / rockfall damage are frequently in excess of $100,000 per single event, this financial cost and the related extensive personal trauma can be minimised by the implementation of suitable building & development practices.

2 HAZARD RECOGNITION, HAZARD MAPS & RISK ASSESSMENTS

Land is a valuable resource that normally increases in value during its transition from a rural to the urban environment; as such, it is important that Planning and Consent Authorities have access to suitable maps which identify the hazards associated with particular parcels of land.

In this regard, in the Australian state of NSW, Section 79(c) of the Environmental & Planning Assessment Act (NSW Government, 1979) requires a Consent Authority to consider a list of relevant matters when dealing with a development application; this normally includes whether a site is exposed to a hazard such as flood or landslip. To this end, most local councils [or Consent Authorities] in NSW now have an Environmental Planning Instrument which incorporates 'hazard maps' for bushfire, flood and landslip and these form the basis for a Council to request an appropriate report from qualified professional persons. These hazard maps however usually only identify the various hazards of an area so as to establish the criteria for the additional studies needed before approving the development, and / or establishing the "risk" of a particular development.

The use of these maps and the associated risk assessments / professional reports are commented on below.

2.1. HAZARD MAPS & RISK ASSESSMENTS

In March 2000, The Australian Geomechanics Society published their latest "Landslide Risk Management Concepts & Guidelines" (Walker, 2000) and distributed the same to local government authorities in Australia. Whilst these guidelines have since been the subject of debate and need revision in some areas, the philosophy contained in the guidelines is now currently accepted as the correct approach to the landslide risk assessment and evaluation process. Within the guidelines, there is provision for the "Hazard Zoning" of land areas; it is this part of the guidelines that is appropriate to the planning / approval process because:

- the risk assessment process requires a notional development;
- funds are not normally available in the overall planning processes of a Consent / Planning Authority for the detailed investigations required for the relevant risk assessment.

It is also to be noted that whilst the risk assessment process is currently widely used for the assessment of specific developments, the process cannot be applied to large areas where:

- the probability of particular events [e.g. a rockfall] is extremely difficult to define, and
- the extent and type of future development is unknown, or uncertain,

because "risk" is a product of **both** probability and consequence. As such, hazard maps (Shirley, 1975 & 1983) are preferable for a Consent / Planning Authority, with the maps normally relying on the usual geological, geomorphological & topographic maps; these maps then form the basis for the Consent / Planning Authority to request appropriately detailed investigations in areas of identified "hazard".

2.2. RISK ASSESSMENT REPORTS

As a prerequisite to a satisfactory risk assessment is:

- the identification of the hazard;
- the definition of the scope and extent of investigations required to properly evaluate the relevant risks and hazards;

it is very important for a Consent / Planning Authority to define the minimum level of work [including an assessment of the impact of the development on the surrounding area] required by a professional before acceptance of the associated risk assessment because:

a) Difficult and sensitive areas require more detailed assessment than those areas which are relatively simple and straightforward.
b) Development works on one site can trigger instability or rockfalls on adjoining / nearby sites.

It is also fundamental to the effective use of hazard maps that specific criteria are provided as to the minimum level of reporting in each zone with the ability for independent checking. This is because some investigators could decide that it would not be in their best commercial interests to highlight a site's difficulties and so choose to write their reports in an ambiguous way to avoid addressing the serious geotechnical issues at the planning stage.

It is thus important for Consent / Planning Authorities to develop objective guidelines for risk assessment reports relating to areas of defined hazard to ensure that only appropriate reports are accepted.

3 BUILDING RISKS

Building in areas of geological hazard nearly always exposes the builder / developer / owner to risks. As such, it is important that the risks of building in such areas are recognised by intending building owners, as a failure to recognise the risks / responsibilities can result in damage to building and / or site structures. The risks of instability, subsidence or rockfall can also impact on a development from outside the site boundaries, or below the site itself.

In the light of the above, some of the risks associated with hillside sites, landslip, subsidence and rockfall are briefly described in the following paragraphs.

