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Article

Geotechnical Characterisation and Stability Assessment of Lime-Stabilised Soils for Highway Embankments

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Abstract: Slope stability analysis is a very significant aspect in civil and geotechnical engineering. It analyses the stability of the structure and helps to prevent the embankment failure as well as the natural hill slopes, river bank etc. to protect environmental structures as well as human life and property. Stabilization of soil helps to improve deterioration and safety of embankment and finally it improves the stability of the structure. The present study is aimed at determining the behaviour of soil with addition of variable amount of admixture. The admixture that is used for improving the geotechnical properties of the soil is lime (CaO). The experimental investigation that are carried out with mixing different percentages of lime viz 3%, 5% and 7% to improve the geotechnical properties of the soil. The change in maximum dry density (MDD), optimum moisture content (OMC), CBR and shear parameters are observed with addition of admixture in various percentages through laboratory test. The stability analysis of highway embankment are evaluated with various slope using Swedish Slip Circle Method.
Keywords: Soil Stabilization, Lime, Swedish Slip Circle Method, Highway Embankment

1. INTRODUCTION

Embankment is a heap of soil mass that is placed and compacted over the existing ground surface for construction of roadway or railway. The adequate design and construction of highway embankment is important to maintain the design of vertical alignment of the road and to prevent the damage of pavement from the surface water. The performance of the road depends on the stability of underlying soil. Unstable soil can create significant problems for pavement of roads. Hence, stabilization of soil is very essential in construction of highway embankment for sustaining capability of traffic load in all-weather condition. Soil lime stabilization considered to be one of the most popular techniques to improve the properties of the clayey soil. From decades clayey soil is most amenable to treatment of lime. When lime is added to fine-grained soil, several reactions occur, some immediately and others gradually. One of the immediate reactions is Base Exchange (ion exchange). Clay particles in soil are negatively charged and typically adsorb ions such as sodium, magnesium, potassium, or hydrogen on their surfaces. The strong positively charged calcium ions from lime replace these weaker ions, resulting in a predominance of calcium ions on the clay particle surfaces. This reduces the plasticity of the soil, and the clay particles tend to agglomerate into larger particles, imparting friability to the mixture.

After the initial stage, further reactions occur between lime and the aluminous and siliceous materials present in clayey soil. In the presence of water, these materials react with lime to form hydrated calcium aluminates and calcium silicates. These are cementitious compounds that contribute to the strength of lime-stabilized soil layers. They improve resistance to frost, increase compressive strength, and enhance the California Bearing Ratio (CBR). The formation of these compounds is permanent, durable, and significantly impermeable, producing a strong and flexible structural layer.

2. MATERIALS USED

In this study, the soil samples were collected from different locations of Arunachal Pradesh (from Papumpare and Keyi Panyor district) for construction of highway embankment. Samples were collected from three locations namely Gohpur, Itanagar, Banderdewa of Papumpare district and from one location in Yachuli of Keyi Panyor district.

The soil samples were found to be low plasticity silty and clayey soils, which need to be improved and stabilized to achieve the desired properties for road embankment construction. The stabilizing agent used for improving the geotechnical properties of the soil samples is lime (CaO). Stabilizing the low plasticity silty and clayey soil with lime ensures that the soil meets the required geotechnical properties for highway embankment construction.

3. METHODOLOGY

Investigation of geotechnical properties of collected natural soil samples and the soil samples mixed with different percentages of lime i.e. 3%, 5% and 7% was carried out through laboratory tests.

The stability analyses of an embankment slope were conducted using Swedish Slip Circle Method. For analyses purpose, different upstream and downstream slopes were considered, namely 0.5:1, 1:1, 2:1, 2.5:1, 3:1 and 3.5:1. The analyses were performed for natural soil samples as well as soil samples mixed with different percentages of lime. The geotechnical properties evaluated for natural and lime-stabilized soils were used in the stability analysis.

The Swedish Slip Circle Method was applied manually for various slopes, and the minimum factor of safety (FOS) was recorded for each soil sample. The factor of safety for each soil sample mixed with different percentages of lime was evaluated. From analyses, it was observed that embankments with flatter slopes are safer and more stable when stabilized with optimum lime content.

4. RESULTS AND ANALYSIS

Grain Size Analysis Curve

Grain size distribution of the soil is performed as per IS: 2720 (Part 4) – 1985. The result shows that Gohpur soil is found to be silty fine sand. Itanagar and Banderdewa soil are found to be silty clay. Yachuli soil is classified as clay soil.

