A Critical Review on Stability of Earth Retaining Structures

[1]Dr. T. Kiran Kumar, [2]E. Kishan Kumar

[1]Professor, [2]Scholar
Civil Engineering Department
K.S.R.M. Engineering College, Kadapa.

***Abstract*: Slope stability is an important consideration in the construction and management of many Civil Engineering projects like Surface mining, Highway and Railway embankments, Landfills, Dams, Bridge abutments, Canals, Large excavation projects etc. Past research conclude the fact that slope stability is directly related to shear strength parameters, surface drainage, saturation levels of slopes of different soil types. Indian Sub-continent is diversified with soils like, Laterites, Black soil, Red soil, alluvial soil, Arid (Desert) soil, Mountain soil etc., which are derived from a wide range of rocks and minerals. These soils exhibit different index and engineering properties which are responsible for strength characteristics of the soil. Soils by their nature can form stable slopes up to a certain critical angle, namely Angle of Repose. For example, sand can resist slope up to 34^0, whereas, for some problematic soils like clay, slopes steeper than 25^0 often fail owing to their swell-shrinkage behaviour. Hence, there is a need to stabilize the slope with an effective Earth retaining structure. This paper will discuss on site investigation of soil type, reconnaissance survey of slope stability problems in that soil, selection of appropriate Earth retaining structure, study the design and cost aspects of the structure.**

***Keywords:* ERS(Earth Retaining Structures), HET (Hole Erosion Tests)**

I. INTRODUCTION

The idea of slope stabilizing developed from the recent centuries where complex structures were to be constructed on difficult soils like hills, mountains, soft soils. One of such traditional methods of slope stabilizing was Stone Pitching. Conventionally, stone pitching has been preferred solution to reduce erosion. But availability of stones poses a great challenge from an environmental and commercial standpoint. And also quarrying of stones has become an environment and legal issue making it scarcer. A brief history of evolution of ERS, suggest that, slope protection works started off with the conventional earthwork techniques to the present day complex mechanically stabilized ERS. In this paper, an attempt has been made to study major types of soils in India and their general slope failures, selecting an appropriate ERS as a counter measure against failure. Design and cost aspects of each ERS are discussed in brief.

II. OBJECTIVES

1. To study the soil type
2. To conduct Reconnaissance survey finding out slope related problems in the soil.
3. To select an appropriate ERS
4. To study design aspects of selected ERS
5. To study typical cost aspects of ERS

III. LITERATURE REVIEW

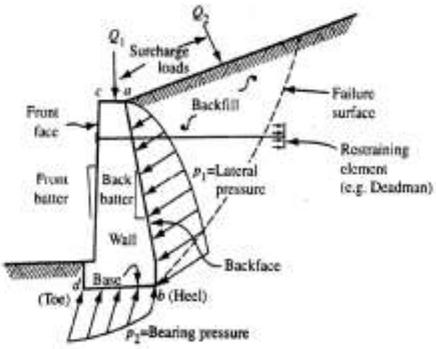
A. Earth Retaining Structure:

Technically, an Earth retaining structure is defined as “a support system meant to hold back earth or soil and maintain a difference in elevation of ground surface.” They support weak earth especially near toe of the slope, against failure. A typical retaining structure is designed to withstand loads exerted by the back fill (retained ground) and other external loads, to safely transmit these loads to the foundation and retaining elements of the structure.

A schematic diagram with a typical earth retaining structure is shown in fig 1.

Research done by O’Rourke and Jones (1990) suggest that ERS can be broadly classified based on load support mechanism, into two major groups, as internally stabilized and externally stabilized systems. An externally stabilized system uses external wall structure to resist backfill loads and other loads, whereas, an internally stabilized system involves reinforcement of soil mass within backfill extending up to the external support. A combination of both externally and internally stabilized system will yield a hybrid system.

Figure 1



Justin Anderson (2017), in the review on emerging trends in ERS, has claimed that, Soil Nailing and Geo-synthetically reinforced soil are the primary tools in repairing shallow slope failures. Though soil nails are effective, they are bound by time, cost and soil constraints. Overcoming this problem, new technique has been developing with high speed of soil nail installation (up to 250 nails per day). They are termed as Launched Soil Nails. Launched soil nails are vigorously used in countries like U.S., Canada, U.K., New Zealand and Australia. Engineers in Yukon are currently investigating whether hollow, launched soil nails be vertically inserted into Roadways overlying permafrost (frozen rock) to stabilize melting rocks.

