Introducing Bio-engineering to the Road Network of Himachal Pradesh

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Abstract

Bio-engineering is the use of vegetation, either alone or in conjunction with civil engineering structures, to reduce instability and erosion on slopes. It should be a fundamental part of the design and construction of all roads in rural (and urban) hill areas, mainly because it provides one of the best ways to armour slopes against erosion. Because of the steep and dynamic slopes found in the Himalayas, most hill roads are engineered near to the margin of safety. Bio-engineering is an effective way of enhancing civil engineering structures to increase stability as far as possible. It is relatively low in cost uses local materials and skill, and provides livelihoods benefits through. economically useful products..

A study has shown that many roadside slopes in Himachal Pradesh (HP) suffer from a range of instability and erosion problems, many of which are conducive to the use of low cost remedies such as bio-engineering. The Public Works Department (PWD) is examining alternatives to standardise civil engineering approaches and in particular is looking at the possibilities offered by bio-engineering, through the experience gathered in other parts of the Himalayas over the last few decades Between 1987 and 1990, the PWD's Horticulture Wing was involved in soil conservation work to resolve shallow failures on road cut slopes. Though this programme has diminished with time, it still demonstrates the inherent capabilities that can be harnessed to good effect.

This paper describes the main types of slope instability found in Himachal Pradesh, their causes (natural and man made), treatment options to safeguard the road network and reduce long term maintenance costs; approaches to bio-engineering that are appropriate to the bio-physical and socio-economic conditions found in the state; institutional mechanisms for these to be successful; capacity enhancement means and tools; and examples of success and failures from other parts of the world. It also documents early experience in the introduction of this type of approach through specific pilots of critical road sections that have been considered under the World Bank funded Himachal State Roads Project.

1. Bio-engineering: Introduction as a Science

1.1 Definitions

Bio-engineering is the use of vegetation, either alone or in conjunction with civil engineering structures, to reduce instability and erosion on slopes. It should be a fundamental part of the design and construction of all roads in hill areas. This is mainly because it provides the best way to armour slopes against erosion, and can also provide a significant contribution to soil reinforcement and other anti-failure measures (Transport Research Laboratory, 1997). It is relatively low in cost, uses local materials and skills, and provides livelihoods benefits through economically useful products. It is often called "soil bio-engineering" to distinguish it from the bio-medical science that uses the same term.

1.2 Engineering effects of vegetation

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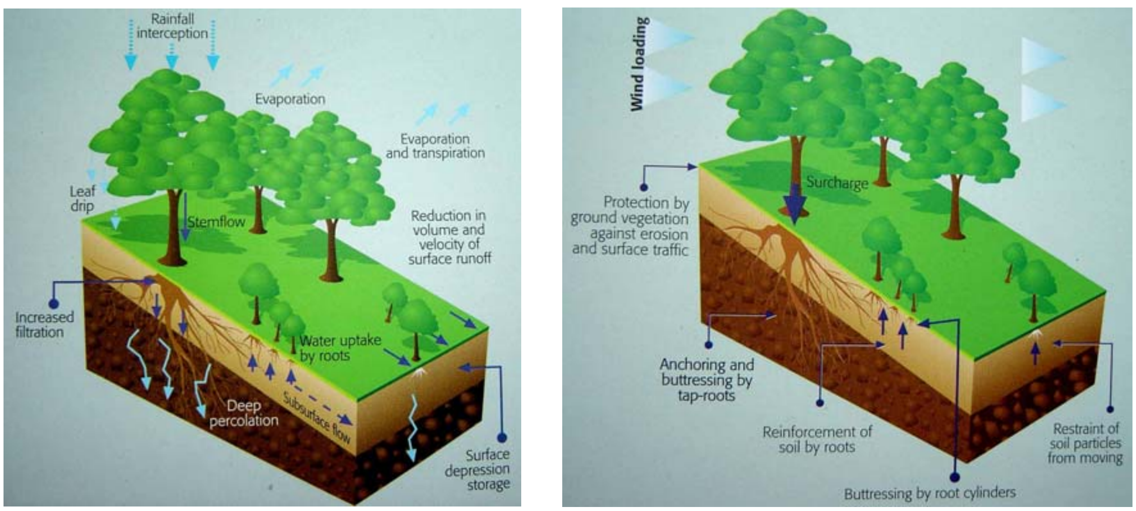
Plants have a number of effects on soils and slopes, which can be categorised as hydrological and mechanical and these are shown schematically in Figure 1. They might be beneficial or detrimental, depending on the local environment and engineering needs of a particular slope. While the contribution made by individual plants to a slope is complex, plants used in combination can provide much greater effects than single plants, but with a similar increase in complexity. For example, a single grass plant can catch a small amount of debris and reinforce a small volume of soil with its roots. But if a line of grasses is planted across a slope, together they form a continuous chain to catch debris, and can provided a linear rather than a point of reinforcement. In the process of serving these functions, however, the contour line of grass will also increase the infiltration capacity of the soil. If the material characteristics are such that this may lead to a critical condition of saturation, then another function, that of drainage, will be required. This can be achieved using grass lines by planting the lines down at an angle rather than across the slope, and the more the line is angled, the less it will catch debris and the more it will help to drain the slope.

