Heliyon 5 (2019) e02473

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.heliyon.com

Numerical analysis of lime stabilized capping under embankments based on expansive subgrades

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ARTICLE INFO

Keywords:
Civil engineering
Geotechnical engineering
Ground improvement
Soil engineering
Construction engineering
Finite element analysis
Expansive soil subgrade
Embankment for flexible pavement
Black cotton soil
Lime stabilized capping

ABSTRACT

This paper investigates the efficacy of an alternative construction methodology proposed by the authors in the form of a 'C'-shaped lime stabilized capping. It is used for confining expansive clay subgrade soil under embankments carrying flexible pavement at their top, to enhance their performance. The role of capping in controlling moisture ingress responsible for swelling is assessed by studying vertical displacements and suctions in expansive subgrade soils. The load-displacement behavior and the variations in suctions of expansive subgrade soil are studied by using Mohr-Coulomb material model and Van Genuchten Hydraulic Model respectively in FEM based Software PLAXIS 3D. It is observed from the results that; the swelling displacements are considerably reduced and suctions under embankment toe are observed to increase. It can therefore be concluded that, the lime stabilized capping consisting of horizontal buffer layer and vertical cut-offs is effective in controlling swelling displacements in expansive subgrades.

1. Introduction

As the embankments based on expansive clay subgrade are subjected to distress due to swell-shrink cycles caused by the seasonal moisture variations, current practices suggest solutions such as partial removal and replacement of such subgrade soil or stabilization. Due to the complex behavior of such expansive soils in the presence of moisture, with varying void ratios and under embankment loads, closed form analytical solutions for estimation of displacements are difficult. Therefore, numerical methods like Finite Difference Method (FDM) and, Finite Element Method (FEM) have been used to find the effect of moisture ingress through unsaturated expansive soils, suction and the corresponding volume changes.

Wray et al. [1] have presented a three-dimensional moisture diffusion and volume change model 'Suction Heave' by using FORTRAN computer program SUCH. They have used Mitchell's equation to represent the movement of water through unsaturated expansive soil and FDM to measure the vertical volume change. Hamdhan and Schweiger [2] compared the results of pore water pressure obtained from FEM and those measured using tensiometers in the field for 11 m high cut slopes in three regions of China. It was observed that, the pore water pressures increased (that is, suction decreased) until the end of first period of rainfall and pore water pressures decreased again during no-rain period. Khan et al. [3] evaluated the effect of rainfall and dry and wet cycle on shallow slope failure based on expansive clay in Texas. The test results obtained from laboratory are used for Finite Element Analysis (FEA) with PLAXIS 2D. They observed that, the combination of reduction in shear strength in fully softened condition and excess pore water pressures, due to the formation of perched water zone near crest, results in slope failure a few years after its construction. Chen and Bulut [4] have presented the concept of horizontal moisture barrier to control the moisture ingress under the base of embankment which is the major factor governing swelling of expansive subgrade. They have analyzed the system with the assumption that, moisture diffusion in expansive soils is similar to heat diffusion and they observed that, for same amount of time, suction increases with diffusion coefficient. Likitlersuang et al. [5] have simulated a railway embankment carrying high-speed train founded on soft clays by numerical modelling using PLAXIS 2D. They observed that current conditions of subgrade result in large displacements and, therefore, suggested cement stabilization of soil for reducing displacements and increasing the stability of embankment. In another study Likitlersuang et al. [6] studied strength and stiffness parameters by using the two material models available in PLAXIS 3D namely, Mohr-Coulomb Model (MCM) and Hardening Soil Model (HSM). They observed that, the

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https://doi.org/10.1016/j.heliyon.2019.e02473
Received 16 May 2019; Received in revised form 22 August 2019; Accepted 10 September 2019

Bangkok clays are simulated better with HSM. Por et al. [7] studied the effect of cement stabilization on the mixtures of Na-Montmorillonite and non-expansive Bangkok clay in different proportions. They observed that, cement stabilization improved the strength and stiffness characteristics and reduced the swelling and shrinkage strain. In another study, Por et al. [8] developed the correlations between index properties and other properties and tested against data from previous studies. They observed that, a large proportion of non-swelling clay is required to be added to expansive clay for its significant strength increase. However, the addition of non-swelling clay in even a small percentage to expansive clay can reduce the plasticity considerably.