3.1. LANDSLIP AREAS

Landslips have a variety of forms and "speed of travel", with landslip speeds ranging from very slow downhill "soil creep" type movements [viz: 0.1 to 3 mm per year] to very rapid forms of landslide that can engulf a structure in a few minutes [e.g. the Thredbo landslip – (George, 1997)]. Also, because the vast majority of movements on hillside sites are slow movements of the surficial soil, land clearing, roadworks, poorly designed drainage systems and a lack of maintenance can greatly aggravate the movements.

Also, whilst it is usually feasible to design for a “slow” soil movement, [creep rates of about 0.1 to 3 mm per year] it is very difficult to design a structure to resist the impact of faster landslip movements and / or sudden slope failures from roadworks.

The risks associated with building in landslip areas therefore chiefly relate to the steepness of the land and rapidity of the actual earth movement itself.

3.2. SUBSIDENCE AREAS

The building risks associated with “subsidence” arise from the construction over land areas subject to "collapse"; these areas can include:

- areas of landfill;
- subterranean tunnelled areas;
- regions where ‘soil pipes’ and / or loessal soils occur;
- areas underlain by limestone cavities;
- soils subject to seismic liquefaction;
- areas undermined by mining.

These are discussed in generic terms as follows.

3.2.1. Internal Soil / Rock Collapse

The chief risks associated with internal soil / rock collapse relate to the lack of identification of the potential for such collapse in advance. In this regard, particular attention is drawn to limestone and other karst areas where naturally formed voids in the ground beneath a particular site can suddenly collapse and result in the destruction of the foundation strata for the particular building structure. Further, as ‘soil pipes’ are often associated with landsliding, any building works in areas where soil pipes occur should also consider landslip.

Care must also be taken when building on some duplex soils which have been affected by subsurface tunnel erosion, and / or areas where soil pipes are known to occur [e.g. granitic soils and pleistocene age sediments near beaches].

Also, whilst landfill areas can be considered inappropriate for building works, urban pressures are increasingly requiring building works over / upon landfill sites. The risks associated with landfill sites are thus not only knowing the nature and type of the fill materials used in the landfill, but also their long-term settlement properties and the inevitable possibility of a localised settlement due to the collapse of a particular material within the landfill.

3.2.2. Collapsible Sands and Loesses

Fine sedimentary sands and loesses are liable to collapse when strongly irrigated [e.g. by greater than normal rainfall], or when subjected to strong seismic vibrations, or even a vibrating roller. Thus, as such materials are common in Australia and overseas, it is important to check the density and grain size distribution of the soil, particularly where layers or pockets of fine sand and / or silt occur.

3.2.3. Mine Subsidence

Whilst most areas of underground mining are controlled by relevant public authorities, the way in which the mining is undertaken can have a profound effect on the building works undertaken at the surface. Further, despite careful planning by mining authorities, significant damage can occur to buildings as a result of the ground behaving in a way not foreseen by the mine operators. As such, this risk needs to be realised by those planning building works in such areas.

It is also noted that as damage to buildings from mine subsidence usually arises from lateral straining of the ground under the building [as well as the associated tilting and settlement], buildings in mine subsidence areas nearly always need to be capable of accommodating "lateral strain".

3.3. ROCKFALL AREAS

The risks posed to building works by rockfall has to date not been commonly recognised; however, the recently increased tendency to plan / construct building works close to cliff lines and within disused quarry areas has now made it necessary to seriously consider the risk of rockfall.

The risks arise from the possibility of a rock falling from above the site onto the proposed building structure, or from a rockfall beneath the site removing some of the support to the building footing system.

Further, as rocks can ‘bounce’ down a slope, the impact trajectory of a particular rock can result in damage to a building structure at a considerable distance away from the rock face or cliff itself. Thus, it is usually necessary to consider the likely trajectory of rocks falling from a slope onto a particular structure **prior to** the location of building works near cliffs.

