Load-Settlement Behaviour of Prestressed Reinforced Soft Soil Foundations of Embankments

Jayamohan J[1], Anciya Fazal R[2] and Soorya S. R.[3]

[1] Professor, LBS Institute of Technology for Women, Trivandrum, Kerala, India
[2] Mtech Student, Marian Engineering College, Trivandrum, Kerala, India
[3] Assistant Professor, Marian Engineering College, Trivandrum, Kerala, India

Abstract. The stability of embankments supported on soft clay foundation is a complex problem. To improve the stability of embankment and its foundation, the most feasible option is to reinforce the locally available soil with suitable geosynthetics since granular soil is now very scarce and costly. The effectiveness of geosynthetic reinforcement embedded in cohesive soil is very less due to build-up of pore water pressure, creep and less interaction with soil. More over geosynthetics demonstrate their beneficial effects only after considerable settlements, since the strains occurring during initial settlements are not sufficient to generate significant tensile stress in the reinforcement. Prestressing the geosynthetic and encapsulating it in a thin granular soil layer is a promising technique to reduce the requirement of granular soil and to increase the load bearing capacity without the occurrence of large settlements. This paper investigates the beneficial effects of prestressing the geosynthetic and encapsulating it in a thin layer of granular soil when used to reinforce a soft soil foundation of an embankment. A series of Finite element analyses are carried out using the FE software PLAXIS 2D, and its results are validated by comparing them with those obtained from laboratory scale load tests. It is observed that the load-settlement behaviour can be considerably improved by reinforcing the soft clay foundation with prestressed geosynthetic encapsulated in a thin layer of granular soil. The improvement is significantly influenced by the magnitude of prestress in the geosynthetic reinforcement.

Keywords: Embankment foundation; Geosynthetic Reinforcement; Prestress; Finite Element Analyses

1 Introduction

Highways and Railways are essential components of development and are vital for the economic growth of the country. The construction of embankments over soft, compressible ground is increasing due to lack of suitable land for infrastructure and other developments. When constructing an embankment over very soft subsoil of low shear strength and high compressibility, the engineering tasks are to ensure stability of the embankment against possible slope failure and to control the subsoil deformation or settlement to within allowable limits. The design of high embankments on very soft soil normally requires the assessment of the following problems: bearing capacity failure, global slope failure, local instability, excessive lateral displacement, and intolerable total and/or differential settlements. Embankments need to be constructed using compacted good quality soil to provide adequate support to the formation and a long-term level surface with stability. But in many sites, the soil available locally will be soft and compressible, resulting in failure or large total and / or differential settlements. An embankment collapse can be disastrous causing serious loss of life, money and time. Reconstructing collapsed embankments can be very costly and from a purely economic standpoint, it would be more beneficial to reinforce the embankment or embankment foundation so that it does not fail rather than reconstruct. Nowadays advances in technology in material science have produced geosynthetic materials for usage in various aspects of civil engineering.

It is well established that a geosynthetic reinforced granular beds effectively reduces settlement and increases the bearing capacity of weak soil. However, these benefits have often been limited due to the scarcity of good-quality granular soil [3]. Buildup of pore water pressure, lesser frictional strength and higher creep potential are the main concerns expressed about the use of cohesive soils in soil reinforcement. The improvement due to Reinforced soil is derived from the stress transfer between soil and reinforcement at the interface. In case of the clayey soils, the interfacial strength between the soil and the reinforcement is low which causes failure at the interface before the full strength of reinforcement can be mobilized [1]. Thus, strength of reinforcement will be underutilized due to early failure of the interface. Hence from an economical point of view, locally available soil should be reinforced. If the locally available soil is clay, it can be reinforced by embedding geosynthetic encapsulated in thin layer of granular soil [1, 2]. But, Geosynthetics are extensible materials and will require some elongation to mobilize sufficient tensile stress in it [4]. The strains occurring during initial settlements are insufficient to mobilize significant tensile load in the geosynthetic and hence the improvement in bearing capacity will occur only after considerable settlements. This is not desirable, since excessive settlements will cause distress to the embankment. Thus there is a need for a technique which will improve the load bearing capacity without the occurrence of excessive settlement of reinforced granular soil. One promising technique is prestressing the geosynthetic layer and encapsulating it in a thin layer of sand when used as reinforcement. The sand will act as a drainage layer and will assist in the dissipation of pore water pressure. It was found that the addition of prestress to reinforcement resulted in significant improvement in the load bearing capacity and reduction in settlement of foundation [5].