Figure 1. Effects of vegetation on Soils and Slopes: (a) Hydrological and (b) Mechanical. From Howell (1999).



Both bio-engineering and civil engineering systems perform *engineering functions*. Table 1 shows the main functions of common structures of each category. Obviously plants cannot emulate all of the functions of civil engineering systems, particularly those having effects deeper than about 0.5 metre, nor can they provide comparable physical strengths except in special circumstances. Also, plant types vary in their ability to serve the various engineering functions. For example, grasses are more suited to armouring the surface, while shrubs and trees fulfil functions such as reinforcing and supporting.

Table 1. Comparison of the main engineering functions performed by civil and bio-engineering structures.

Civil Engineering Techniques		Bio-engineering Techniques	
Technique	**Function**	**Technique**	**Function**
Stone Pitching	Armour	Horizontal Grass	Armour, Catch, Reinforce
Revetment	Armour	Diagonal Grass	Armour, Drain, Reinforce
Dentition Work	Armour	Palisades	Catch, Reinforce, (Support)
Check Dam	Catch, Support	Brush Layering	Catch, Reinforce, (Support)
Retaining Wall	Support, Catch	Shrub Planting	Catch, Reinforce, Anchor, Support
Drainage Systems	Drain; Some Support	Tree Planting	Reinforce, Anchor, Support
Bolster	Support, Armour, Catch	Bamboo Planting	Catch, Armour, Reinforce, Support

Under most circumstances, bio-engineering can be effectively combined with appropriate and low cost geotechnical applications to provide the most cost-effective, integrated solution to slope stability problems. This is important for places like Himachal Pradesh because, with the steep and dynamic slopes found in the Himalayas, most hill roads are engineered near to the margin of safety. Bio-engineering is the most affordable and effective way of enhancing civil engineering structures to increase stability as far as possible. The vegetative structures are also flexible, being capable of absorbing movement and recovering from damage. In this respect, bio-engineering is simply part of wise and sustainable asset management since it helps to ensure the life of physical structures, and reduces overall maintenance costs. On roadsides, plants reduce the supply of debris from degrading slopes, which is one of the greatest contributors to road maintenance costs through blocked drains and damaged pavements.

In this context, vegetation is very important in the control of erosion and shallow forms of instability (1 to 3 metres in depth at most). Some typical applications of bio-engineering are described in Table 2. However, it must also be appreciated that the beneficial effects may be insignificant under extreme conditions, particularly in tropical and monsoonal climates, and that it plays no significant role in the stabilisation of deeper failures of soils or rock.

Table 2. Description of the Main Systems of Bio-engineering.[2]

System Type	Design And Function
Grass Planting	Grass seed is spread on to the slope, armouring the surface. Alternatively, grass is hand-planted in lines across the slope. The lines armour the slope and catch debris. Angled lines planted by hand may also help to drain the surface, but catch little debris.
Shrub and Tree Planting	Shrubs or trees are planted at regular intervals on the slope. As they grow, they create a dense network of roots in the soil. The main engineering functions are to reinforce and, later, to anchor. In the long term, large trees can also be used for slope support.
Brush Layering, Palisades and Fascines, *etc*	Woody cuttings are laid in lines across the slope, usually following the contour, in particular configurations. These form a strong barrier, preventing the development of rill, and trap material moving down the slope. In the long term, a small terrace will develop. The main engineering functions are to catch debris, and to armour and reinforce the slope. If they are angled, these structures can provide a drainage function.
Composite Systems	A range of composite systems are commonly used. Examples are: Live check dams, which armour and reinforce gully beds and catch debris; vegetated stone pitching, which provides strong armouring for ephemeral water courses; planted geotextiles, where the geotextile provides armouring, later supplemented by the vegetation, which also reinforces the soil.

Vegetation as a key component in off-road engineering is also environmentally sound and effectively forms a practical application of several environmental mitigation measures. In the hills, roads are an inseparable part of the slopes that they cross and they must be fully integrated into this landscape if they are to be sustainable. Bio-engineering techniques offer the best way of blending roads into the landscape and limiting damage to surrounding agricultural, horticultural and forest land. They allow the restoration of something of the original vegetation and ecosystems, and particularly of tipping sites and spoil disposal areas. Through both implementation and later productivity, they offer social and economic benefits for poor rural farmers. These benefits assume even greater significance due to the very small land holding size in the hills.

1.3 Use of Bio-engineering in Slope Stabilisation and Protection

Slope stabilisation is a special branch of engineering in its own right. In India, it is given considerable treatment in standard texts such as Khanna (1999) and the IRC's Guidelines for Hill Roads (Indian Roads Congress, 1998). Yet despite this, and the widespread international understanding of the topic, there is still a tendency for cost considerations to lead to road construction or widening with a wholly inadequate amount of attention given to the stabilisation and protection of slopes.