3.4. FIRE & BUSHFIRE RISK

Whilst a detailed discussion of bushfire risk is beyond the scope of this paper, the clearing of hillside sites in the interests of fire safety may cause instability on marginally stable slopes. As such, a better practice would be to encourage the planting of wet season, deeply rooted shrubs before the existing vegetation is removed.

Also, as the practice of constructing wide timber decks has been found (Woolnough, 2002) to be a major cause of building destruction during a bushfire event, non-combustible decks are preferable in bushfire prone areas.

4 GENERAL GUIDELINES FOR BUILDING ON HILLSIDES

Whilst some initial guidelines were developed in 1976 (Burgess & Shirley, 1976) and more extensive guidelines prepared by Walker (Walker, 1985 & 2000), the current publications only provide limited information on hillside building methods and slope stability / rockfall issues. Thus, the guidelines in this paper have been assembled to provide more specific guidance to planners, owners & builders. It is however to be noted that as the guidelines are ‘generic’, the fundamental pre-requisite to the adoption of any of the guidelines is a rational assessment of a site's stability, rockfall and subsidence issues.

4.1. EFFECTS ON ADJOINING LAND

A pre-requisite to building on a hillside is the recognition that landslips, their causes and their consequences do not respect arbitrary property boundaries. Thus, alterations to landform, loading conditions or subsurface drainage patterns on one block may result in movement or instability on another.

Examples of potentially unsafe interactions between adjoining sites include:

- Excavations close to the site boundaries destabilising a neighbouring building.
- Placement of fill at the top of a slope resulting in slope failure on an adjacent / close by site.

- Boulders rolling downhill from cliffs above a site, or rock blocks becoming detached from a cliff face and falling onto a site.
- The location of buildings close to cliff lines, or former quarry faces on an adjacent site.

Consequently, any works proposed on a given block of land should be viewed not only in respect of their possible effects on that block, but also in relation to the possible effects on the surrounding blocks.

4.2. SITING & PLANNING ISSUES

Houses should not be sited on, or in the path of, obviously unstable land. In addition, as road and embankment fills are commonly subject to "creep" and may have only marginal stability, it is very important to ensure that any fill placed above a building site is stable before commencing construction. If there is instability above, or below the building site, then stabilisation works should be undertaken before commencement of building operations; such works may also require ongoing maintenance.

Also, as the creation of a cut / fill "building platform" on which to construct a house is often a significant cause of instability, building platforms involving fill should be avoided; it is however very important that any building platform should be properly drained and not pond water on the slope. Therefore, the types of building normally constructed on flat land [e.g. those using concrete raft slab construction] should not be used on hillside slopes, unless an especially designed "very stiff" raft is used with minimal excavation. Experience has also indicated that houses with minimal cut / fill and designed to blend in with the natural landscape perform the best.

Where 'soil creep', or other slow moving instability is expected behind and above the proposed building, the provision of a clear space (at least 1.2 m wide) can be an effective way of avoiding large lateral loads on the building. However, as soil creep is an indication of long term movement of a slope, the building and its footing system should be designed to accommodate / deflect the potential lateral loads resulting from the hillslope movement.

Careful consideration must also be given to:

- The design of vehicular driveways to ensure that the associated excavations and fills do not create a stability problem.
- Site & roofwater drainage; in particular, the design of the drainage system so that the pipework is to the side of the house, rather than behind or above the house.
- Methods of ensuring that the necessary maintenance of the installed drainage systems is carried out [e.g. by the imposition of "positive" land title covenants].
- Emergency access & egress from the building.

4.3. EARTHWORKS & EROSION CONTROL

The stability of a block of land can be drastically altered by the undertaking of inappropriate earthworks, such as:

- Deep excavations and fills.
- Loose placement of fill on a slope.
- Placement of filling in creek beds, watercourses, etc..

Care must therefore be taken to minimise the ground disturbance and the extent of cuts / fills.