The purpose of this paper is to investigate the possibility of reinforcing the embankment having soft soil foundation with multiple layers of geogrid. The improvement due to encapsulating the multiple layer geogrid in thin layer of sand is also studied. The beneficial effects of prestressing the geosynthetic and encapsulating it in a thin layer of granular soil when used to reinforce a soft soil foundation of an embankment is also investigated. A series of Finite element analyses using the FE software *PLAXIS 2D* are carried out to study the improvement in load-deformation behaviour. The results of finite element analyses are compared with those obtained from Laboratory scale load tests for validation. The parameters varied are the number of geogrid layers and encapsulated geogrid layers and magnitude of prestress in foundation reinforcement. It is observed that the load settlement behavior of lateritic soil embankment can be improved considerably by reinforcing with geogrid encapsulated in thin layer of sand and the load settlement behavior of embankment foundation can be improved considerably by reinforcing the embankment with prestressed geogrid encapsulated in thin layer of sand.

2. Laboratory Scale Load Tests

The laboratory scale load tests are carried out in a combined test bed and loading frame assembly. The details of materials used and experimental setup are presented below

2.1 Materials Used

Locally available clay is used for the soft soil foundation; Lateritic soil for embankment and sand for encapsulating the geosynthetic in this investigation. Biaxial Geogrid is used as reinforcement in foundation and embankment and Woven Geotextile is used as Basal reinforcement. The properties of clay, sand and geogrid are presented in tables 1, 2 and 3 respectively. The properties of lateritic soil and geotextile are presented in tables 4 and 5 respectively.

Table 1 Properties of Clay

Properties	Value
Specific Gravity	2.63
Optimum Moisture Content (%)	18
Dry Unit Weight (kN/m^3)	15.61
Liquid Limit (%)	58
Plastic Limit (%)	22
Plasticity Index	36
IS Classification	CH
Friction angle (ϕ °)	5
Cohesion (KPa)	25

Table 2 Properties of Sand

Properties	Value
Specific Gravity	2.65
Friction angle (ϕ °)	31.2
Cohesion (kPa)	0
Effective Grain Size D10 (mm)	0.13
D60 (mm)	0.90
D30 (mm)	0.34
Coefficient of Uniformity C_u	6.92
Coefficient of Curvature C_c	1.00

Permeability (m/sec)	$1.07x10^{-4}$
IS Classification	SW

Table 3 Properties of Geogrid

Property	**Value**
Tensile Strength (kN/m)	30
Aperture Size (mm)	26x20
Mass per Unit Area (g/m^2)	225
Colour	Black
Type	Biaxial

Table 4 Properties of Lateritic Soil

Properties	**Value**
Specific Gravity	2.6
Optimum Moisture Content (%)	15.5
Dry Unit Weight (kN/m^3)	18.83
Liquid Limit (%)	49
Plastic Limit (%)	36.34
Plasticity Index	12.66
Friction angle (ϕ °)	32
Cohesion (KPa)	13
Percentage of gravel (%)	3.07
Percentage of coarse sand (%)	16.93
Percentage of medium sand (%)	49
Percentage of fine sand (%)	16.27
Percentage of silt and clay (%)	4.73
D_{60} (mm)	1
D_{30} (mm)	0.425
Uniformity Coefficient (C_u)	6.67
Coefficient of Curvature (C_c)	1.204
IS Classification	SW