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[2] Detailed technical information on bio-engineering measures is available in manuals such as that by Howell (1999), and in the more practical text books such as Schiechtl and Stern (1996). The "grey literature" of soil conservation also contains a wealth of practical information on this topic, though not always directly appropriate to the road sector

In practice, *slope stabilisation* depends on the use of a retaining structure, which can be drawn from a menu of standard and specialist techniques such as those shown in Table 3. The vast majority of walls alongside roads are of the simpler and lower cost types, for the obvious reason of cost effectiveness. In order to achieve high levels of strength, physical structures are always required and bio-engineering measures can only complement the civil engineering solution adopted. In fact, vegetation can provide protection and reinforcement of backfill and surrounding slope areas, protection from scour and the undercutting of the foundations and sides of structures and a flexible extension to a wall through large bamboos, shrubs or trees close to it adding to the engineering functions of catching, supporting and buttressing.

Table 3. Comparison of Retaining Wall Types

Wall Type	Maximum Safe Height	Typical Width:Height Ratio	Advantages	Limitations
Dry masonry	4 metres	1:1 to 0.6:1	Well drained, flexible, relatively low in cost and blends well with the surroundings.	Low strength threshold (susceptible to lateral pressures and traffic vibrations); limited height of construction.
Composite masonry (crib construction)	8 metres	0.75:1 to 0.5:1	Better drained and cheaper than mortared masonry.	Strength not as good as for mortared masonry.
Mortared masonry	10 metres	0.75:1 to 0.5:1	Relatively easy to construct on steep terrain; most durable wall type.	Requires good foundations and cannot tolerate settlement; poor through drainage.
Gabion (wire crate)	10 metres	Width = ½ h + 0.5	Flexible without rupturing; tolerates poor foundations, and weak and saturated ground conditions; well drained; relatively low cost for strength.	Construction requires a relatively wide foundation footprint to achieve the same shear strength of mortared masonry.
Reinforced earth	8 metres	Depends on design; substantial horizontal clearance usually required to develop required tension resistance.	A high level of flexibility and the potential for a well-landscaped, "natural" finish.	Reinforcing is expensive and relatively difficult to obtain in remote areas; stability calculations are complex and it is difficult to achieve the correct compaction and tension.
Soil nailing	5 metres	Depends on design	A potential stabilisation option where space is limited for other types of retaining wall.	Costly; requires advanced technical skills and specialist equipment to build.
Mass concrete and reinforced concrete	10 metres	Depends on design	Strongest type of retaining wall.	Relatively costly; requires large quantities of cement and crushed aggregate, and advanced technical skills to build; poor through drainage.
Anchored reinforced concrete	10 metres	Depends on design	A strong wall type for certain situations where space is limited for other types of retaining wall.	Very costly; requires a sound bedrock foundation, advanced technical skills and specialist equipment to build.
Bored-pile wall built in situ	5 metres	Depends on design	Allows through drainage between piles, in sites with identifiable failure planes within reach of piling.	Very costly; requires advanced technical skills and specialist equipment to build.

Slope protection can be achieved using physical civil engineering measures, but is much better undertaken using bio-engineering systems. It is only in sites prone to particular attack that some form of revetment walling is advisable, such as at the toe of a weak soil slope where cattle are likely to be driven; or where running water is common, that stone pitching (small-scale rip-rap) is necessary. Surface coverings of cement-stabilised aggregate or other compounds can be very problematic due to the difficulties of drainage and consequent build up of pore water pressures. Beyond these specific locations, usually very limited in roadside positions, vegetation is generally cheaper, more effective and environmentally advantageous.

As Table 2 shows, most bio-engineering systems also strengthen slopes through providing reinforcement or support. Authors such as Ekanayake et al. (2004) point out that “soils with roots produce stress-displacement curves with higher peak strengths at larger shear displacements than soils without roots”. This is unpredictable, however, on account of the infinite variability in the environmental factors that determine the growth characteristics of specific plants in particular situations. But what is predictability in geotechnics, when it is impossible to measure all of the relevant parameters affecting the stability of a slope? Theoretical models and calculations may only serve to simulate an accuracy that does not actually exist. The fact is that vegetation improves the coherence of slopes in almost every case and therefore contributes more than just surface protection; it provides a very valuable protection and strengthening of the top 500 mm or so of a slope, the zone in which all erosion and the great majority of mass failures occur.

There is a natural inclination to make direct correlations between the places that have been the focus of research and development projects over the years and the mountainous regions of northern India. However, such correlations can only be valid if the overall environment governing the performance of slopes in two regions are closely similar. It is crucial to be fully aware of the parameters that control stability on each slope under investigation and to take full account of the factors that will affect the short term and long term slope management. It is advisable, therefore, to assess carefully all the factors that comprise the overall slope environment.