Retaining walls should always be provided to excavations in materials other than established bedrock, unless it can be shown that the excavations will not initiate land instability. Alternatively, excavations should be 'battered-back' at a stable slope; such slopes are usually not steeper than about 2H:1V [horizontal to vertical ratio].

Where cuts greater 600 mm are contemplated, or seepage is noted from the ground, geotechnical advice should be sought prior to carrying out the excavation. There may however be some situations (e.g. a slope with a wet toe) where even 600 mm is excessive.

Where possible, site filling should be avoided and surplus spoil removed from the site. However, if filling is unavoidable, the fill should be properly 'keyed' into the slope and compacted in layers in accordance with good engineering practice (Standards, 1996). Care should also be taken to ensure that natural watercourses and underground water efflux points are not blocked by fill.

Fills greater than 600 mm thick should be avoided unless the stability of the slope under the additional weight of filling has been well established; there may however be some situations where even 600 mm is excessive.

Any filling within close proximity [generally about 3 to 4 metres] of the toe of a cliff line, or steep slope should comprise free draining material.

4.4. EFFLUENT DISPOSAL ISSUES

For preference all household effluents should be removed from the site by a suitable sewer system. Where this is not feasible, effluent disposal systems of the "spray irrigation" type are usually preferable to absorption trenches.

Absorption trenches are usually not suited for effluent disposal on hillside sites unless the allotments are relatively large [viz: larger than 0.5 Ha for a conventional house]. This is because lots smaller than 0.5 Ha usually do not have sufficient area for the absorption of effluent without the site stability being affected.

4.5. STORMWATER DRAINAGE

Stormwater drainage normally consists of two types: open drains and pipes, or closed conduits. It is preferable that all roof and concentrated surface runoff (e.g. from driveways, paths, etc.) be led direct to a public [e.g. Council] system, or natural watercourse. Suitable sediment traps and detention [or retarding] tanks may also be required to control the rate of discharge.

Where the landform is altered (e.g. by excavation for a house site or driveway), suitable surface gradients should be provided, as well as appropriate drainage systems, to prevent the ponding of water on the hillslope and / or concentrated water flows over the hillslope.

Experience has indicated that drains need to be laid at a gradient of at least 1% to ensure continued operation and drain gradients steeper than 2½% [i.e. 1V:40H] need to be 'lined' and bedded in a 'non-erodible' material [e.g. cement stabilised soil] if erosion and scour is to be avoided.

Where there is potential for seepage from drains into the subsoil, the drains should be lined. This is particularly important in steeper hillslopes and near sensitive, or potentially unstable land because the absorption of water from unlined hillslope drainage has been the cause of a number of serious slides and slumps.

Stormwater pipework should be laid in a stable stratum [i.e. below the level of soil moisture variation and potential soil creep] and provided with inspection pits at regular intervals. The design of inspection pits does however need special care; for preference, pits should only be located in stable ground and flexible joints provided between pits and pipelines. Where it is not possible to lay the pipe within a stable foundation, then the pipework should have a capacity to accept movements without leakage or damage [e.g. rubber ring jointed PVC pipes with extended spigot joints].

Plastic [viz: PVC or polypropylene] pipes are also generally preferable in landslip / hillside areas as their inherent flexibility and relatively large individual pipe length considerably reduces their risk of leakage.

At the junction of an open / piped drain, a sump and grating should be provided to catch sand, silt, etc., to reduce the frequency of the necessary "flushing" maintenance. Further, effective grass planting near drains can minimise siltation of drainage systems.

Where shrink / swell soils are encountered, plastic / steel pipes should be used to avoid tree & shrub roots entering the pipes because the roots can cause pipe blockages and / or damage.

4.6. SUBSURFACE [SUBSOIL] DRAINAGE

Where it is necessary to construct subsoil drainage, it is important that such drainage operates for a very long period of time with minimal maintenance. Also, as the basic purpose of the drain is to intercept and drain seepage, the invert of the drain must be carefully located, and adjusted to suit the "as encountered" site strata. It is also important that the invert of the subsoil trench is evenly graded to the outlet, with the subsoil pipe being laid at the base of the trench.