As mentioned, ERS are widely used in most of the Civil Engineering projects. In Highways, retaining structures are used at places where space is insufficient for construction of cut or fill slopes. In Railways, ERS are used at critical cross sections like culverts, bridge abutments, river intersections etc. In the construction of multi-storeyed buildings, deep excavations are a must for foundation works and so slope protection works are mandatory. Other places where ERS are frequently used are Canal embankments, dams, Underground constructions etc.

To arrive at an optimized solution for slope stability, soil investigation should be carried out to determine the soil type and its behaviour when used as a slope backfill.

T. Bhattacharya (2013), in the article "Soils of India" has mentioned that, twenty four soil groups are grouped under eleven major soil groups based on their mineralogical composition and engineering behaviour. Out of which, six different soil groups are taken into consideration for study, which are namely Black cotton soils, Laterites, Red soils, Alluvial soils, Arid soils and Mountain soils.

Wan & Fell (2002, 2004) conducted hole erosion tests (HET) on laterite soils and suggested that cut slopes steeper than 60^0 cannot be stable considering effect of precipitation, ponding and slope angle.

Jie Xiao, He-ping Yang, Jun-jui Zhang, and Xian-yuan Tang (2018), in their works on expansive soils, found out that surficial failures of most of the expansive soils that are subjected to dry-wet cycles, often occur during or after rainfall post prolonged drought.

N.Benahmed, S.Bonelli (2012), in their research on "Internal Erosion of cohesive soils", where Kaolinite mineral and granular soil is used as a sample, found out that critical shear stresses depend upon dry density, water content and clay percentage of the soil. Failures in black soils were often observed in lands affected with heavy rain after a prolonged drought. The study also found out the reason to be small effective cohesion, swell-shrinkage behaviour, over consolidation. The undrained shear strength before swelling is 3 to 5.5 times greater when compared to shear strength after swelling. A sudden increase in moisture content will reduce the shear strength of soils cause a slope failure. These results prove that, stability of any kind of soil type is directly related to shear strength, saturation levels and drainage properties. Also the strengths calculated from in-situ tests are less than that of those calculated from laboratory tests using undisturbed samples.

Namdar, Azam Pelko (2006), in their research on mixed soil models using Red soils, have found that, Red soils showed a Factor of safety of 2.4 against failure whereas it reduced to 1.37 after saturating the sample. They proved that soil structure geometry, soil minerology have a direct relation to the strength of slope stability.

J. Michael Duncan, Stephen G. Wright, Thomas L. Brandon (2014) have mentioned in their works on "Soil Strength and Slope Stability", that alluvial soils mostly comprise of fine sands (non-plastic) and clay (plastic). They show broad range of behaviour from fine sands to the behaviour of clays to the other extreme end. It is difficult to differentiate between drained and undrained samples collected in case of non-plastic silts. Hence the strength prediction of these soils becomes complex.

Other granular soils (arid soils) formed from igneous and metamorphic formations, like sand, gravel and rock fill slopes are verified for their shear strength using angle of internal friction (phi). This angle is influenced by density, gradation and confining pressure. Although, particle shape, size and strength control internal friction angle, they cannot be measured and analysed.

IV. METHODOLOGY

A. Soil Investigation:

In the present study, soil groups taken into consideration are Black soils, Laterites, Red soils, Alluvial soils, Arid soils and Rocks. Field identification of these soil types is typically limited to determining basic characteristics of soil like colour, texture, plasticity without much requirement of major equipment. Apart from determining soil type, for detailed investigation following checklist need to be addressed.

- Interpretation of topography
- Collection of existing data
- Boring Investigation
- Geophysical survey
- In-situ test
- Laboratory tests

B. Reconnaissance :

Slopes are subjected to environmental and climatic conditions like freezing and thawing, heavy storms, winds etc., which affect the slope stability very badly. Failures are not only seen in plastic soils like black soils but also in granular soil owing to the above specified reason. Hence, after determining the soil type and its basic properties, site conditions should be checked for possible slope failures. This can be done by observing adjacent slopes, crack pattern, fissures and discontinuities in rocks, presence of folds, faults, dip & strike directions of outcrop etc., through the following steps.