Table 5 Properties of Geotextile

Property	**Value**
Colour	White
Type	Woven
Tensile Strength (kN/m)	67.95
Aperture Size (mm)	0.150
Mass per Unit Area (g/m^2)	243
Puncture Strength (N)	905

2.2 Experimental Setup

The load tests are carried out in a test bed and loading frame assembly. The test beds are prepared in a tank which is designed considering the size of the model embankment and its zone of influence. The dimensions of the test tank are 1000 mm length x 750 mm width x 750 mm depth. An inverted Tee Beam of flange width 100 mm is used to apply the strip load. The web of the Tee Beam is stiffened using MS angle sections. The loading tests are carried out in a loading frame fabricated with ISMB 300. The load is applied using a hand operated- mechanical jack of capacity 50kN. The applied load is measured using a proving ring of capacity 100kN. The settlement of the embankment is measured using two dial gauges kept diametrically opposite to each other. The details of the test set up is shown in Fig. 1.

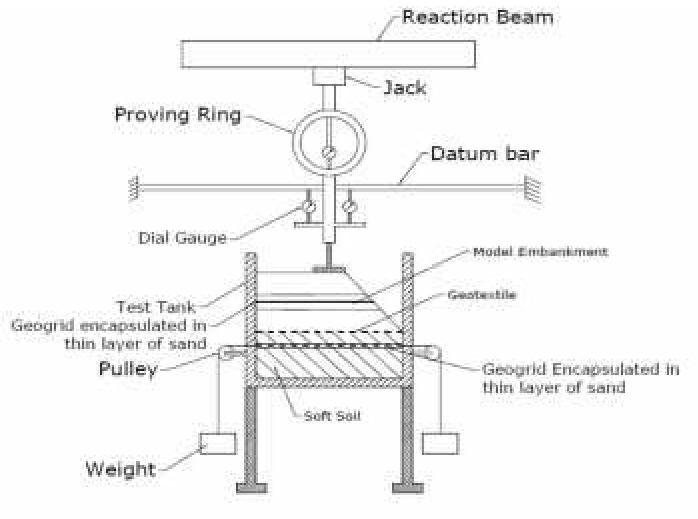

Fig. 1. Test Setup

3. Finite element Analyses

In the present study the laboratory model is analysed numerically by carrying out Finite Element analyses using the commercially available finite element software *PLAXIS* 2D. For simulating the behaviour of soil, different constitutive models are available in the FE software. In this study, Mohr-Coulomb model with drained condition is used to simulate the soil behaviour as it is the simplest model which is based on the basic soil parameters that can be obtained from direct shear tests; cohesion intercept and internal friction angle. Since an embankment foundation is simulated, a plain strain model is adopted in the analyses.

The displacement of the bottom boundary is restricted in all directions, while at the vertical sides; displacement is restricted only in the horizontal direction. The initial geostatic stress states for the analyses are set according to the unit weight of soil. The soil is modelled using 15 noded triangular elements. Mesh generation can be done automatically. Medium mesh size is adopted in all the simulations. The reinforcement is modelled using the 5-noded tension element available in the software. To simulate the interaction between the reinforcement and surrounding soil, an interface element is provided on both upper and lower surface of reinforcement. The interaction between soil and reinforcement is simulated by choosing an appropriate value for strength reduction factor R_{inter} at the interface. The interface shear parameters between the geogrid and sand is determined by carrying out large scale direct shear tests using a shear box of size 300 x 300 x 200 mm. The value of R_{inter} determined from shear tests is 0.81. The soil is modeled using 15-node triangular elements.
In Finite Element Analyses, Embankment is modeled with top width 1.2 m, Base width 2m, side slope 1:2 and height 0.2 m. Basal reinforcement of woven geotextile is provided at the interface between embankment and the foundation. Geogrid reinforcement encapsulated in thin layer of sand is provided at a depth of 0.05B from the bottom of embankment, where B is base width of embankment. The thickness of thin layer of sand encapsulating the geogrid is 0.02B. Prestress is modeled as a horizontal uniformly distributed load applied to the geogrid. In this analysis a staged construction procedure is adopted to simulate the various construction stages. At first the excavation for embankment foundation is modeled. Then sand up to the base of geogrid is modeled. Then the geogrid is modeled and prestress is applied. In the subsequent stages, sand above geogrid, clay, basal reinforcement and embankment with encapsulated 2 layer geogrid are modeled. Analyses of the geometric models are carried out in the output module of the program. Analyses are carried out for a prestress of 0%, 1%, 2% and 3% of the tensile strength of geogrid.