There is, in fact, no logical clear distinction between the use only of physical civil engineering structures and their combination with plants in some kind of bio-engineering system. Table 4 summarises the various engineering functions that must be performed by structures in the stabilisation, strengthening and protection of slopes and shows how both approaches (physical and biological) can be employed to optimum effect.

1.4 International experience

The options for the use of vegetation in engineering are numerous and have been covered well in the literature. Techniques are well established, with particular practical experience coming from the Alpine countries, particularly Austria (Schiechtl, 1980) and the United States (Gray and Lieser, 1982), which have formed the basis of recent thinking and practice. The current most comprehensive examples of text books are Coppin and Richards (1990), Gray and Sotir (1996), Morgan and Rickson (1995), and Schiechtl and Stern (1996). Conferences regularly either focus on bio-engineering (e.g. Barker et al., 2004), or contain a significant number of articles on the subject (e.g. HMG Nepal and PIARC, 2003). Country-specific examples of adaptation for particular application in the road sector may be found in many instances, such as the Caribbean (Clark and Hellin, 1996), Nepal (Howell, 1999) and Hong Kong (Geotechnical Engineering Office, 2000). More general texts on the use of vegetation for land stabilisation include the use of vetiver grass promoted over many years by the World Bank (National Research Council, 1993).

The biggest success with bio-engineering in association with low cost geotechnical engineering works is probably in Nepal, where extensive research in the 1980s was put into practice in the 1990s (Howell, 1999). This experience is still being widely applied in the current programmes of the Government of Nepal itself, as well as those supported by the World Bank, the Asian Development Bank, the UK Department for International Development, the Swiss Development Co-operation and other donors (see, for example, the Nepali Times of August 2006). The results of innovative research in the late 1980s and early 1990s in Nepal that worked on a range of livelihoods opportunities in the management of roadside slopes in rural areas now forms the basis of pro-livelihoods rural road development on a significant scale.

Table 4. Engineering Functions of Stabilisation Options.

Engineering function	Civil engineering solution	Potential drawbacks *	Bio-engineering alternative	Bio-engineering solution	Potential drawbacks	Possible optimal combination of both
Support a weak soil mass by the provision of toe support. This can be achieved either by creating a heavy, immovable weight at the base of the slope, or by altering the slope to create an effect of buttressing and arching (where the soil between buttresses is supported from the sides by compression). The buttresses and arches of a building have similar engineering functions.	Retaining walls of masonry (bound or unbound) or gabion.	Drawbacks mainly relate to cost, foundation conditions and through drainage.	Large heavy vegetation, such as trees, at the base of a slope can provide support in the form of buttresses; or on a micro scale, clumps of grass can buttress small amounts of the soil above them. A lateral arching effect is created across the slope, between plants. Requirements are for extensive, deep and wide-spreading root systems, and many strong, fibrous roots.	Most trees, with the specific selection dependent on local environmental factors..	Trees take a long time to establish, and do not offer a continuous line of support across the slope.	Retaining wall with trees above, beside and below, maximising the overall support of the slope.
Anchor a mass of weak surface material, through potential failure planes, into firmer strata below. This may be possible where a particularly incoherent mass overlies stronger materials, such as where colluvium rests above a relatively unweathered rock mass.	Soil anchors, soil nails and rock bolts.	Depends on there being a stronger underlying mass; difficulties of cost, design and construction.	Vegetation that will extend its roots below the potential failure planes. If the potential failure is deeper than about 0.5 metre, this is achieved only by large woody plants with big vertical roots (tap roots). Requirements are for plants with deep, strong, long, and vertically oriented roots.	Shrubs and trees that are deeply rooting.	Deep roots take a long time to develop and are unpredictable because of unknown subsurface conditions.	Combination of an artificial anchoring system and trees.
Reinforcement of the soil to reduce deformation. This is particularly important to reduce shallow failures, especially when soils are saturated.	Reinforced earth systems.	Artificial soil reinforcement is complex to design and construct, and difficult to achieve on steep slopes.	Provide a network of roots that increases the soil's resistance to shear. The degree of effective reinforcement depends on the form of the roots and the nature of the soil. Requirements are plants with extensive roots with many bifurcations, and many strong, fibrous roots.	Densely rooting clumping grasses planted in lines; brush layers and palisades; some shrubs and trees.	None: plant roots always contribute to the shear strength of the soil.	Built-up slope with soil layers interspersed with geotextile, and planted with grass etc.
Drain excess water from the slope, to reduce pore water pressure and increase slope strength and coherence. It is especially important to avoid the saturation of material, which leads to slumping due to a reduced loss of internal friction.	Surface or sub-surface drains, designed as per site conditions.	Surface drains require additional maintenance, often ignored in off-road situations.	Vegetation can be planted in a configuration that enhances drainage. Vegetation can also help to reduce pore-water pressure within the slope, by extracting water from the roots and transpiring it out through the leaves. Requirements are for plants to be planted in closely-packed lines; they must have an ability to resist scour and a high leaf area to enhance transpiration.	Downslope and diagonal vegetation lines, particularly those using clumping grasses. Most shrubs and trees.	Requires a good understanding of site conditions, and careful application of appropriate measures.	French drains and angled grass lines feeding surface water into the drains.
Armouring of the slope against surface erosion from both runoff and rain splash.	Revetments and surface coverings.	Too expensive to apply on a large scale; can only be used in select critical locations.	A continuous cover of low vegetation. Plants with high canopies alone do not armour the slope (the terminal velocity of a rain drop is reached after a fall of only 2 metres, and some canopies generate larger rain drops). The requirement is for a dense surface cover of vegetation, with a low canopy and small leaves.	Grass lines or a complete grass carpet of clumping or spreading grasses.	None: this is what grass does best.	Vegetated stone pitching, for gully floors and episodic water courses.
Catch eroding material moving down the slope, as a result of gravity alone or with the aid of water.	Catch walls and fences.	On steep slopes it may not be possible to construct a secure wall above the road.	Vegetation stems can perform this function. The requirement is for strong, numerous and flexible stems, and the ability to recover from damage.	Micro scale: clumping grasses. Larger scales: shrubs with many stems and bamboos.	It takes some years for plants to become sufficiently robust to perform this function reliably.	Catch wall with shrubs or large bamboos above.