- Failure type & Local information
- Dimensions of failure- apparent depth of failure, scarp depth and breadth, slope angle and height, distance of failure from crown or toe of slope.
- Cause of failure- determining natural or manmade activities that contributed to failure
- Failure impact- analysing effect on existing structures alongside the slope
- Slope materials information- origin of soil, physiographic classification.
- Slope characteristics table- slope gradient, aspect (convex/concave), vegetation density, ground water table, surface drainage.
- Vegetation Table- type and land cover details.

C. Selection of ERS:

For a given soil type, a unique slope failure is seen. Hence, soil types with their possible corresponding slope failures are listed out. Slope failures are generally categorized into,

- Soil slope collapse
- Rock Fall
- Land slides
- Debris Flow
- Embankment failure.

Following Table 1 shows slope failures often seen in corresponding soil type.

Various techniques have been in use for avoiding the above mentioned failures and are termed as Earth retaining structures. ERS are broadly classified as the following,

- Earth Work
- Vegetation
- Anchoring
- Wall Resisting Structures
- Piling work

Table 1

S.No.	Soil Type	Slope Failure
1	Black soil	Soil slope collapse
2	Laterite	Debris Flow
3	Red soil	Soil slope collapse
4	Alluvial soil	Embankment Failure,
5	Arid soil	Land Slides
6	Rock	Rock Fall

i. Earth Work:

Cutting or filling are the two main operations carried out in Earth work. Other randomly used techniques were Terracing, Diversions etc. The process of slope stabilization here in this case, involves design of standard slope, drainage, slope protection. After slope design, drainage design plays a vital role in the safety of slope. The effect of water on slope stability can be explained in two ways as slope surface water and increase in pore water pressure. The surface runoff will lead to erosion whereas high pore pressure will decrease shear strength of soil.

Pitching is another form of earthwork where a slope is supported with a number of supporting units arranged in a way to avoid soil erosion. Stone pitching, concrete pitching and Block pitching are basic types of pitching.

ii. Vegetation:

It is the most effective and ecologically friendly method of slope protection. The main objectives of Vegetation are,

a. Reduce soil erosion by surface runoff
b. To reduce infiltration of water
c. Bind soil interface at the root level and densify sand.

Other than protecting slope, vegetation also improves landscape of the area. Main vegetation works include,

Closed turfing, is a method where sod is directly applied on the face of slope. Hydro seeding, a method for gentle slopes where a mixture of seed, fertilizer, and water is sprayed over the face of slope. Seed mud spraying, is for steep slopes. This is as similar to hydro seeding mixture, to which spray gum is added to hold the seeds on such steep slopes. Vegetation mat, bag, hole, block are kinds of readymade vegetation methods with fertile seeds.

iii. Anchoring:

Rock bolting, ground anchoring and Soil nailing are the main techniques under this section, prescribed when the objects to be protected are important. Rock bolting is a shallow fitting method whereas ground anchoring is inserted deep into the soil. Another major difference between both is that, rock bolts applies force that fills the joints, prevents loosening and in the case of ground anchors, slopes are protected by tensile reinforcement.

iv. Wall resisting structures:

A rigid support is generally provided against the movement of soil using a wall called Retaining wall. Retaining walls are used to support shallow slope collapse or toe collapse failures. They also support as foundation work for structures say crib work etc. Major types of Retaining walls:

1. **Block / stone masonry walls**- Generally opted when the soil is dense and the estimated failure is small. They must be made of wet masonry.
2. **Gabion walls**- Gabions are steel bound frames with stones of different size are filled with to fabricate along the side of a slope.
3. **Gravity Retaining walls**- use their dead weight to resist the lateral earth pressures from backfill. Since heavy dead loads are needed, the dimensions of the wall become heavy making it uneconomical. And also no reinforcement is provided in the wall.
4. **Reinforced Earth Wall**- Shortly called as RE-wall, reinforced earth walls provide the best alternative to other retaining structures. They overcome the problems of land insufficiency, steep slope (almost vertical), time constraint and safe design even for heavy loads.
5. **Rock shed**- a method where constructions are protected by covering them using reinforced concrete or steel structures over them. Mostly used to reduce road disasters by rock mass failure.

v. Piling Works:

These are nothing but flexible retaining walls inserted into soft soils, generally made of steel. Concrete piles can also be inserted if deep cut slopes are excavated.