4. Results and Discussions

A series of laboratory scale model tests are carried out on unreinforced embankments resting on unreinforced foundations, Reinforced embankments resting on unreinforced foundation, Reinforced embankments resting on reinforced foundations and reinforced embankments resting on prestressed encapsulated geosynthetic reinforced foundations. The experimental results obtained from the laboratory scale load tests are validated by carrying out Finite Element analyses and comparing the results. The effects of magnitude of prestress in the reinforcement, effect of encapsulation of reinforcement and effect of number of layers of reinforcement in the embankment are presented. The results are presented in terms of non-dimensional parameter namely, Improvement Factor.

4.1 Influence of Reinforcing the Embankment

Fig 2 presents the variation of Vertical stress versus Normalized settlement (S/b, where S is the settlement and b is half the base width of embankment) curves for Unreinforced Embankment resting on unreinforced Foundation and various cases of Reinforced Embankment resting on Unreinforced Foundation from experimental studies and FEA. It is observed that the improvement in load settlement behaviour is maximum for the embankment with 3 layer geogrid and basal reinforcement. Strength of the embankment improves with the number of geogrid layers. At 0.5% normalized settlement the stress taken by the embankment with three layers of reinforcement is almost 200% of that taken by an unreinforced embankment.

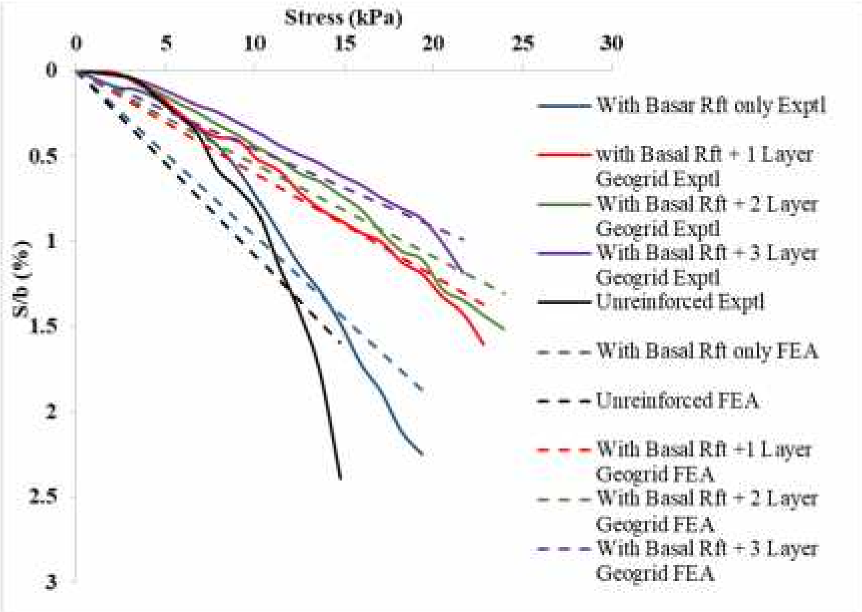

Fig. 2. Vertical stress v/s Normalized Settlement Curves for reinforced embankments resting on unreinforced foundation from laboratory scale load tests and FEA

4.2 Influence of Reinforcing the Embankment with Encapsulated Geosynthetic

The variation of Vertical stress versus Normalized settlement curves for various cases of Embankment reinforced with geogrid and encapsulated geogrid resting on Unreinforced Foundation from experimental studies and FEA are presented in Figure 3. It is observed that the improvement in load settlement behaviour is maximum when the embankment is reinforced with triple layer geogrid encapsulated in a thin layer of sand. The thickness of sand layer is 0.01B, where B is the base width of embankment. Strength of the embankment improves with the number of geogrid layers. At 0.5% settlement, when the embankment is reinforced with 3 layers of geogrid the improvement is observed to be 90% and when it is reinforced with 3 layers of encapsulated geogrid the improvement is almost 200%. It is seen that the results obtained from Finite Element Analyses are almost linear and the experimental results are non-linear.