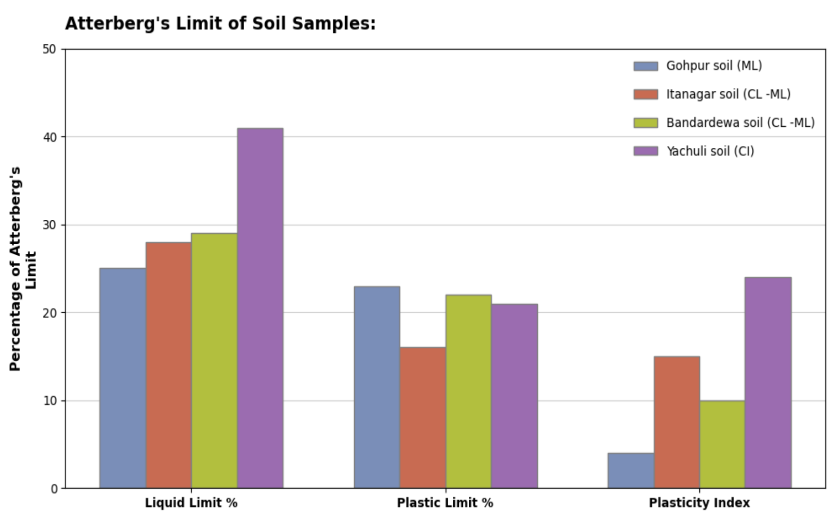

Figure 1:- Atterberg's Limit of Natural soil samples

Figure 1 shows that the liquid limit in the present study was found to be less than 50%. The plastic limit was found to be less than 30%. The plasticity index of two soils in the study was less than 10%, while the other two soils had values greater than 10%.

Effect of lime on compaction characteristics

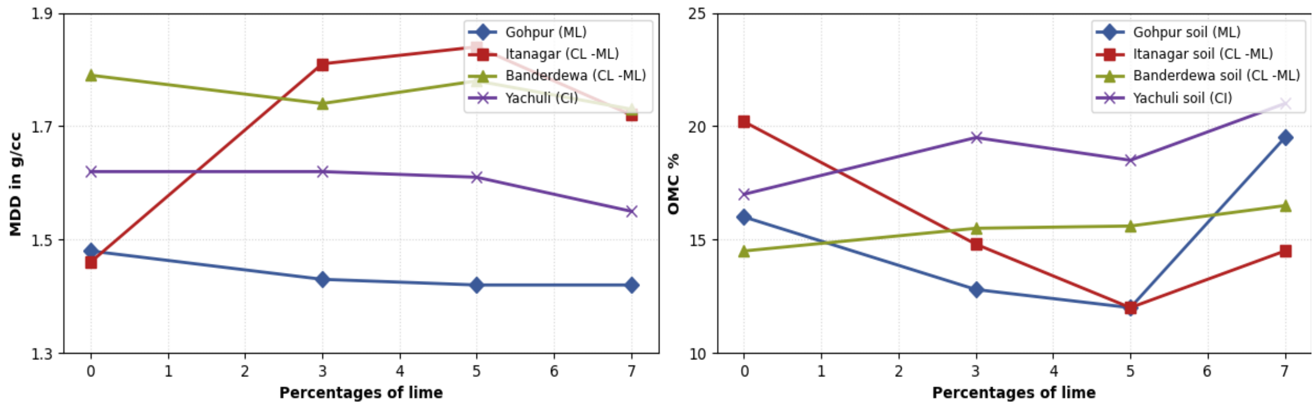

Fig 2: Comparison of OMC of soil samples with different percentages of lime

Figure 2 shows the variation of MDD and OMC of soil samples with different percentage of lime. The MDD of untreated Gohpur soil was found to be 1.489 g/cc and decreases to 1.42 g/cc. The decrement of about 4.63% occurs when 7% lime is mixed with the soil. Therefore, MDD decreases with increasing lime percentage, while OMC increases with increasing lime content in Gohpur soil.

The MDD of untreated Itanagar soil was found to be 1.47 g/cc and OMC 20.11%. With addition of 3% and 5% lime, MDD increases to 1.80 g/cc and 1.834 g/cc respectively, but decreases with 7% lime addition to the CL-ML soil. The maximum MDD is observed with 5% lime, showing an increment of about 19.80% compared to untreated soil. The OMC of the CL-ML soil decreases up to 5% lime addition and increases when 7% lime is added.

The OMC of the CL–ML soil decreases up to 5% lime addition and increases when 7% lime is added. The decrement of OMC is about 40.23%.

The MDD of untreated Banderdewa soil was found to be 1.802 g/cc and OMC 14.67%. With 3% lime addition, MDD decreases to 1.75 g/cc and OMC increases to 15.583%. At 5% lime, MDD increases to 1.778 g/cc and OMC rises to 15.75%. With 7% lime, MDD decreases again, while OMC increases to 16.68%. Therefore, with increasing lime percentage, Banderdewa soil shows decreasing MDD but increasing OMC.