* See also Table 3.

Other examples of bio-engineering works are numerous and many can be found in the documents to which reference has already been made. The great breadth of international experience is nowhere fully documented, though the International Erosion Control Association, while somewhat Americo-centric, probably has the best reach to documented broad expertise through its publications, especially its large annual conferences (see http://www.ieca.org).

One of the key lessons from the practical experience gained in other countries is that geotechnical and bio-engineering disciplines need to be integrated in their approach to slope management. Neither is a total solution on its own and this is illustrated by failures that have occurred when either the wider slope conditions have been ignored or the engineering or planting materials used have proven inappropriate for the site.

2. Case Study of Himachal Pradesh

2.1 Slopes and instability

Himalayan geology has been described in numerous books, as well as in the memoirs of the Geological Survey of India and the Journal of the Geological Society of India. A comprehensive account of the subject can be found in the huge recent tomes edited by Saklani (2005-06). Practical treatments of slope dynamics in relation to infrastructure are particularly to be found in publications by the International Centre for Integrated Mountain Development (e.g. Deoja et al., 1991; Deoja, 1994; Tianchi et al., 2001). The Indian Roads Congress (1998) has recognised the special conditions to be found in the nation's mountainous areas, devoting an entire manual to the subject of hill road engineering.

Terrain varies in Himachal Pradesh from the lower belt, which is dominated by the Shiwaliks (particularly in the southern parts of Ponta, Solan and Nalagarh), to the higher reaches more normally thought of as part of the "Himalayas" (such as in Kinnaur district). Hence the geology and soils are also entirely different, and therefore treatments must be adapted for the different regions of the state. In assessing slope instability in relation to roads in the Himalayas and their foot hills, it is necessary to distinguish between natural and man-induced failures. The southern part of Himachal Pradesh, where most of the state's roads are found and which is predominantly part of the Shiwaliks, has materials that tend to be weak and non-cohesive, due to prolonged weathering and natural disturbance that results from the region's active geological history. As a result, natural slope movements are common; but the resulting fragility means that man-induced failures are also widespread. There are several reasons for this, but the key issue is that in such geomorphologically sensitive terrain, land management and construction must be carried out with considerable care; yet to do this takes extra time and cost relative to sites in lowland and plain areas, and additional resources are often not available in the more marginal uplands. The result is increased damage to slopes through a lack of attention to good engineering practice.

The intensive unscientific cutting of hills for new roads and widening of existing roads with increased use of heavy machinery have also added to geological disturbances, resulting in the greater instability of hill slopes and more slope failures. Every year the triggering of landslides occurs frequently in different locations, as a result of intensive periods of the annual monsoon rains, flash floods, snowfall in higher areas and wide variations in day and night temperatures and seasons. Bad quarrying and the careless disposal of surplus materials are other sources of roadside landslides. In this context, innovative and cost-effective solutions need to be explored and applied on an experimental basis to control instability wherever feasible.

Plate 1. A View of the Highly Dissected Terrain near Shimla.

Plate 2. A typical roadside slope failure, caused by careless spoil disposal.

A simplified assessment of the main slope problems encountered by the Public Works Department is given in Table 5, along with an outline of the ways in which they might be resolved. This demonstrates that there are both large and small failures, and that some are not "the fault" of the road.

While standard civil engineering measures are usually required for the bigger failures, the more prevalent smaller problems can mostly be resolved using bio-engineering measures.