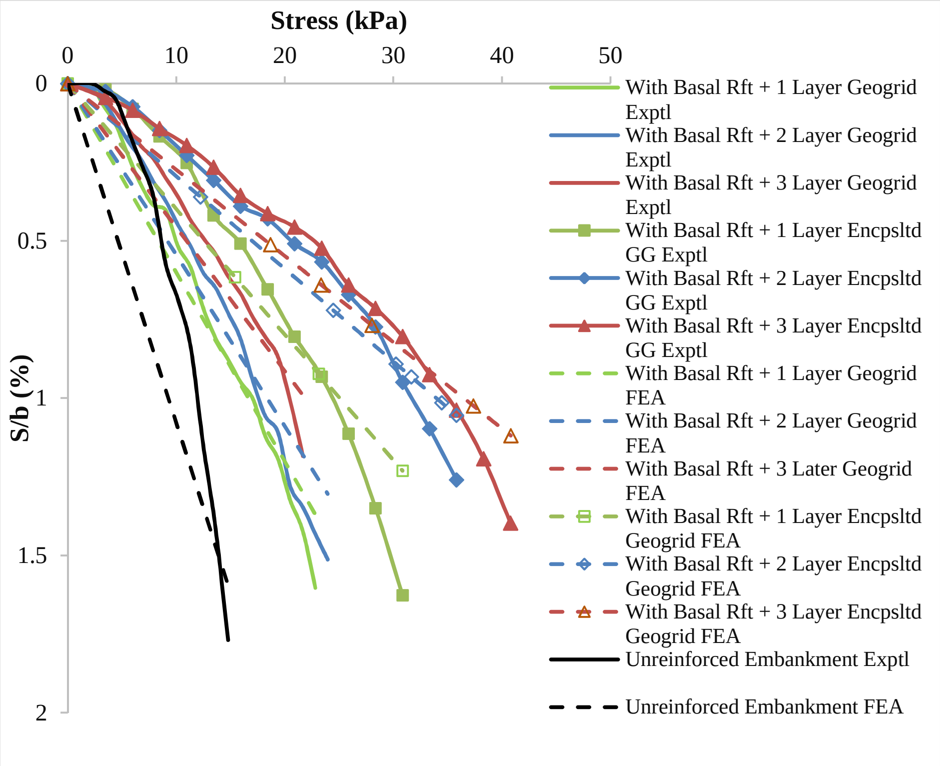

Fig. 3. Vertical stress v/s Normalized Settlement Curves for various cases of Reinforced Embankment resting on unreinforced foundation

4.3 Influence of Reinforcing the Foundation with Encapsulated Geosynthetic

Figure 4 represents the variation of Vertical stress versus Normalized settlement curves for various cases of Reinforced Embankment resting on Reinforced Foundation from experimental studies and FEA. It is observed that the improvement in load settlement behaviour is maximum for the reinforced embankment resting on the foundation reinforced with encapsulated geogrid. The thickness of encapsulated sand layer is 0.01B, where B is the base width of embankment.