As we go through the available literature, it is noticed that, the researchers have investigated various aspects using FEM based software like PLAXIS or Abaqus with the main aim of studying the pore pressures and displacements for load deformation analysis. Many of the researchers have used the Mohr-Coulomb Model, some have used Soft Soil Model [9] and some have used Hardening Soil Model [5, 6] for simulating expansive soils. The main reason for swelling of expansive soils is the moisture ingress and swelling pressure goes on increasing as the moisture approaches Optimum Moisture Content (OMC) of soil at a density of soil equal to Maximum Dry Density (MDD) [10]. Many researchers have tried a variety of solutions including removal and replacement of expansive clay subgrade by Cohesive Non-Swelling (CNS) material [11] for controlling the volume changes occurring due to swell-shrink cycle in these expansive clay subgrade soils. However, use of CNS has additional procurement cost and also gives rise to problems like disposal of expansive soils. Also, some investigators have observed that, the CNS is not effective after the first swell-shrink cycle [12]. Therefore, lime is, comparatively more effective compared to other stabilizers. However, lime stabilization of expansive subgrades to complete depth of active zone up to 1–1.5 m of expansive soils is uneconomical.

The present study, therefore, attempts to assess the effect of 'C'-shaped lime stabilized capping provided under the base of embankment on swelling displacements. This capping consists of a horizontal lime stabilized buffer layer and the vertical cut-offs provided at either end of buffer layer. The buffer layer projects 2 m beyond the toes of embankment on either side and is provided between embankment base and expansive subgrade soil. Due to lime stabilization and curing provided thereafter, this buffer layer increases in its modulus as compared to untreated expansive subgrade. This layer is therefore, assessed for its role in reducing vertical displacements by providing an even and stiffer layer under the base of embankment. This projected buffer layer is also expected to have its role in controlling moisture ingress in vertical direction from the projected parts. This 'C'-shaped capping of lime stabilized expansive soil consisting of buffer layer together with vertical cut-offs will control moisture ingress thereby reducing the swelling displacements. PLAXIS 3D is used in the present study to simulate the physical model and analyze the behavior for beneficial effects.

2. Materials & methods

2.1. Expansive soil

Expansive Black Cotton soil deposits are observed in many regions of India. Ahmednagar situated in Central Maharashtra, India, predominantly consists of expansive Black Cotton (B.C.) soil, where distress is observed in pavements founded on these soils. Therefore, samples were collected from the three locations near Ahmednagar named as location A, B and C. The expansive soil was observed up to a depth of 1 m and the properties of soil were observed to change at a depth of about 0.5 m. Therefore, soil samples were collected at 0.5 m and 1 m. These depths are named as depth 1 and depth 2 respectively. Therefore, corresponding soil samples at these locations and depths are A-1, A-2, B-1, B-2 C-1 and C-2.

The Liquid Limit (LL), Plastic Limit (PL), Shrinkage Limit (SL) and Plasticity Index (PI) were found in stabilized and unstabilized states. The swelling properties, namely, Free Swell Index (FSI), Swelling Pressure (SP), and Swelling Strain (SS) in vertical direction obtained in earlier studies carried by the authors [10] for both unstabilized and stabilized states. The optimum percentage of lime as seen from these studies was 5 %. These properties are presented in Table 1. It can be observed from the index and swelling properties of soil reported in Table 1 that, all the soils have liquid limit more than 60 % and the plasticity index around or more than 40 %. The authors observed in their earlier studies [10] that, the swelling pressures in unstabilized states reduce at OMC+2 % as compared to their magnitudes at OMC. Therefore, as the soils are to be compacted in the field corresponding to moisture of OMC+2 %, the swelling pressures in case of lime stabilized soil at 5 % lime are evaluated by molding the samples in consolidometer at the moisture content of OMC+2 %. These magnitudes are reported in Table 1. It is observed from results in Table 1 that, the soil C-2 is most swelling in nature having swelling pressure magnitudes at OMC equal to 245.17 kN/m^2. Therefore, the present analysis is done for location 'C'.