Table 5. Practical Summary of Slope Stability Problems found in the Road Sector of Himachal Pradesh

Problem	Cause/mechanism	Outline of resolution
Natural failures		
Mass failures in deeply shattered rock strata on steep valley sides; these often have a fine matrix with larger angular fragments (mixed residual soil and colluvium), leading to saturated flow.	Planar or shear failures caused by a combination of long term (geological time) slope steepening and weak, deeply weathered or otherwise disturbed materials. Usually triggered by heavy rain.	Depends on site, but can usually be resolved by a retaining structure at the toe of the failure plane, dendritic surface or sub-surface drainage, and a range of appropriate bio-engineering measures.
Large-scale creep of long, steep hillsides: these are on the margin of instability and movement is easily started, either by the road being formed, through some other physical event or simply as a result of unusually heavy rain. However, the road is not the fundamental cause of the failure.	Usually deep-seated planar or shear failures, again caused by a combination of long term slope steepening and weak or disturbed materials. Ground water is a common causal factor, and river under-cutting may also be a problem. The failure plane may be above or below the road bench, but is rarely related to it.	These always need detailed studies to understand the slope dynamics, and the result may be that there is no cost-effective solution. Major retaining structures might be advantageous, but intensive sub-surface drainage systems are usually needed. Bio-engineering may only help by channelling surface water into drains.
Man-induced Failures		
Valley side damage from tipped debris: the scale varies, but some examples are 50 to 100 m long.	Man-induced erosion or planar failures, through the deposition of unconsolidated debris on to steep slopes, at angles that cannot be sustained.	These slopes generally reach a semi-stable angle of repose in 1 or 2 monsoons. After this, erosion protection is required, achieved by robust bio-engineering techniques such as brush layering, with shrub and tree planting in between.
Small hill side failures in over-steep cut slopes.	Man-induced planar failures or rock falls, caused by cut slopes being left too steep or improperly formed, or by quarrying stones from for retaining walls and other maintenance tasks.	In most cases the slope needs to be trimmed to an even grade, often as steep as 40 or 50°, depending on material. It can then be planted, most commonly using grass slips in diagonal lines. Sometimes a low toe wall helps as a revetment.
General degradation of cut slopes, including erosion and mini failures of small volumes of debris.	Man-induced erosion or planar failures; sometimes because of recent widening. This may remain a problem for 10 to 15 years after slope formation if protection works are not undertaken.	These can generally be resolved using bio-engineering. Grass line planting, horizontal or diagonal, is necessary on steep sections, and dense shrub planting or palisades if there is a more gentle lower section (to catch debris). Sometimes a low toe wall helps as a revetment.
Failures due to other activities, such as side road excavations, debris tipped from above, houses built too close to cut slopes, over-use of explosives in blasting etc.	Usually man-induced erosion, planar failures or rock falls.	Depends on site. Often it requires a damaging activity to be stopped before action is worthwhile. In the case of blast-shattered rocks, masonry dentition may be required.

The majority of landslides in Himachal Pradesh are shallow and a highly effective way to control them would be the regeneration of vegetative cover as part of routine maintenance operations on all categories of hill roads, along with the provision of adequate drainage arrangements. However, for deep-seated landslides a holistic and balanced approach would be required. It is important to bear in mind the fact that no two slope failures are the same, because there is almost always more than one cause, and many features display a range of failure mechanisms. Hence it is essential to build up a detailed understanding of the geomorphological processes giving rise to the problems on each site before a solution can be proposed scientifically. Practical guidelines such as those given by Deoja et al. (1991) help to show how the causes and mechanisms of landslides occur.

2.2 Options for Slope Stabilisation and Protection

The PWD's current practice is to construct retaining or breast walls for stable slopes, and install gabions (wire crates) in unstable sections. The gabion or wire crate walls are very effective in sliding areas because they are flexible and permeable, and adjust themselves to foundation movements. Their applicability depends partly on the slope angle, which generally varies from 25 to 45 degrees, with exceptions. But large physical structures of this nature are expensive and with its limited funds the PWD must explore and adopt the most economical measures for slope protection on a case-by-case basis. The Department has a capacity for the planting of roadside trees (through its Horticulture Wing), and so the obvious strategy is to build on that capability to development a more scientific integration of vegetation in engineering works.

Plate 3. An Example of a Gabion (wire crate) Wall - Failure such as this need Additional Treatment.

The most common difficulties encountered in slope stabilisation works in terrain of the type found in Himachal Pradesh are as follows.

- There is a lack of working space on steep slopes.
- Very deep foundations are needed to find bedrock below colluvium and this is often unachievable because of the need to consider worker safety.
- Variable material strengths may mean that foundation conditions deteriorate with depth. This can occur in both colluvial slopes and in situ materials, where weathering effects can vary considerably.
- Drainage requires a careful site-specific design and not standard construction. Prepared designs based on office drawings are always flawed if they are applied without a significant amount of adaptation to ground conditions.
- Drainage is essential, but drains impose a significant recurring off-road maintenance burden.
- There is a lack of site assessment and geotechnical skills among most highway engineers. These are specialist areas not adequately covered by training courses. In addition, those with adequate training are often too senior to undertake such intensive field assessment.

