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Biostabilization of Mandaman dump slope, India

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Synopsis

An integrated study of the biological stabilization of a coal-mine overburden dump slope has been carried out at Mandaman, 35 km from Dhanbad in eastern India. Native grasses—bamboo (*Dendrocalmus strictus*) and *kashi* (*Saccharum spontaneum*)—are important species that can stabilize the dump slopes. The grasses have good soil binding capacity and help to control soil erosion and improve dump stability. Field observation of their growth performance has indicated that the mean grass height and root depth are 232 (±74) cm and 46 (±5) cm, respectively, after three years and the below-ground root biomass is 474 (±69) g m^{-2}. The mechanical and hydrogeological actions of the grass roots have improved the shear strength properties of the dump material. Numerical modelling has shown that the roots of these grasses increase the factor of safety of the dump slope from 1.2 to 1.4 and thus play a substantial role in the maintenance of long-term stability.

Huge quantities of overburden are removed in the course of opencast mining operations. In recent years a substantial increase in the rate of accumulation of waste materials has led to increases in the height of dumps to minimize the area of ground that they cover. This trend brings with it the danger of dump failures, gully erosion and various associated environmental problems.[1] Revegetation is widely used as a means of stabilizing dump slopes and controlling their erosion,[2,3] thereby helping to maintain ecological equilibrium in the area.[4]

In the context of slope stability soil bio-engineering technology offers several potential improvements over current methods. Soil bio-engineering is a combination of mechanical, biological and ecological concepts that are integrated to arrest and prevent shallow slope failures and erosion. Perhaps the greatest advantage is cost-effectiveness. Another key advantage is that once vegetation becomes well established (usually after the first growing season) it becomes self-repairing, requiring little maintenance. Finally, when compared with other stabilization techniques, soil bio-engineering presents a much more aesthetically pleasing and environmentally sound alternative.

The effects of vegetation growth on a dump slope can be categorized as hydrogeological and mechanical.[6] From the former standpoint, roots are important in enhancing dump stability by intercepting rainwater and by controlling evapotranspiration and the resulting pore pressure reduction.[7,8] Their mechanical effect consists in reinforcement of the dump material and enhancing its shear strength; this action is closely related to the density, depth and strength of the roots.[9–12] However, little work has yet been done on the quantitative evaluation of biological stabilization.

Numerical modelling has the capability of contributing to understanding of the stabilization of dump slopes by plants and quantifying the improvement in stability. In particular, the technique offers the flexibility of assigning various material properties to different layers to simulate field conditions.[13,14]

Study site

Location and description

The stabilization of a dump slope by revegetation was studied at the Mandaman coal-mine overburden dump in India. This is located in the Kapasara area of Eastern Coalfields, Ltd., about 35 km from the Central Mining Research Institute, Dhanbad (23° 47′ north, 86° 43′ east). The topography of the area is undulating. Mining was previously carried out by opencasting, but the bord-and-pillar method of underground working is now used. The dump was formed in 1988 by backfilling with a shovel–dumper combination. The maximum dump height, slope angle and elevation above mean sea-level at the dump top are 30.5 m, 36° and 151.4 m, respectively (Fig. 1).

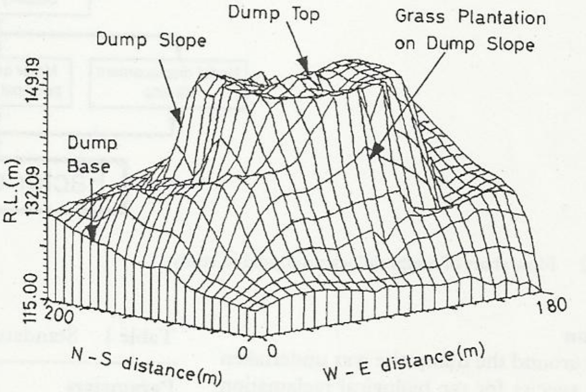

Fig. 1 Three-dimensional plot of Mandaman dump (R.L., relative to mean sea-level)

Climate

The climate of the area is dry tropical and the year can be divided into a cold winter (December–February), a very hot summer (April–June) and a rainy season (July–September). Within the annual cycle the mean daily minimum temperature ranges from 10 to 28°C and the mean daily maximum temperature varies between 26 and 45°C. The average annual rainfall is around 1400 mm, of which 1200 mm occurs between late June and September.