As subsurface drains normally only pick up small quantities of water, they should be kept separate from the stormwater system; the drains can however be laid in the same trench as a stormwater pipe.

To ensure the effectiveness of a subsoil drain, it has been found that the subsoil pipe [usually a corrugated or rigid slotted PVC pipe] must be surrounded with a gravel large enough not to be washed into the holes of the pipe. As such, the smallest particle size of the material surrounding a subsoil pipe should be about the width of the slot in the pipe. However, as this material typically ranges from 5 to 14 mm, it is usually too coarse to prevent the migration of 'fines' from the soil into the gravel. Therefore, it is usually necessary to provide a geotextile, or a specially designed "soil filter" between the gravel and the soil being drained.

Experience has also shown that:

a) The selection of the correct geotextile is critical to the long term performance of a subsoil drain, with the geotextile being of sufficient strength to prevent puncturing by the gravel or coarse sand; as such, a rounded, or non-angular gravel is to be preferred.
b) Provided that the subsoil drain gravel filter is protected against siltation & clogging by a suitable soil filter or geotextile, the use of a "geotextile sock" around the subsoil pipe is incorrect and should not be used. Such a sock can also lead to a failure [i.e. "clogging"] of the subsoil drain.
c) As subsoil drains can become clogged from silt and / or bacterial growth with time, it is essential that flushing points and clean-out pits / sumps be provided.
d) Subsoil pipes should be cleaned / flushed on a regular basis. In this regard, it is noted that corrugated subsoil pipes cannot be effectively flushed by inserting a hose from the downstream end; as such, flushing points for this type of pipe should be provided at the upstream end of the pipeline.

5 PREFERRED CONSTRUCTION METHODS

To assist in planning of the typical hillside building structure, some suggestions on preferred construction methods are outlined in the following paragraphs:

5.1. LANDSLIP / SOIL CREEP AREAS

As building works are commonly undertaken in areas which are subject to slope instability, including soil creep, with these areas typically being "hillside sites", the following "preferred methods" have met with some success:

5.1.1. Building Types & Structure

Split-level houses are generally more suited to hillside construction than single level buildings. Further, timber "pole type" houses have been found to be a cost effective solution to hillside building. Also, to make a sound decision regarding house type, the site contours should be accurately established before the architectural and engineering plans are prepared.

Site contour levels should also extend onto the nearby / adjoining land so that the effects on the adjoining land of the proposed building works can be established.

Where the house structure is founded on footing piers that have to pass through a soil layer that is [or may possibly be] subject to 'soil creep', it is important that:

a) The house footing system is designed to accommodate the likely lateral loads resulting from the creeping soil.
b) A 'flexible house structure' is adopted to ensure that any small footing movements do not result in significant structural problems or building damage.

5.1.2. Flexible House Structures

In many hillside situations, an economic solution is to provide a building which can tolerate some movement of the soil materials within / upon which the building is founded. The essential theses of design for such structures are flexibility and ductility. The flexibility allows the building to deform a small amount without visible structural damage, and the ductility is to enable the building to "structurally hold together" should an extreme event [e.g. the impact of a debris landslide] occur.

'Flexible house structures' should thus have the ability to maintain their structural integrity during flexure and be securely "tied together" at all connections. Common types of flexible house structures include timber or metal framed buildings, clad with timber, metal walling or FRC sheeting.

By contrast, brick and concrete structures are usually rigid and inflexible and will crack after only small movements. Further, should large deformations occur, such buildings can become a hazard to building occupants as the various connections in the structure are seldom able to resist significant [i.e. >60 mm] movements.

5.1.3. House Footings

Generally, footings should be taken into bedrock, with the depth of embedment being determined by the quality of the bedrock and lateral load to be resisted. Provision should also be made for differential movements of the footings unless all the footings are located on the same quality of founding strata.