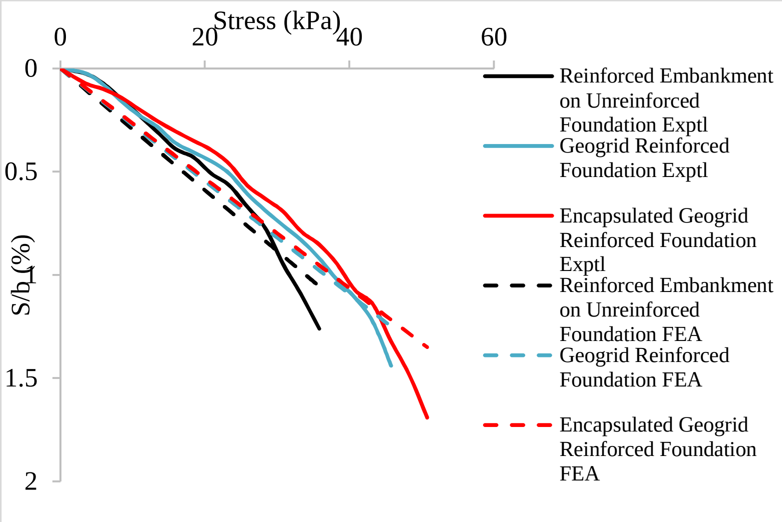

Fig. 4. Vertical stress v/s Normalized Settlement Curves for various cases of Reinforced Embankment resting on Reinforced Foundation

4.4 Influence of Reinforcing the Embankment Foundation with Prestressed Encapsulated Geosynthetic

Figure 5 presents the variation of Vertical stress versus Normalized settlement curves for various cases of Reinforced Embankment resting on Foundation reinforced with prestressed encapsulated geogrid from experimental studies and FEA. It is observed that the load – settlement behaviour considerably improves with application of prestress. At 0.5% settlement the foundation reinforced with encapsulated geogrid shows an improvement of almost 200%. When it is reinforced with 2% prestressed encapsulated geogrid the improvement is observed to be almost 300%. Maximum improvement is attained when the magnitude of prestress is 2%. Further increase in magnitude of prestress is not beneficial.

The improvement in bearing capacity of reinforced soil is influenced by the mobilized tensile force of reinforcement and the stress transfer between reinforcement and the surrounding soil. Even though increase in prestress improves the mobilized tensile force in the reinforcement, it adversely affects the stress transfer between reinforcement and surrounding soil. Hence bearing capacity initially increases with increase in prestress and later reduces when the prestress increases beyond a particular value. It is in agreement with Jayamohan et al.(2016).