Geology and soil

The site is in Raniganj coalfield, the birthplace of coal mining in India, and constitutes the eastern member of the chain of the Gondwana coalfields grouped under the Damodar valley.

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The bedrock is formed of medium- to coarse-grained sandstone clay with ferruginous bands and carbonaceous shales. The soil surface layer is 10–12 cm thick, grey-brown to very pale brown, sandy loam to clay loam with a subangular blocky structure. Ferromanganese concretions and clay are found in the subsoil. The overburden consists of alluvial loose sand, gravel, shale and sandstone.

Methodology

The methodologies adopted for the field and laboratory studies are presented systematically in Fig. 2.

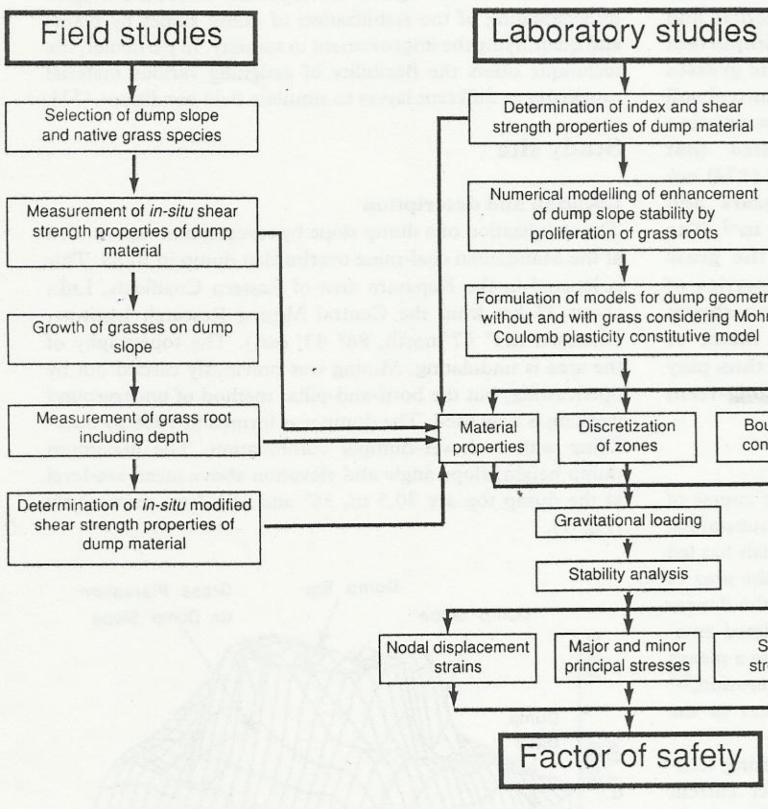

Fig. 2 Flow chart of methodologies adopted in study

Biological reclamation

Reconnaissance in and around the dump site was undertaken to select suitable grass species for the biological reclamation of the slope. Bamboo and *kashi*, which are the two dominating native grass species, were chosen. Both these grasses produce roots with good soil-binding capacity. Grass tillers were collected from the laboratory plant nursery and transplanted on the dump slopes at 0.25 m × 0.25 m spacing after the onset of rain during July, 1993. The grass-root biomass was estimated by digging monoliths[10] measuring 0.5 m × 0.5 m × 0.5 m at the time of peak biomass, i.e. in October, 1996. These samples were dried in an oven at 80°C until the weight became constant. The growth performance of the grass species was analysed by statistical methods.[15]

Properties of dump material

The physico-mechanical properties of the dump were studied in the laboratory in October, 1996, to obtain index and shear strength properties. The dump material samples were collected and analysed by standard methods.[16–22] The procedures applied with respect to various index and shear strength parameters are presented in Table 1.

In-situ jack shear test

To obtain the *in-situ* shear strength of the dump materials (with and without grasses) *in-situ* jack shear tests were carried out by the standard method.[23–25] A block of known dimensions (40 cm high × 80 cm wide × 100 cm long) is made and is pressed gradually to failure from a fixed reaction face. The length of the soil block to be tested is equal to the length of the equipment. Observations are recorded at various stages of failure. The sides of the test block are separated from the main soil mass by a narrow cut 15–20 cm wide and to the full depth, which is loosely backfilled by the excavated soil (Fig. 3). Both the reaction face of the pit and the test block must be vertical so that the load applied is horizontal.