Footings taken through creeping, or potentially moving, soil and into bedrock should be designed to resist the lateral loads that may be imposed by such soil movement / creep. In addition, suitable provisions should be made for movements in the building architectural finishes as a result of the theoretical soil loadings.

Note: Experience has shown that an effective way of providing the required lateral footing strength is to interconnect the footings down the slope with a narrow strong concrete "shear beam" which is cast at / below the sloping ground level.

Excavations for footings should normally be inspected by an experienced Geotechnical Engineer, or Engineering Geologist prior to placement of concrete to confirm that the footing is founded upon / within the required 'bedrock' [i.e. rather than on floaters or detached blocks of rock], or other specified stable stratum. This inspection is particularly important in talus materials, close to cliff lines [see Figure 1] and in 'slabby' bedrock areas.

To avoid surficial soil instability on steeply sloping sites, it is preferable to minimise the extent of footing trenches open at any one time and align footing beams perpendicular to the land contour.

Where it is necessary to align footing beams parallel to the land contour, the footing beam should be located above the ground and the beam supported by piers. Where this is not feasible, the excavations for the footings should only remain open for a short time [to minimise the risk of water ponding in the excavations] and the footing beams designed to resist possible lateral soil loads.

5.1.4. Retaining Walls

Retaining walls always need to be built with care and embrace sound engineering practice [e.g. comply with the Australian Standard on Retaining Walls (Standards, 2002)]. In hillside areas, retaining walls should also be designed by an engineer well experienced in soil stability problems, drainage and civil engineering.

In hillside situations the magnitude and distribution of earth pressures on a retaining structure can be very different to the pressures computed by conventional analyses. Where soil creep or pre-existing slip planes are present, very considerable earth pressures [possibly approaching "passive soil pressures"] can be induced on walls.

It is also preferable for retaining walls to be isolated by a gap [to enable access for cleaning, etc.] between 'habitable', or 'dry' areas of houses / buildings. Where soil creep is expected, this gap should be created outside the main building structure and at least 1.2 m wide; whilst the gap may be reduced in areas where soil creep is not expected, it should generally not be less than 500 mm.

Retaining walls are usually considered to fall into two groups, viz: inflexible and flexible walls.

a) **Inflexible walls** are those which do not move under load and are usually constructed of reinforced concrete, reinforced concrete blocks, etc.. In hillside situations, these walls are also often provided with anchors into the slope / bedrock behind the wall. As the walls need to be designed to resist very large earth pressures [usually passive earth pressures] inflexible walls are usually only used where small wall movements cannot be tolerated.

   Inflexible walls should generally be founded upon / within a completely 'stable' stratum [e.g. bedrock].

b) **Flexible walls** are those walls which can move a small amount under load [i.e. with observable but not structurally damaging deformations] and are thus able accept to overload should downslope soil movements [e.g. soil creep] occur. Flexible walls are thus normally more appropriate to hillside situations where soil slope movements may occur as they can usually be designed for "at rest" earth pressures, rather than "passive" earth pressures. Flexible walls are often constructed of concrete / timber crib units, timber sleepers, gabions [rock filled wire baskets], precast concrete segmental walls, rock boulders, etc..

   Flexible walls must however be located sufficiently clear of the building so that the walls can move independently of the building structure and without loading the structure.

Whilst on a hillside site a simple & efficient flexible wall is of the 'post and waler' type, such walls need a careful design which takes into account the relatively small passive resistance available from the downhill slope.

5.1.5. Retaining Wall Drainage

The provision of effective drainage behind a wall is most important because a lack of proper drainage increases the load on the wall by about 1½ to 2 times; also, the build up of seepage water behind a retaining wall can cause softening of the wall foundation and / or the ponding of water on the slope which can of itself initiate soil instability.