The MDD and OMC of untreated Yachuli soil were found to be 1.63 g/cc and 17.093%. MDD decreases and OMC increases with increasing lime percentage up to 7%. The maximum MDD is observed in untreated soil, while the minimum MDD occurs with 7% lime. The maximum OMC is found with 7% lime, while the minimum OMC is in untreated soil. The increment of OMC from 0% to 7% is about 18.02%, and the decrement of MDD from 0% to 7% is about 4.90%.

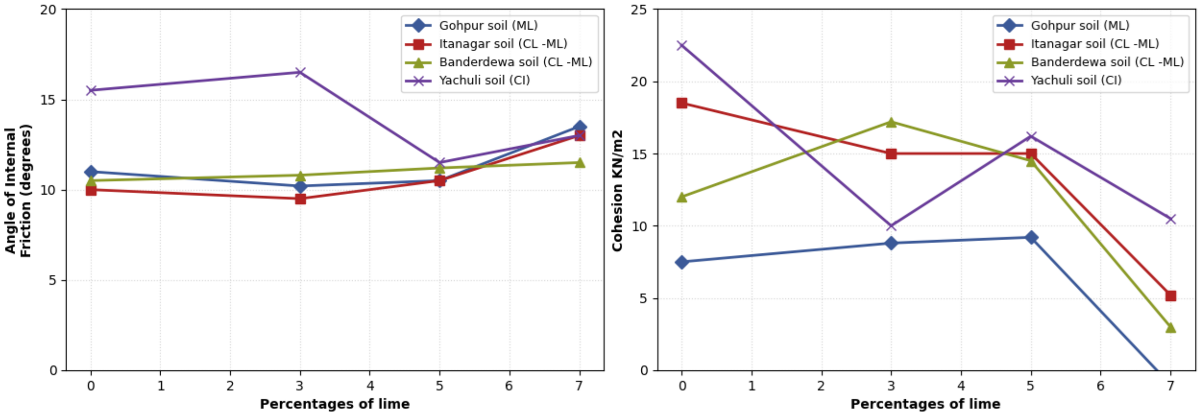

Figure 3:- Comparison of Angle of Internal friction and Cohesion of soil samples with different percentages of lime

Figure 3 shows that the angle of internal friction of Gohpur soil decreases with increasing lime content up to 5%, but increases again with the addition of 7% lime. Both Itanagar and Banderdewa soils exhibit a similar trend, with friction angle increasing as lime percentage increases. The friction angle of intermediate clayey soil rises with 3% lime, then decreases, and shows a slight increment again at 7% lime.

The cohesion value is maximum at 5% lime addition in Gohpur soil. Itanagar soil shows a decreasing trend in cohesion with increasing lime percentage. Banderdewa soil exhibits an increase in cohesion at 3% lime, followed by a decrease at higher lime contents. Intermediate clayey soil shows a reduction in cohesion at 3% lime, then an increase at 5%, and a decrease again at 7%.

Effect of lime on share parameter using direct share test

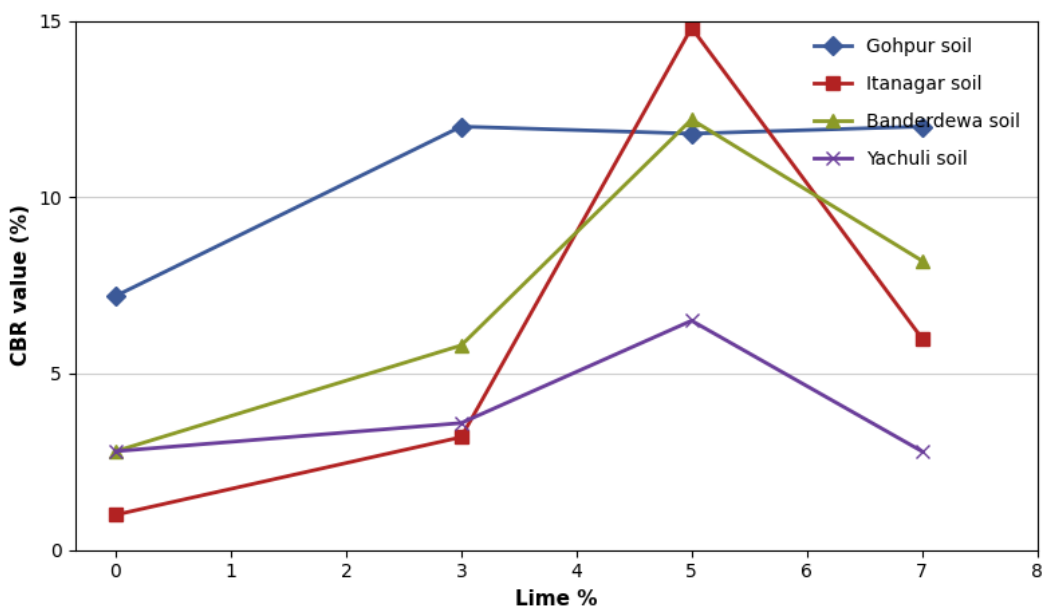

Figure 4 shows that the strength of Gohpur soil increases initially with lime addition, then decreases at higher percentages. Both Itanagar and Banderdewa soils exhibit a similar trend: strength increases up to 5% lime, followed by a decline. The CBR value of untreated Yachuli soil is 2.743%, which rises to 6.03% after the addition of 5% lime, indicating maximum strength at this level. Therefore, 5% lime addition to CI soil yields the highest strength improvement.