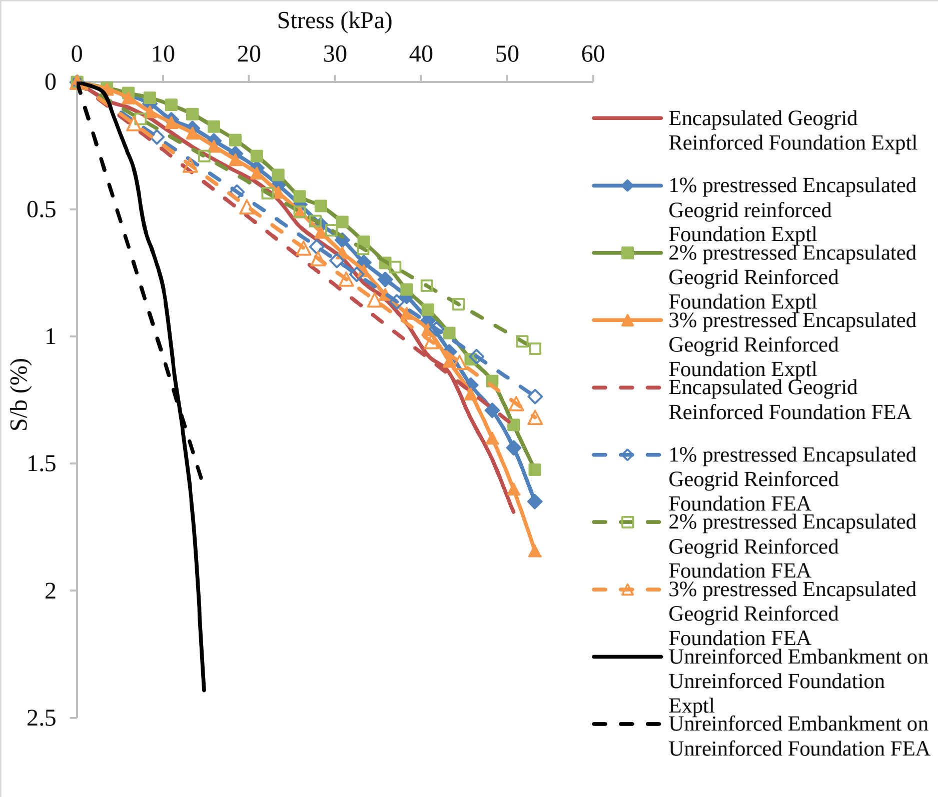

Fig. 5. Vertical stress v/s Normalized Settlement Curves for various cases of Reinforced Embankment resting on Foundation reinforced with encapsulated prestressed geogrid

4.5 Improvement Factor

To quantify the improvement in load-settlement behaviour due to various factors, an Improvement factor is defined as the ratio of stress at 0.5% settlement of reinforced embankment to that of unreinforced embankment resting on unreinforced foundation at the same settlement.

Figure 6 presents the variation of improvement factor with different number of layers of geogrid for different cases of embankment with and without encapsulation. It is observed that the improvement Factor increases with the number of layers of geogrid within the embankment. It is further improved with the encapsulation of geogrid in a thin layer of sand. A slight difference is observed between the experimental and numerical results.

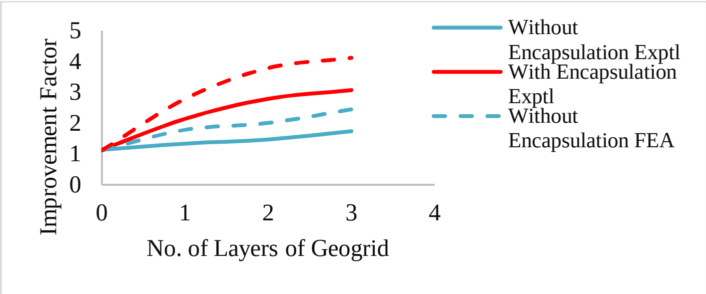

Fig. 6. Variation of Improvement Factor with number of layers of geogrid with and without encapsulation

The variation of improvement factor with magnitude of prestress is presented in Figure 7. It is clear from the figure that the improvement Factor increases with the application of prestress. Maximum improvement is attained when the magnitude of prestress is 2%. Further increase in magnitude of prestress is not beneficial. A slight difference is observed between the experimental and numerical results.

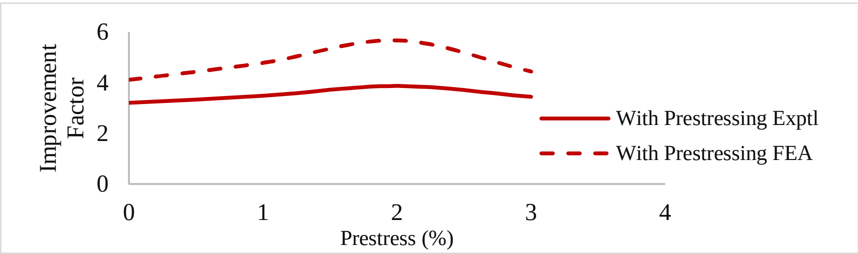

Fig. 7. Variation of Improvement Factor with prestress

5. Conclusions

Based on the results obtained from experimental studies and finite element analyses, the following conclusions can be made on the behavior of prestressed reinforced soft soil foundations of embankments.

- The load-settlement behaviour considerably improves with the number of reinfocement layers in the embankment.
- Reinforcing the soft cay foundation with Geosynthetic encapsulated in a thin layer of sand considerably improves the load-settlement behaviour
- Improvement can be further enhanced by prestressing the geosynthetic
- Improvement Factor is significantly influenced by the magnitude of prestress

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