The practical options for bio-engineering in environments such as those found in Himachal Pradesh can be summarised as the following.

- Grass planting: large clump grasses can be planted in various configurations, such as contour, diagonal or even down slope lines, depending on the characteristics of the materials, and perhaps combined with a jute or synthetic geotextile. This provides erosion control and shallow reinforcement.
- Vegetative structures using hardwood cuttings: brush layers, fascines and palisades, with the angle of the lines determined by the type of material and slope on which they are applied. These also control erosion, catch debris and provide strong, fibrous root reinforcement.
- Tree planting, as part of a plant community with under storeys of shrubs and grasses: a wide range of possibilities are available, to suit all environmental conditions. Tree roots offer greater reinforcement and anchorage.

Many of the bio-engineering techniques most appropriate to the roadside slopes of Himachal Pradesh require the intensive use of grass planting, using slips produced through vegetative propagation. This is technically straightforward and suitable species are available locally, but current nursery capacity of the HPPWD will need to be expanded to provide an adequate volume of soil beds to allow the bulking-up of grass clumps. Current capacity is adequate for the provision of other bio-engineering materials (containerised seedlings and rooted hardwood cuttings), though a range of different species will need to be introduced. These will all be either local, or derived from ecologically similar sources in nearby states.

Slope instability also affects the National Highways as well as the state roads. Although the 1235 km of National Highways in Himachal Pradesh are fully under the Ministry of Shipping, Road Transport and Highways (MOSRT&H), Government of India, a separate Chief Engineer (National Highways) of the PWD manages all affairs in the state and also acts as the state co-ordinator for MOSRT&H. It must ensure that the best practices are applied irrespective of the classification of the road and as the National Highways carry the most traffic and have greatest strategic importance, they should logically be given the highest priority.

2.3 Institutional Requirements

The introduction of bio-engineering to an infrastructure management system run by civil engineers inevitably requires a number of different skills. The main issue that has to be grasped by engineers is that plants cannot be procured without some advance preparation, and that works have to be scheduled more precisely in line with seasons; this is particularly important under the monsoon climate that prevails in northern India. Table 6 demonstrates how bio-engineering adds a number of steps, some of them time critical, to the routine of civil engineering works. Even when foresters, agriculturalists or horticulturalists are brought into the equation to assist, the matter is not straightforward, since the principles of vegetative slope stabilisation, and the particular species used in bio-engineering, are mostly different from standard farm and forest practices, and therefore are neither well known by labourers nor available from standard nurseries.

The timeliness of work is critical because of the importance of planting in the early monsoon rains, to ensure the maximum level of growth on the marginal roadside sites. This can be difficult when contracts run behind schedule, and the sites cannot be handed over for bio-engineering at the right time. Quality control is also important due to the fact that bio-engineering techniques have low margins of safety. Inert materials (such as stone, concrete and steel) allow the engineer to over-design slope stabilisation measures where there is doubt over the factor of safety. This is much harder to do using the cheaper materials of bio-engineering, and hence the standard of workmanship must be of top quality to ensure that the function required is achieved. One of the most common reasons for lapses in quality is sometimes the limited interest shown by the larger civil works contractors, because the overall value of bio-engineering works is low relative to other construction costs.

Table 6. Assessment of Planning and Implementation Inputs for Civil and Bio-Engineering Works (after Howell, 1999).

Step	Activity	Civil engineering		Bio-engineering	
		Input?	Time critical?	Input?	Time critical?
1	Initial plan	✓		✓	
2	Prioritise works	✓		✓	
3	Divide the site or slope into segments	✓		✓	
4	Assess the site	✓		✓	
5	Determine conventional civil engineering works	✓		✓	
6	Choose the right bio-engineering technique			✓	
7	Design the civil and bio-engineering works	✓			
8	Select the species to use			✓	
9	Calculate the required quantities and rates	✓		✓	
10	Finalise priority against available budget	✓		✓	
11	Plan plant needs (*i.e.* order seeds, nursery stock)			✓	✓
12	Decide implementation/prepare documents	✓		✓	
13	Prepare for plant propagation			✓	✓
14	Site arrangements	✓		✓	
15	Prepare the site for work	✓	✓	✓	✓
16	Implement the civil engineering works	✓	✓		
17	Implement the bio-engineering works			✓	✓
18	Monitor the works	✓		✓	
19	Maintenance	✓		✓	
Total Number of Steps		**14**	**2**	**17**	**4**

It also takes time for vegetation to become established and reach full strength, which adds to the necessity for a change of mindset among professionals; civil engineering structures are at their strongest very soon after construction, and have a relatively predictable decay path. By contrast, it is difficult to predict the contribution of vegetation to slope strength and integrity, and in some situations this can expose design engineers to potential criticism.