5. SLOPE STABILITY ANALYSIS USING SLICES METHOD

Using the Swedish Slip Circle Method, the minimum factor of safety (FOS) of highway embankments was calculated. The slope stability analysis was carried out considering different side-slopes: 0.5H: 1V, 1H: 1V, 1.5H: 1V, 2.5H: 1V, 3H: 1H, and 3.5H: 1V, for both upstream and downstream conditions. The height of the embankment was taken as 3 m for all cases.

The soil properties considered for slope stability analysis included cohesion (c, kN/m^2), angle of internal friction (ϕ, degrees), and unit weight (γ, kN/m^3), which were evaluated through laboratory experiments with varying lime percentages. The specific gravity values were found to be 2.68 for Gohpur, Itanagar, and Banderdewa soils, and 2.75 for Yachuli soil.

Table 1:- Input parameters of Itanagar soils for analysis of Highway Embankment.

Soil Sample (Location)	Percentage of admixture (Lime)	γ (kN/m^3)	γ_{sat} (kN/m^3)	C (kN/m^2)	φ (degree)
Itanagar	Soil + 0% lime	12.407	18.883	19.151	10.204
	Soil + 3% lime	20.325	20.895	16.748	10.387
	Soil + 5% lime	19.267	21.067	16.317	11.365
	Soil + 7% lime	19.267	20.354	8.153	14.560

Table 1 presents the variation in the maximum dry density, optimum moisture content, cohesion, and angle of internal friction of Itanagar soil with different lime contents. The results indicate that lime addition substantially modifies the engineering properties of the soil. The maximum dry density increases up to 5% lime, while the cohesion shows a gradual reduction beyond the initial improvement observed with lime addition. The angle of internal friction generally increases with increasing lime content, indicating improved interparticle friction and shear resistance. Overall, the results demonstrate that lime stabilisation influences both the compaction characteristics and shear strength parameters of Itanagar soil, with 3%–5% lime showing comparatively favourable improvement in the investigated properties.

6. ANALYSIS OF VARIOUS SLOPE STABILITY WITH DIFFERENT SOIL

Case I: Design of Highway Embankment with Slope 0.5:1 for Both U/s and D/s.

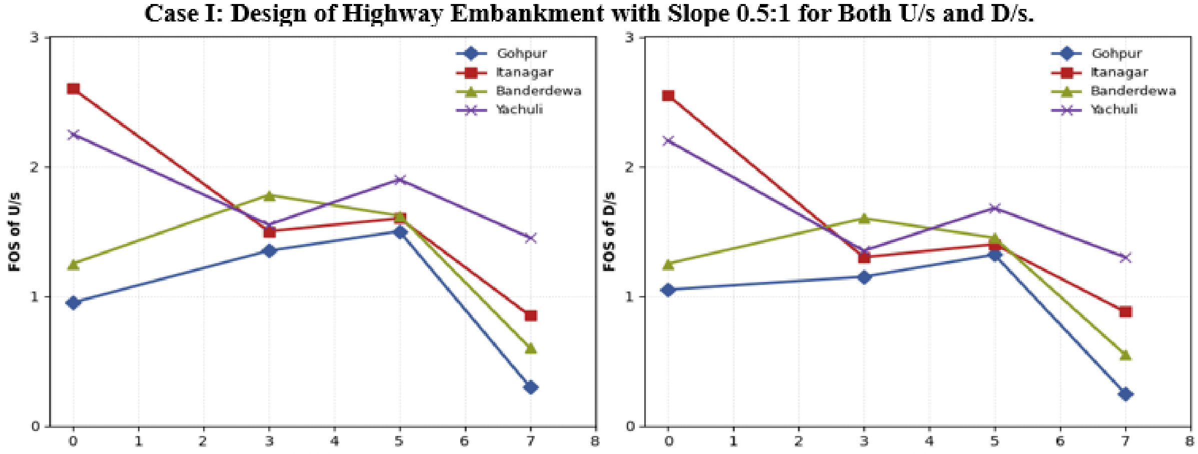

Figure 5:- Variation of FOS of an upstream slope and downstream slope 0.5:1 with addition of different percentage of lime