Table 1 Standard procedures for dump material testing

Parameters	Procedures
Grain size distribution	Sieve analysis
Moisture content	Calcium carbide method
Bulk density	Measurement of weight and volume
Dry density	Constant weight method
Specific gravity	Pycnometer
Void ratio/porosity	Measurement of weight and volume
Liquid limit	Liquid limit test apparatus
Plastic limit	Thread (3 mm) test
Permeability	Falling head test
Shear strength parameters (c and ϕ)	Direct shear and triaxial tests

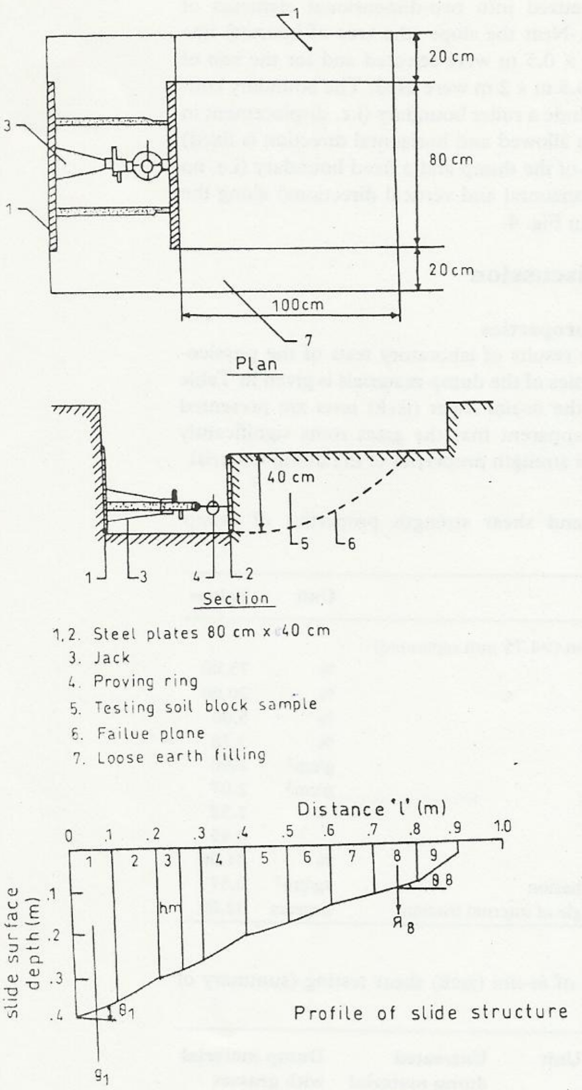

Fig. 3 *In-situ* jack shear test for dump material

The shear jack assembly is lowered into the pit and placed in the testing position. The load is applied in increments of 0.5 t. It is maintained for a period of 10–15 min, after which the load is increased to the next stage. (It was noticed that after the application of some load the block of soil starts moving along a sliding plane, exhibiting cracks and heaving of the failed material.) The application of load is continued until the test block has moved horizontally by approximately 10 cm. The load at the start of movement (P_{max}) and at the time when the block moves 10 cm (P_{min}) are recorded. After the test the assembly is removed from the pit. The true shape of the sliding surface is determined by removing the soil that has sheared off along the sliding plane. After the removal of the failed soil the depth of the failure surface is measured at three locations along the width of the block and at 10-cm intervals along its length. The average value of the depth, h, which is measured at three locations, is used to determine the shear strength parameters. The shear strength parameters cohesion, c, and angle of internal friction, ϕ, were determined in the manner described below.

A cross-section (see Fig. 3) was drawn for all the test pits by making use of the average depth of the sliding surface and it was then subdivided into a suitable number of slices. The weight of each slice, w, and length, l, along the sliding plane were determined. Further, the weight of the whole sliding mass, W, was determined from the equations

$$w = \gamma h_m x b \tag{1}$$

$$W = \sum_{i}^{n} w_n \tag{2}$$

where h_m is mid-height of the slice, m, γ is unit weight, t/m^3, x is width of the slice, m, b is width of the test block (i.e. 0.8 m) and n is number of slices.

By using the values of P_{max}, P_{min} and the lengths and weights of the slices the values of cohesion and friction angle were calculated from the equations

$$c = \frac{P_{max} - P_{min}}{bX} \tag{3}$$

$$\tan\phi = \frac{mA - B - cX}{(mB) + A} \tag{4}$$

where

$$m = \frac{P_{max}}{bW}$$

$$A = W\cos\theta_n$$

$$B = W\sin\theta_n$$

and

$$X = \sum_{i}^{n} x_n$$

Numerical modelling

The finite-difference method (FDM) was selected for numerical modelling of the problem. In this method the whole domain is discretized into small two-dimensional zones (elements), which are interconnected with their grid points (nodes). For each zone the differential equation of equilibrium is approximated. This results in a system of simultaneous equations that are generally solved by iteration methods. A two-dimensional FDM package, FLAC version 2.27 (developed by Itasca Consulting Group Inc., U.S.A.), was employed for the analysis.