Experience has also shown that the most common cause of failure of walls in hillside situations is a lack of suitable drainage behind the wall. In this regard, the following are considered relevant to a wall's drainage:

a) The surface drainage / run-off should be isolated from the subsurface drainage system; for preference, the upper 200 to 300 mm of wall backfill should be impervious so that a seal is formed over the granular material forming the subsoil drain.
b) Weepholes are generally more effective in the long term.
c) Where it is not practical to provide weepholes, a suitable subsoil drain should be provided at the base of drainage system behind the wall and the subsoil pipe provided with 'flushing points' and suitable inspection pits to enable regular maintenance.
d) Whilst the subsoil drainage system behind a wall is usually provided by a free draining gravel [e.g. washed 10 mm gravel] and a subsoil pipe, there are many geocomposites which can prove to be an economic substitute.

5.2. SUBSIDENCE AREAS

As noted earlier, the design of buildings in areas subject to 'subsidence' depends upon the type and nature of subsidence that is likely to occur; as such, it is important to distinguish between construction over a landfill area and an area of 'natural subsidence'. However in both cases, a fundamental pre-requisite to the design of buildings in a subsidence area is the ability to tolerate movement.

5.2.1. Landfill areas

The amount of subsidence should first be predicted together with the likely amount of differential movement based upon the depth of the landfill present and time since the landfill had been emplaced. Also, prior to designing any structure on a landfill, the health risks should be properly assessed.

All heavily loaded and 'settlement sensitive' structures should be founded on piles / piers taken to bedrock, or other stable strata beneath the landfill.

Where it is necessary to found a structure on top of the fill [e.g. a road or drainage structure], it is preferable that a "reinforced soil" foundation system be created on top of landfill to minimise the "differential" component; this "reinforced soil" foundation system can also provide a measure of protection against a localised subsidence created by a void forming in the fill underneath the structure.

Provision should also be made in the structure footing design for:

- Removal of gas and waste products from the landfill.
- The sealing off, or treatment of, the possible toxic / putrescible wastes in the landfill.

5.2.2. Natural subsidence areas

Fine sandy soils [especially including silts] which have been deposited either by wind or water action, or sometimes as pyroclastic ejecta [viz: fine material blown from a volcano] are especially liable to both slip and collapse. As such, in areas where these materials are found it is essential to check both the grain size distribution & in situ density of the material so that the potential for settlement and / or liquefaction can be ascertained.

If liquefaction is suspected, then it will be necessary to undertake appropriate densification of the suspect materials [e.g. compaction by vibroflotation, use of stone columns, etc.] as a part of the site work.

In areas affected by subterranean tunnel erosion and / or soil pipes, or areas underlain by karst [viz: limestone & dolomite] deposits, the extent of voids under the land will determine the permissible loads on the surface, with larger structures being either avoided, or piles taken through the suspected voids.

5.2.3. Mine Subsidence Areas

Structures in areas subject to mine subsidence need to take into account the lateral strains induced by the subsidence, as well as the tilts and settlements normally associated with the subsidence. It also needs to be recognised that in some areas, the subsidence induced by mining activities can continue at a slow rate for many years, or even decades, after the mining has been completed.

For preference, building structures should be articulated, and in the absence of other specific requirements by the relevant public authority, a concrete raft footing system used.

In long buildings, structural separations should be provided between the various sections of the buildings to enable the building to ‘articulate’ through a predicted subsidence event.

5.3. ROCKFALL AREAS

In rockfall areas the usual problem is one of the impact of a boulder, or large rock from above the site on the proposed structure. Thus, it is essential to have a careful geological survey of the area above / below the site **prior to** the design of any buildings within the zone of influence of the cliff area from which the rockfall is likely.

Figure 1 shows the usual "zone of influence" of a cliff.