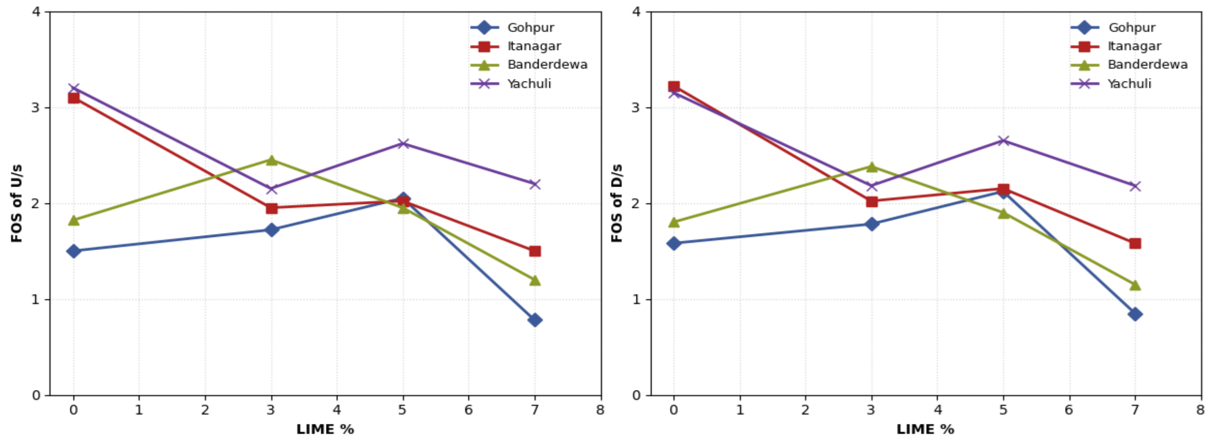

Figure 6:- Variation of FOS of an upstream slope and downstream slope 0.5:1 with addition of different percentage of lime

Case II: Design of Highway Embankment with Slope 1:1 for Both U/s and D/s

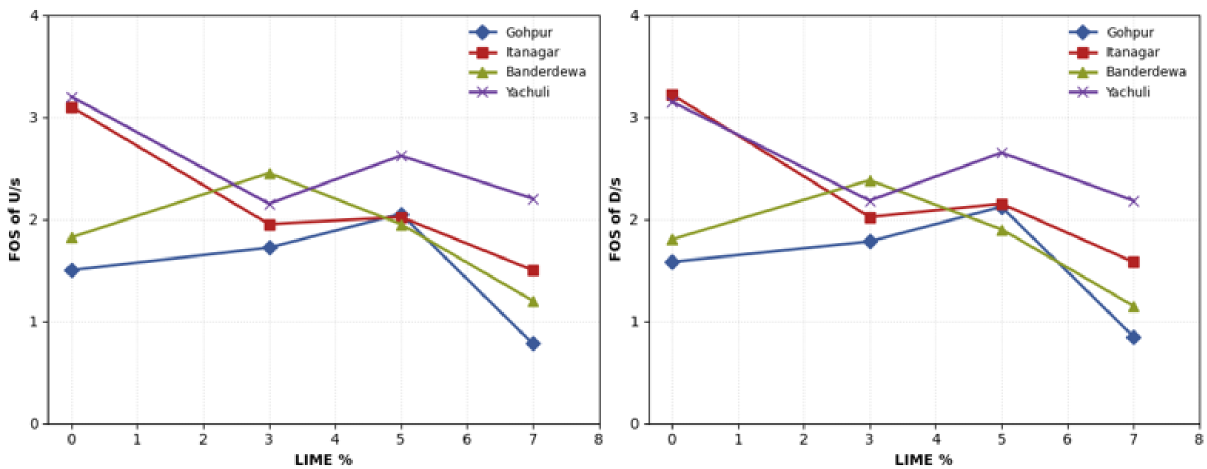

Figure 6:- Variation of FOS of a upstream and downstream slope 2:1 with addition of different percentage of lime

Case III: Design of Highway Embankment with Slope 2:1 for Both U/s and D/s.