Two models were formulated to simulate the field conditions with and without grasses and were analysed by FDM. The dump's geometry, material properties and boundary conditions were assigned to the models. It was assumed that the dump formation is gravity-loaded and no external load was applied on the model. The nodal displacement (i.e. movement of an element due to gravitational loading) of each zone was calculated first. From the nodal displacements strains were calculated and from the strains maximum shear stresses were calculated. Lambe and Whitman[26] reported that dump failure occurs through shear stress. The factor of safety (FOS) was therefore calculated for each zone, utilizing the Mohr–Coulomb plasticity constitutive relation. This model assumes an elastic, perfectly plastic solid in plane strain that confirms to a Mohr–Coulomb yield condition and non-associated flow rule.[14] The FOS is generally defined as the ratio of available shear strength of the dump material to the shear resistance required to maintain equilibrium.

Contours of FOS were drawn by the kriging method[27] for the whole domain.

Formulation of models

Field observations indicated that the average depth of the grass roots was 0.5 m after three years. The Mohr–Coulomb plasticity constitutive model was used to represent the behaviour of the dump materials, as discussed above. To study the effect of planting such grasses the properties measured in the field were assigned to the whole domain in the first model to simulate the untreated dump material (Fig. 4) and a modified layer 0.5 m thick with c and ϕ values measured for grassed areas was included to represent a planted dump in the second model (Fig. 5).

The slope angle and the height of the dump in the revegetated area were observed to be 35° and 30 m, respectively. A base length of 70 m was selected in consideration of the geometry of the dump and the influence of stress. The whole domain was discretized into two-dimensional elements of two different sizes. Near the slope (the area of interest) fine elements of 0.5 m × 0.5 m were selected and for the rest of the area elements 0.5 m × 2 m were used. The boundary conditions applied include a roller boundary (i.e. displacement in vertical direction is allowed and horizontal direction is fixed) along the rear side of the dump and a fixed boundary (i.e. no displacement in horizontal and vertical directions) along the base, as indicated in Fig. 4.