2.4 The Way Forward

During our initial assessment of bio-engineering possibilities in Himachal Pradesh, the following main technical areas were identified as requiring skill development among the majority of professional level staff. These sub-disciplines are poorly covered in almost all civil engineering courses, because slope stability in the Himalayas is a relatively small niche.

- Site assessment: the geological element in slope structure, geomorphological processes, the identification of erosion and landslide causes and mechanisms, and determination of treatment strategies.
- Plants in engineering: the role of vegetation in slope stability, bio-engineering systems appropriate to the biophysical conditions in HP, integration with standard civil engineering measures, plant species selection, propagation and construction techniques.
- Bio-engineering planning and implementation: the programming of bio-engineering works in relation to the seasonal calendar and construction schedules, critical paths for plant propagation, site preparation and works implementation; and the options for phasing works over more than one year.

Despite these potential difficulties, the use of bio-engineering is fully compatible with the approach outlined for the State Roads Project, which is currently in preparation by the Government of Himachal

Pradesh and the World Bank. Its use would promote both the pro-environmental and improved asset management objectives of the project. It also supports the aims of institutional development and the move towards a sector-wide approach, through the broadening of capacity in Himachal Pradesh to manage its infrastructure assets better by using cost-effective solutions for slope stabilisation. The planned widening of roads will involve massive hill cutting, resulting in yet more unstable slopes, and with the disposal of surplus debris, the stability of slopes will be a key environmental issue to be mitigated under the HP State Roads Project. In the light of this, the introduction of these techniques is a good practical example of the Bank's stated aim of helping the Government of Himachal Pradesh to gain access to global knowledge for mitigating the adverse effects of unscientific road construction and the stabilisation of unstable slopes.

The HPPWD is moving towards accreditation for quality assurance systems under ISO 9001[3]. It has also been agreed to aim for accreditation for ISO 14001, which covers environmental issues of corporate activities, including an environment policy and overall environment strategy and management systems[4]. Both are important for the introduction of a well organised system of slope stabilisation and protection works.

The Department would develop specific environmental measures, such as how to cope with spoil during maintenance (as distinct from during construction and widening). Hence part of the environmental strategy must be the assigning of designated dumping sites in safe areas and the acceptance that additional haulage costs will be balanced against reduced maintenance costs. Other related topics that will be covered under this strategy include general construction management, labour and equipment camps, waste disposal, worker safety, traffic management, preservation and plantation of trees, and water use in construction. All of these have some level of bearing on the best practice use of bio-engineering techniques.

The Department has some in-house capacity, but will eventually need to reform, so that it becomes more streamlined and efficient. The implementation of the State Roads Project through a Corporation (the Himachal Pradesh Road and Other Infrastructure Development Corporation Limited or (HPRIDC) is a welcome first step in this direction. It is important that the introduction of bio-engineering works follows a strategy that promotes this modernisation of governance, rather than adding to the organisation that needs to be reformed. Operations through the HPRIDC are subject to separate accounting and a more open financial management system, and this will be advantageous in the use of new techniques. Yet there will still be close collaboration with government, and hence considerable capacity development spin-offs. In essence the project is to be implemented by the HP government through the HPRIDC, using the PWD for execution. Upgrading works will be executed by contractors to be supervised by an independent engineer (Supervision Consultant) under this project. A Technical Examiner (also independent consultant) will assess the Periodic Maintenance Works. On a pilot basis, bio-engineering works using local plant species will be given trials to rehabilitate some vulnerable locations and identified dumping sites along road stretches subject to periodic maintenance.

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[3] ISO 9001 certification means that an organisation has an effective management system which is capable of consistent performance, and that this has been established through an independent examination conducted against the published global International Standard.

[4] ISO14001 requires an environmental policy to be in existence within an organisation, fully supported by senior management, and outlining the policies of the organisation, not only to the staff but to the public. The policy needs to clarify compliance with environmental legislation that may affect the organisation and stress a commitment to continuous improvement. Emphasis has been placed on policy as this provides the direction for the remainder of the management system.

Plate 4. A Plant Nursery of the PWD's Horticulture Wing.

Plate 5. A Slope Stabilised by Planting Undertaken by the PWD's Horticulture Wing under a previous initiative.

Some minor institutional changes appear to be necessary, particularly in the upgrading of the Horticulture Wing, to add an engineering element. At present the staff operating this part of the PWD's remit are horticulturalists with a good understanding of plants but a limited comprehension of their role in slope stabilisation. They need to work hand-in-hand with engineering staff, who will also need to develop their knowledge of vegetation in engineering.

It is likely that under the Human Resource Study and Force Account Productivity, the HPPWD will have to identify an up-to-date human resources development strategy that incorporates continuous capacity development of professional staff and increases the productivity of its large gang labour respectively. This is to be welcomed in any case, and the training of engineering staff in the techniques of bio-engineering might well provide a useful first step in this direction.

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