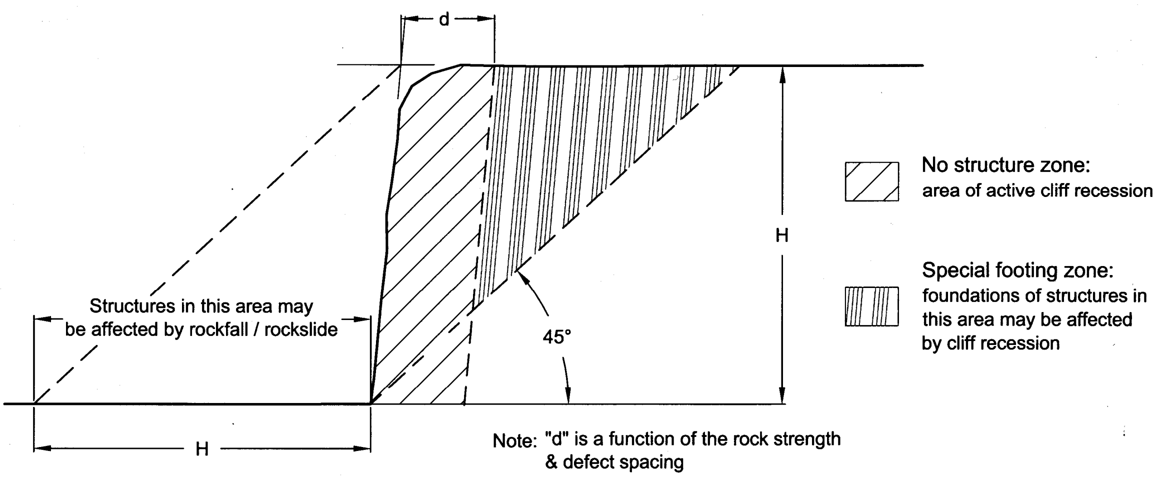

FIGURE 1: INFLUENCE OF CLIFFS ON STRUCTURES

It is also usually regarded as unacceptable to locate a building within an area where a rock might impact on the building from above. As such, where building works are contemplated near a cliff, it is necessary to provide rockfall protection systems [e.g. rockfall netting, rock anchoring, rockfall catch fences, etc.] as a part of the design of the building. Rockfall protection systems must also incorporate an "energy absorption" system if the design loads are to be kept within reasonable limits. Such systems can include springs, draped cables, gravel pits, old tyres, etc..

Also, because of the relatively short life of most rockfall protection systems [viz: 20 – 30 years] provision for replacement, as well as repair / maintenance, should be incorporated into the system.

5.4. COASTAL CLIFF AREAS

In the vicinity of coastal cliff lines, any building works should normally be limited to exclude the area / distance equal to the height of the cliff [see Figure 1] without a detailed geotechnical survey of the cliff area itself. Such a survey should also at least determine the possible mode & rate of recession of the cliff.

Also, as cliff recession processes are a continuing long-term process with joints within the area behind cliff face opening with time, it is also usually necessary to design the building to accommodate lateral strain and joint opening [possibly in a manner analogous to the lateral strains induced by mine subsidence].

6 CONCLUSIONS

The guidelines presented in this paper should be seen as a 'progressive step' in the development of appropriate guidelines for safer building in areas of landslip, subsidence & rockfall. It is however considered that the further development of the guidelines should recognise:

a) Whilst landslip, subsidence & rockfall risks are controlled by rainfall, drainage, rock types and their associated dynamics (viz: geomorphology & seismicity), these risks can be vastly increased / changed by human intervention.
b) Unduly conservative development limits [e.g. only allowing buildings / structures in areas of Low Risk] removes potentially valuable land from development and would severely restrict man's use of much interesting and inspiring landscape.
c) Hazard mapping [zoning] and risk assessment procedures should be seen as a "process by which a site's problems are identified and managed", rather than a prescriptive process of negating development.
d) Whilst building works in areas of landslip, subsidence & rockfall are always associated with increased risk [viz: Low to Moderate Risk, and sometimes even a High Risk], the simple existence of the risk should not become a barrier to properly planned development.
e) The adoption of rational geotechnical & engineering investigations in areas of "identified hazard" can result in the formulation of procedures to safely construct buildings / structures in areas of Moderate and even High Risk; as such, the banning of certain forms of development on the grounds of a perceived "risk" does not appear justified and could greatly inhibit engineering innovation.

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