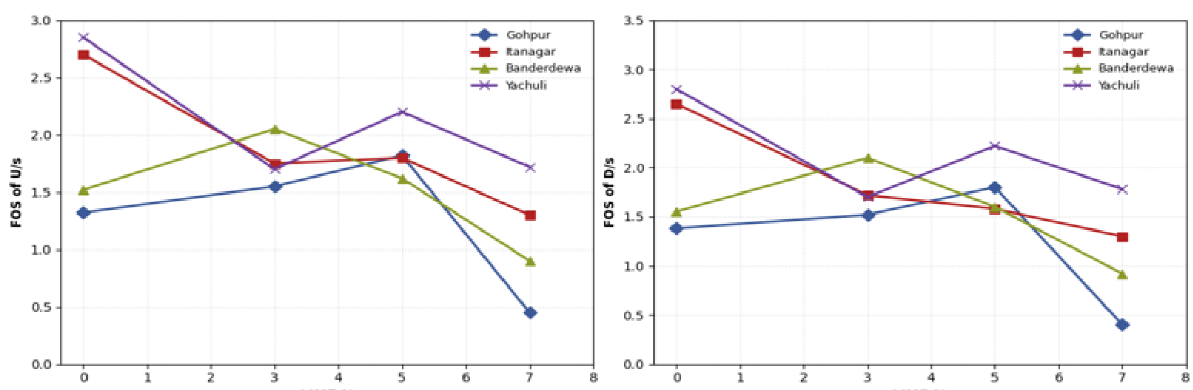

Figure 7:- Variation of FOS of upstream slope and downstream slope 1:1 with addition of different percentage of lime

Case IV: Design of Highway Embankment with Slope 2.5:1 for Both U/s and D/s.

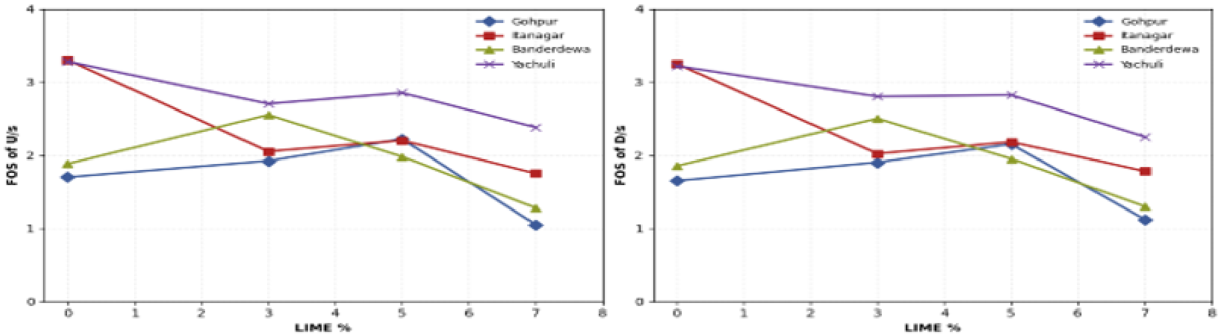

Figure 8:- Variation of FOS of a downstream slope 2.5:1 with addition of different percentage of lime

Case V: Design of Highway Embankment with Slope 3:1 for Both U/s and D/s.

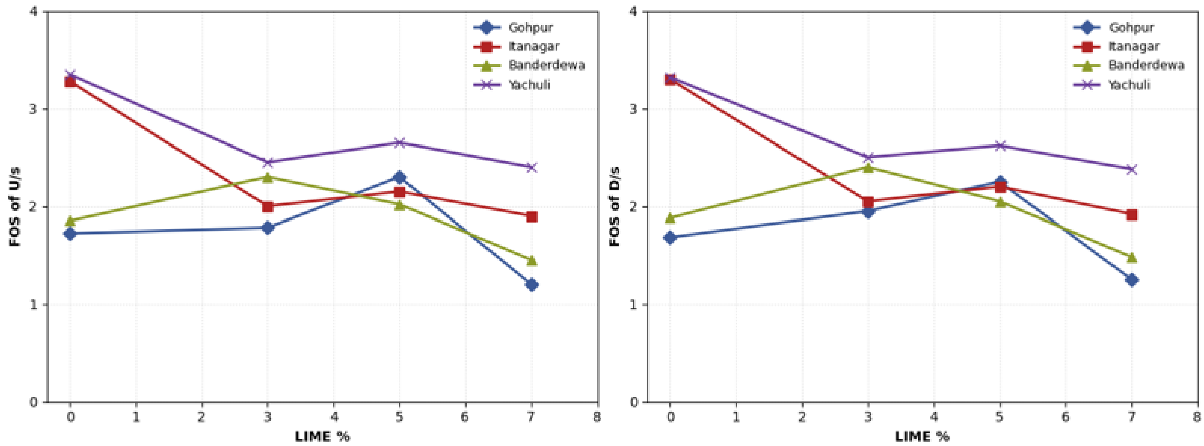

Figure 9:- Variation of FOS of a downstream slope 3:1 with the addition of different percentage of lime

Case VI: Design of Highway Embankment with Slope 3.5:1 for Both U/s and D/s.