D. **Design Aspects of ERS:**

i. Earth work:

- Slope gradient range (V: H) – 1:0.3 to 1:1.5.Cut slopes details for different soils are tabulated in **Table 2**.
- Berm width – 1.0 to 4.0 m
- Berm interval – 5.0 to 10.0 m
- For pitching works, design criteria for pitching are given in **Table 3**.

ii. Vegetation:

- Slope gradient range - <60^0
- Hydro seeding is most commonly used technique.
- Type of vegetation depends on soil fertility and mineralogical composition.

iii. Anchoring:

- Rock Bolts – Bolt length and width are defined by various engineers, out of which, Dejean and Raffoux(1976) have proposed the following relations in **Table 4**.

Table 2

S.No.	Pitching	Height of slope	Paving thickness	Geological condition
1	Stone	< 5m	25 to 35 cm	Non-cohesive
2	Block	< 3m	12 to 35 cm	Collapsible soils
3	Concrete		>20 cm	Jointed rocks
4	RCC		>20 cm	Large/steep slopes

Table 3

S.No.	Rock type	Relation
1	Strong homogenous rock	L= 1m
2	Weak rock	L= 0.3to0.5B
3	Strong stratified rock	L>= 1.5 m

S.No.	Soil type	Slope height	Cut Slope gradient (V:H)
1	Hard rock	-	1:0.3 to 1:0.8
2	Soft rock	-	1:0.5 to 1:1.2
3	Sand		1:1.5
4	Sandy soil Dense - Loose -	 <5m 5-10 m <5m 5-10m	 1:0.8 to 1:1.0 1:1.0 to 1:1.2 1:1.0 to 1:1.2 1:1.2 to 1:1.5
5	Clayey soil	<5m 5-10m	1:1.0 to 1:1.2 1:1.2 to 1:1.5

Table 4

- Gound anchors –
  - Fixation length – 3 to 10 m.
  - Free length – more than 4m
  - Spacing of ground anchors – at least 2m

- ○ Minimum no of row – 2
- ○ Direction of anchors – parallel to soil mass movement.
- • Soil Nailing –
- ○ Desired soil type – firm low plastic soils.
- ○ Density of nail – one nail for every 1 to 6 sq. meter of finished slope
- ○ Diameter of nail – 12 to 32 mm
- ○ Length of nail – less than 5m.

iv. Wall Resisting Structures:

- • Stone/Block wall –
- ○ Min foundation depth –0.3m.
- ○ Density of drain holes – one for every 2 to 3 sq. meter of wall.
- • Gabion wall –
- ○ Cross section of wall – 1x1 sq. meter.
- ○ Length of wall – 2 to 5 m.
- ○ Grade of fill – 250 to 100 mm.
- ○ Drainage – not required.
- • Gravity retaining walls –
- ○ Minimum thickness at top of wall – 35 cm
- ○ Width of footing slab should be 0.5 to 0.7 times the height of wall.
- • Mechanically Reinforced Earth wall –
- ○ For design, FOS should be calculated against Sliding, Overturning, Bearing capacity and Overall stability.
- ○ Critical FOS values are tabulated in **Table 5**.

Table 5

S.No.	Structure under consideration	Min FOS	Max LRDF resistance factor
1	Slopes supporting structures	1.5	0.65
2	Slopes adjacent to structures	1.3	0.75
3	Embankment side slopes	1.25	-
4	Cut slopes	1.25	-
5	Land slides	1.25	-

- • Rock shed wall –
- ○ Impact force should be considered in design calculations.
- ○ Absorption layer should be designed to take the impact forces.

E. Cost Aspects of ERS:

Generally, cost analysis for ERS will be calculated per sq. meter area of finished slope face in case of Highway works. For some typical ERS, elements which vary the total cost are to be studied.

- • Pitching - facing elements influence the total cost of construction. Stones are comparatively costly owing to their unavailability, when compared to concrete pitching works.
- • Gabion wall - Density of walls, quality of wire mesh and filter cloth are factors that decide cost.
- • Ground anchors – they are generally costlier when compared to any other ERS but are effective in protecting the slopes.
- • Horizontal drain holes – Not much variation is seen in costs.
- • RE walls – In this case, cost of construction depend on availability of backfill material, filter cloths and reinforcement detailing.
- • Rock bolts/Soil nails – they are comparatively cheaper than RE walls. But they are effective substitutes to RE walls only in limited cases.