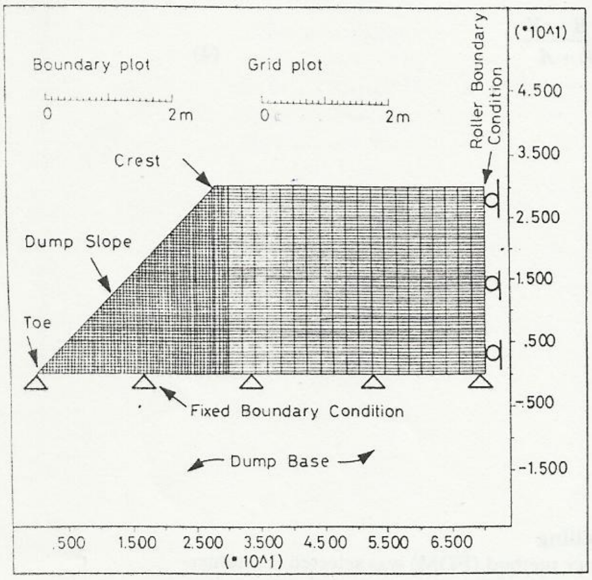

Fig. 4 Geometry of dump used for numerical modelling with boundary conditions

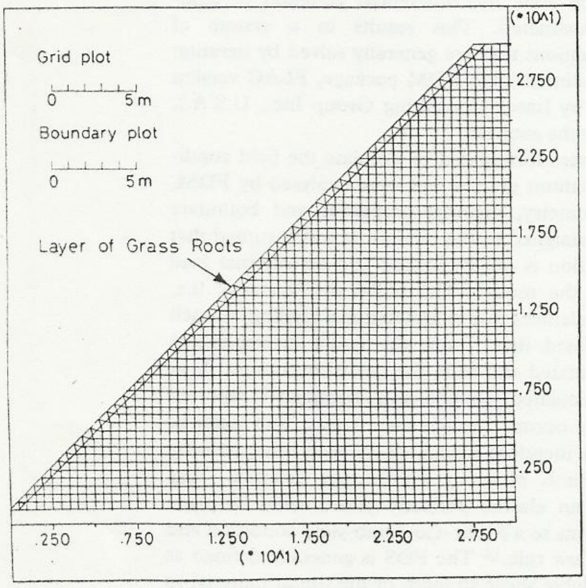

Fig. 5 Area of interest with different dump material properties

Results and discussion

Dump material properties

A summary of the results of laboratory tests of the physico-mechanical properties of the dump materials is given in Table 2. The results of the *in-situ* shear (jack) tests are presented in Table 3. It is apparent that the grass roots significantly enhanced the shear strength properties of the dump material.

Table 2 Index and shear strength properties of dump material

Parameters		Unit	Values
Grain-size distribution (>4.75 mm separated)			
Sand		%	75.00
Silt		%	20.00
Clay		%	5.00
Moisture content		%	3.78
Bulk density		g/cm^3	1.90
Dry density		g/cm^3	2.07
Specific gravity			2.52
Void ratio			0 45
Porosity		%	31.00
Shear strength:	Cohesion	kg/cm^2	0.57
	Angle of internal friction	degrees	32.00

Table 3 Results of *in-situ* (jack) shear testing (summary of five tests)

Parameter	Unit	Untreated dump material	Dump material with grasses
Cohesion, c	kg/cm^2	0.60 (±0.1 1)	0.98 (±1.4)
Angle of internal friction, ϕ	degrees	32.50 (±1.5)	33.50 (±2 0)

The shear strength properties of the constituent material play a vital role in a dump's stability. The determination of reliable shear strength values is a critical part of any dump slope design since small variations can result in significant changes in slope stability. For most of the evaluation of the stability of a dump slope it is appropriate to use the straight-line failure relationship also known as the Mohr–Coulomb failure law.[23] Shear strength is defined as the maximum resistance to shear stress. Chaulya[28] determined that the shear strength of spoil material increases as the cohesive strength increases while the normal stress and angle of internal friction remain the same. This increase in shear strength enhances the stability of the dump. Also, the shear strength of spoil material increases as the angle of internal friction increases, which, in turn, enhances the stability of the dump.

The shear strength of the soil is enhanced by the root matrix. Fine roots (1–20 mm diameter) contribute most to soil reinforcement, whereas larger roots seem to play no significant role.[29] Cherubini and Geiasi[6] found that loretta grass (*Lolium perenne*) increased the cohesion of soil as a function of root density, whereas Suyama[11] observed an increase in strength with root density for two species of tree—young European alder and young Japanese cedar. A linear relation was found in the first case and an exponential relation in the other. Waldron[30] analysed core samples drawn at various depths from homogeneous and stratified clay soils; the cores were 60 cm long and 25 cm in diameter and were permeated with alfalfa, barley and Swiss stone pine (*Pinus cembra L.*) roots. It was found that alfalfa roots provided the most effective reinforcement in all kinds of soil and could increase shear strength by as much as 290%—a much higher value than was observed with any other plants. Waldron[30] also reported a linear relation between measured strength increments and the root area ratio in soils cultivated with barley.

Many possible interpretations to explain the reinforcement mechanism theoretically can be found in the literature; all of them are in basic agreement that an increment in confinement stress is created because strain is prevented in the direction of the reinforcement, up to a limit value of the critical confinement stress.[6]

The hydrogeological effects of the vegetation cover are: (i) its ability to absorb water—the soil and subsoil can receive more water without reaching critical saturation; (ii) water is subtracted and retained through the biological cycle; and (iii) negative pore pressures are created, by which stability is improved. Another aspect of the vegetation cover is that it restricts the range of moisture and temperature variation on the soil surface; should the green cover be removed, stress conditions inside the mass could increase considerably owing to the dilating and contracting effects of temperature and moisture changes.[6]

Performance of grasses

Field studies of the grasses have indicated that the mean grass height, root depth and below-ground root biomass are 232 cm (±74), 46 cm (±5) and 474 g m^{-2} (±69), respectively, after three years of growth on the dump slope.[31] The value for the below-ground biomass is within the range of 455 (±43) g m^{-2} that has been reported for the natural succession of plant species on a 12 year-old slope at another dry tropical coal-mine spoil dump in India.[10] This plant biomass also contributes to soil fertility and, ultimately, productivity of the revegetated overburden dump. Consequently, proliferation of roots takes place on the dump, which ultimately enhances its stability.