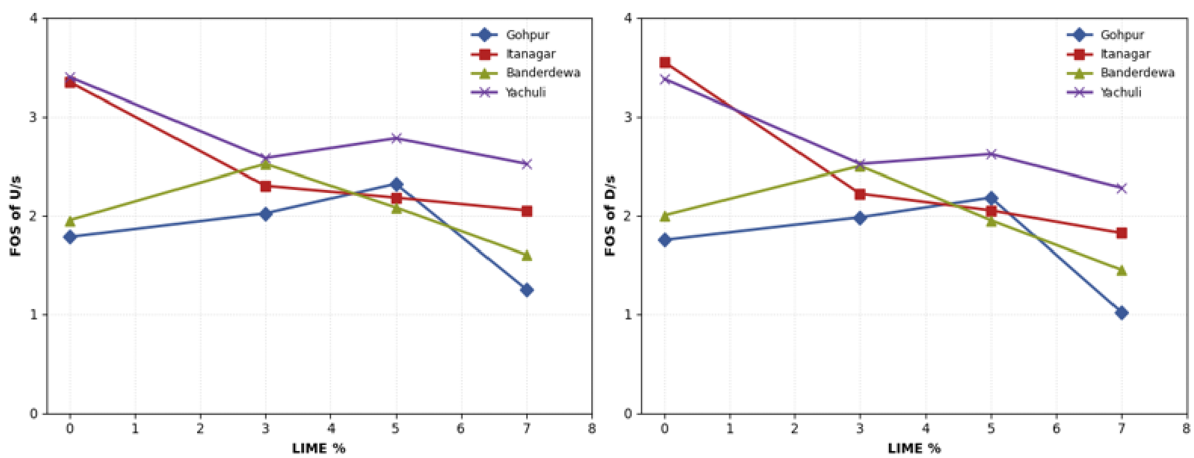

Figure 10:- Variation of FOS of a downstream slope 3.5:1 with the addition of different percentage of lime.

6. STABILITY OF FOUNDATION AGAINST SHEAR:

The height of the embankment was considered to be 3 m, and the foundation depth below the embankment was taken as about 5 m. The slope of the embankment varied from 0.5H: 1V to 3.5H: 1V. The parameters used for the stability analysis of the foundation below the embankment were evaluated from laboratory analysis.

Table 2:- Parameters for Stability Analysis of Foundation for Yachuli Soil

Soil + Percentage of Lime	Soil + 0%	Soil + 3%	Soil + 5%	Soil + 7%
$C_{embankment}$	22.68	12.143	18.40	13.207
$C_{foundation}$	5.5	5.5	5.5	5.5
$\varphi_{embankment}$	15.57	17.067	12.67	14.36
$\varphi_{foundation}$	24	24	24	24
$\gamma_{dry\ embankment}$	18.72	19.04	18.76	18.42
$\gamma_{sat\ embankment}$	19.97	19.60	19.86	19.53
$\gamma_{dry\ foundation}$	15	15	15	15
$\gamma_{sub\ foundation}$	18	18	18	18

Table 2 presents the variation in the relevant soil parameters for the natural soils and soils stabilised with 3%, 5%, and 7% lime. The results show that the measured parameters vary with lime content, indicating that lime addition modifies the engineering characteristics of the soils. The values obtained at different lime contents provide a basis for evaluating the influence of stabilisation on the strength and stability behaviour of the soils. Overall, the tabulated results indicate that moderate lime contents, particularly 3%–5%, produce favourable changes in the soil properties, while further addition to 7% does not consistently result in additional improvement.