V. RESULTS AND DISCUSSIONS

Soil slopes show different failure patterns with respect to their strength and drainage characteristics. But some types of failures happen only in a certain kind of soils owing to their natural behaviour. For example, surficial failure (soil face showing cracks, fissures) is typically seen in black cotton soils rather than in any other soil. Taking these points into considerations and following the above methodologies, **Table 6** has been formulated showing different ERS solutions to a given soil type.

Cohesive soils like black soils show plastic nature, high swell-shrinkage, and are determined by surficial cracks and fissures. Sudden road collapse, mass movements are mostly seen in such soil slopes. Removal of these slopes is the best method, but if not possible, pitching is suitable. Retaining walls are useful in limited cases where drainage layers are provided to avoid piping failure (internal erosion). Cut walls (flexible retaining walls) show good results for stiff clays.

Laterites have high shear strength when dried and show poor shear strength when wetted. When provided with good drainage facilities, these soils are proven to be of good performance in cut slopes. In extreme weather conditions catch walls, catch gabions and check dams are most commonly preferred earth retaining solutions.

Unlike laterites, red soils do not show decrease in shear strength upon wetting. Because of porosity, drained strength tests are conducted for shear strength calculation. Soil collapse is seen in these soils upon action of surcharge. Vegetation is the economic method of stabilizing slope. Apart from that, avoiding the soil using tunnel or bridge can be preferred. But in inevitable situations, RE walls, ground anchors, drainage holes, pitching are adopted.

Alluvial soils are a combination of non-plastic (sand) and plastic (clay) sediments carried by rivers. Hence their engineering behaviour is difficult to predict. But during heavy storms, runoff causes debris flow failure of slopes. Catch gabions, concrete gabions, check dams are techniques for these soils as they avoid erosion problems. But they are all ineffective without sufficient drainage provision. Hence, drainage works are significant in these soils.

Arid soils, being loose granular deposits, have low shear strength. Hence, route relocation and diversion will avoid failure losses. But in unavoidable situation, retaining walls with deep foundations will offer a feasible solution. Concrete Piling can also be adopted to improve soil characteristics.

Rock slopes, are good at shear strength. Hence, rock cutting and Berm or road side drains are sufficient. But at critical places where rock is jointed and unconformities are encountered, Rock bolting, Ground anchors, catch wall works are used.

VI. CONCLUSIONS

1. In-situ tests and field investigation reports determine soil type.
2. Effective Failure analysis will lead to an economically and ecologically feasible solution.
3. A fair checklist for selection of ERS is a must.
4. Though design aspects of each ERS are different, critical design criteria should never be ignored.
5. Cost estimation is done as per square meter area of finished slope surface.

Table 6

* The proposed ERS in the table are appropriate. They might alter according to the importance of structure and necessity of slope protection.

S.No.	Soil Type	Site Conditions	Earth Retaining Structure preferred	Critical Design Criteria	Critical Cost affecting elements
1	Black cotton soils	Surficial failure, cracks are seen, plastic high plasticity	Slope removal, Drainage, cut slopes, Pitching, RE walls in limited case.	Flexible Retaining walls – design flexural capacity, depth of embedment	Type of sheet material, thickness, construction methodologies alter the costs.
2	Laterites	Red in color, high dry strength, reduced strength after wetting	Avoiding by culverts, Catch gabions, check dams	Gabion wall – gradation of fill material, wire mesh reinforcement	Required density of wall and filter cloth will affect total cost.
3	Red Soils	Red in color, but granular texture, high porosity	RE walls, cut slopes, ground anchors	Ground anchoring – fixation length, free length, type of anchor	Type of anchor used will increase the cost.(helical /concrete/cross drive anchors)
4	Alluvial soils	Fragmented soil masses, sudden collapse, high moisture content	Vegetation, sub-surface drainage, construction of culverts	Horizontal drain holes – diameter of drain, depth of installation.	No fluctuation in costs in seen. Costs are due to drain hole size and depth of installation.
5	Arid soils	Loose dry sand deposits, highly porous,	Piling, Retaining walls with deep foundations	Retaining walls - dimensions of wall, reinforcement, back fill material	Cost variations are due to availability of backfill, reinforcement provided.
6	Rock slopes	Hard rock is seen, joints, fissures and unconformities are seen	Rock bolting, Rock fall catch net, soil nailing in limited case	Rock bolting – bolt length, width and diameter	Cost depend on bolt /nail dimensions and method of installation (drilled/grouted)

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