Overall, the behaviour of the soil–root or soil–fibre system is a function of the tensile strength of the roots or fibres, strain modules of the roots or fibres, the length-to-diameter ratio of the roots or fibres and the friction properties of the roots or fibres and of the soil.[6,11]

Stability

The results of the numerical modelling indicate that the maximum displacement of elements occurs near the crest of the dump, i.e. the top portion of the slope (Fig. 6). Dump failure generally occurs after significant movement over a long period and any deformation monitoring programme should focus, therefore, on the crests of the slopes.[32] For a large dump with a steep, high slope continuous monitoring of deformation is essential and a wireline extensometer with a continuous recording facility may be used. Wireline extensometers are the simplest type of equipment for this purpose, being easily readable and readily adjusted.[25]

From the stress analysis of the dump slope it was observed that grass roots reduced the stress concentrations near the surface of the dump slope by comparison with a barren slope. It was also observed that the FOS increased from 1.2 to 1.4 as a consequence of the planting of grasses on the slope and the attendant enhancement of shear strength, and the path of the critical failure surface also changed. Contours of Mohr–Coulomb FOS are plotted in Fig. 7 for the dump with and without grasses. The depth from the dump slope surface of the critical failure surface (i.e. the surface along which dump failure occurs) is greater for the slope with grasses. The enhancement of the FOS and change in critical failure surface are due to mechanical action of the grass roots.[6,30] These are important factors for maintaining long-term stability of coal-mine overburden dump slopes.

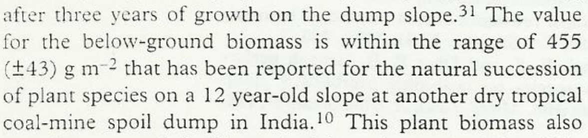

Fig. 6 Displacement of elements in *y* direction

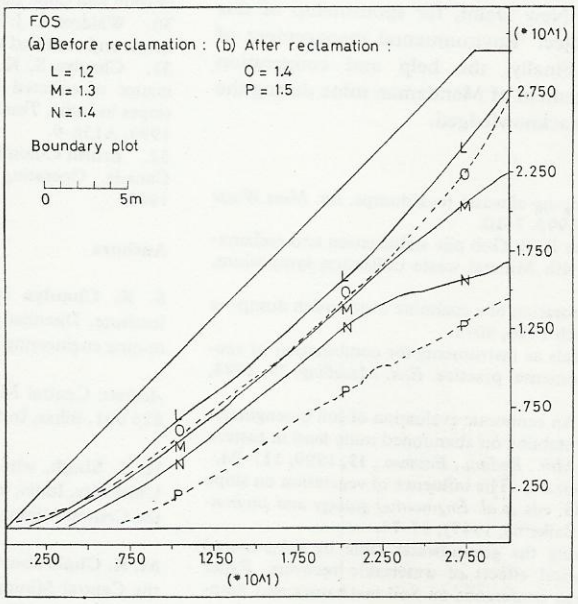

Fig. 7 Factor of safety for dump before and after biological reclamation

Conclusions

It may be concluded from the analysis that grass roots play a crucial role in the stabilization of coal-mine overburden dump slopes. Mechanical reinforcement of the dump material is provided by the proliferation of the roots. The shear strength of the dump material is also enhanced by the root matrix, which, in turn, increases the long-term stability of such slopes. Soil bio-engineering has excellent potential as a technology for slope stabilization of overburden dumps. Although labour-intensive and site-specific, this technology outshines its conventional counterparts by offering a combination of significant structural and mechanical support, long-term cost-effectiveness that stems from the low maintenance requirements and compatibility with the natural environment.

Vegetation controls erosion and contributes to the stabilization of shallow mass movements. Essentially, this role derives from the canopy effect, hysteresis of precipitation inflows, the reduction of soil moisture by transpiration, mechanical reinforcement provided by the roots and the creation of a humic layer that is capable of countering the leaching and runoff effect of water.

In most instances mine dump failure occurs after significant deformation that is accompanied by warning signals. The results of a numerical modelling analysis of slope stability have indicated that the maximum deformation occurs near the crest region and any deformation monitoring programme should therefore focus on the crest of dumps. In the case of steep, high faces on dumps continuous monitoring of deformation is recommended by wireline extensometers fitted with continuous recording equipment so that the risks of dump failure can be minimized.

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