7. COMPARISON OF FOS OF FOUNDATION AGAINST SHEAR:

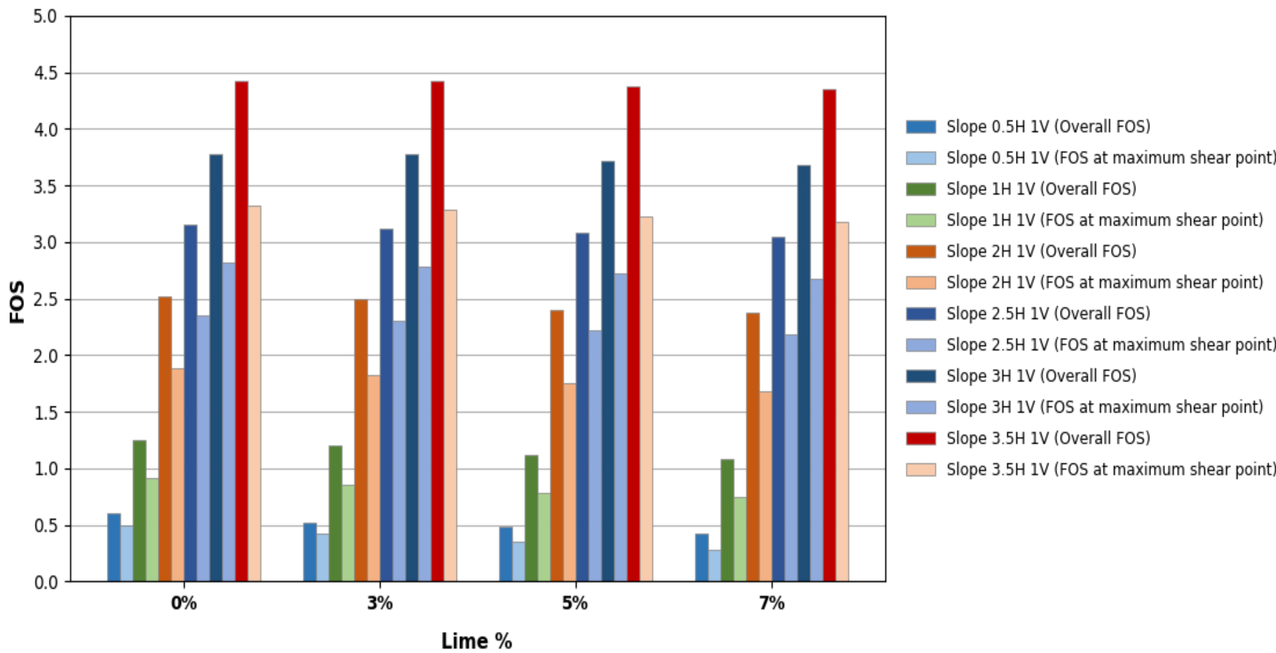

Figure 11 presents the variation in the Factor of Safety (FOS) against foundation shear failure for embankments constructed using Gohpur soil with different lime contents. The results indicate that the FOS increases with an increase in lime content, demonstrating the beneficial effect of lime stabilisation on foundation stability. The foundation remains stable for slope configurations ranging from 2H: 1V to 3.5H: 1V. Under the most critical conditions, steeper slopes do not provide adequate safety against shear failure; however, as the slope is flattened, the FOS increases and the foundation attains a stable and safe condition.

A similar trend is observed for Itanagar, Banderdewa, and Yachuli soils. For all the investigated soils, the FOS increases with increasing lime content, while satisfactory foundation stability is achieved for slope configurations ranging from 2H:1V to 3.5H:1V. These results indicate that lime stabilisation, together with an appropriate slope geometry, can effectively improve the shear stability of foundations supporting highway embankments.

8. CONCLUSION:

The results indicate that the addition of lime significantly influences the compaction and shear strength characteristics of the investigated soils. The Maximum Dry Density (MDD) of Gohpur soil (ML) decreases with increasing lime content, whereas the MDD of Itanagar and Banderdewa soils (CL–ML) increases up to 5% lime addition and subsequently shows a slight reduction at 7% lime. A similar trend is observed for Yachuli soil (CI), for which the MDD increases up to 5% lime and decreases slightly at 7%. The Optimum Moisture Content (OMC) of Gohpur and Yachuli soils increases with increasing lime content, which may be attributed to the additional water required for lime hydration and the associated chemical reactions. The finer lime particles also provide a greater surface area for interaction with water and soil particles, thereby increasing the moisture requirement. In terms of shear strength parameters, the cohesion of Gohpur soil increases up to 5% lime addition, beyond which the soil exhibits predominantly cohesionless behaviour. For Itanagar and Banderdewa soils, cohesion increases up to 5% lime and shows a slight reduction at 7%. This improvement in cohesion can be attributed to cation exchange and the subsequent flocculation and agglomeration of clay particles. The calcium ions supplied by lime replace weaker exchangeable cations such as sodium, magnesium and potassium on the clay particle surfaces, resulting in coagulation of the clay particles and the development of a more stable and aggregated soil structure. The angle of internal friction also increases with lime content, primarily due to the modification of soil fabric and improved interparticle interaction resulting from particle flocculation and agglomeration. Consequently, lime stabilisation improves the load-bearing capacity of the soil. The reaction of the siliceous and aluminous constituents of the soil with lime in the presence of water produces cementitious compounds, particularly calcium silicate hydrates and calcium aluminate hydrates, which contribute to increased strength, improved CBR and enhanced durability of the stabilised soil.

The slope and foundation stability analyses further demonstrate the beneficial effect of lime stabilisation. The Factor of Safety (FOS), evaluated using the Swedish Slip Circle Method, increases with lime content up to 5% and also increases with flattening of the slope from 0.5H:1V to 3.5H:1V. Similarly, the FOS against foundation shear failure improves with increasing lime content and remains comparatively higher for flatter slope configurations, particularly within the range of 2H:1V to 3.5H:1V. Based on the combined laboratory and stability analysis results, the use of 3%–5% lime is considered suitable for improving the engineering performance of the investigated natural soils for embankment construction. The stabilised soils are found to be suitable for embankment slopes of 2.5H:1V, 3H:1V and 3.5H:1V. The results further indicate that relatively flatter highway embankment slopes provide a higher Factor of Safety and, consequently, a more reliable and stable embankment configuration. Thus, an appropriate combination of lime stabilisation and slope geometry can effectively enhance the strength and stability of highway embankments constructed using the investigated soils.

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