2.2. Stabilizing material

Quick lime powder was used for stabilization of the expansive soil. Researchers in the past have used a variety of stabilizing materials including cement, fly ash, and geosynthetics. However, cost of cement is comparatively high and the manufacturing process of cement is not environment friendly. In India, the fly ash is no more free of cost and if the project site is far away from the thermal plants from where fly ash is obtained, then it adds to cost of transportation. The stabilization occurs because of lime in fly ash otherwise fly ash in itself is an inert material. The class 'C' fly ash contains lime (CaO) up to 60 %–65 % whereas the percentage of lime (CaO) in class 'F' fly ash mainly available in India, is 5–10 %. Therefore the high percentage (up to 15 %–20 %) of fly ash required for stabilization [13], further adds to the cost of a project. On the other hand, lime can be easily blended in percentages from 3 % to 7 % with expansive soil by using usually available equipment on site like grader, Rotavators, etc. Therefore, in this study, lime is considered as stabilizing material.

2.3. Constitutive models for numerical analysis

FEM based software PLAXIS 3D was used for Finite Element Analysis. Mohr-Coulomb Model is used for simulating expansive soil. In actual field conditions, it may be noted that the water table level is well below

Table 1
Index and swelling properties of subgrade soils in unstabilized and lime stabilized states (at 5 % lime) (Anaokar and Mhaiskar [10]).

Properties	Soil A-1	Soil A-2	Soil B-1	Soil B-2	Soil C-1	Soil C-2
IS Soil Classification	CH	CH	CH	CH	CH	CH
AASHTO Classification	A-7-5	A-7-5	A-7-6	A-7-6	A-7-6	A-7-6
LL Unstabilized (%)	99	78	66	71	93	89
LL Stabilized (%)	58	78	55	59	75	80
PI Unstabilized (%)	63	44	38	45	66	63
PI Stabilized (%)	23	35	22	21	33	43
SL Unstabilized (%)	18	23	20	21	11	12
SL Stabilized (%)	57	52	49	41	58	65
FSI Unstabilized (%)	188	66	111	90	138	180
FSI Stabilized (%)	125	83	80	82	110	100
SP at OMC Unstabilized (kN/m^2)	176.52	68.65	137.29	88.26	156.91	245.17
SP at OMC+2% Unstabilized (kN/m^2)	73.55	31.38	16.67	6.37	13.73	29.42
SP at OMC+2% Stabilized (kN/m^2)	58.84	21.57	0	0	9.81	15.69

the expansive soil layers to cause any swelling strain. Therefore, to simulate the field conditions of wet expansive soil occurring due to precipitation, properties of these soils corresponding to wet conditions are applied. Positive volumetric strains in positive 'Z' direction are applied through the Selection Explorer section of the software PLAXIS 3D. Application of volume strain is necessary, as Mohr-Coulomb Model does not account for swelling. The magnitude of volume strain causing swelling is obtained from laboratory swelling test using consolidometer. The authors suggest the use of locally available expansive soil for lime stabilized buffer layer, which can then be cured after stabilization for 45 days to get the sufficient strength. The geometry of the model is shown in Fig. 1. The 'C' shaped lime stabilized capping consists of horizontal buffer layer to be provided between embankment base and expansive subgrade projecting 2 m beyond embankment toes on either side. This buffer layer between embankment base and expansive subgrade is expected to resist the strains generated due to volume change caused by swelling of expansive subgrade.

This layer will also provide a relatively stiff and level surface under the base of embankment, thereby reducing the distress at surface caused by displacements in subgrade. The vertical cut-offs will be provided below the buffer layer projecting 2 m beyond the toe at either end of the layer, thereby forming the 'C'-shaped capping. This capping will control moisture ingress in the expansive subgrade below the embankment base and will reduce swelling. Therefore, the depth of cut-offs is varied in the analysis to assess its effect. Hardening Soil Model is used for Sandy Murom underlying the expansive soil as well as to represent the material of pavement embankment. Ground Water Levels and related saturation conditions are simulated by Van-Genuchten hydraulic model in PLAXIS. The properties of input parameters for Mohr Coulomb Model simulating unstabilized and stabilized Expansive Soils are presented in Table 2.

In the Table 2, The meanings of the terms and symbols used for properties of soils are as follows: -

Dry (U) C-1 = Unstabilized Soil C-1 in Summer at S.L., Dry (U) C-2 = Unstabilized Soil C-1 in Summer at S.L; OMC (U) C-1 = Unstabilized Soil C-1 in Monsoon at OMC; OMC (U) C-2 = Unstabilized Soil C-2 in Monsoon at OMC; Natural (U) C-1 = Unstabilized Soil C-1 under capping zone at void ratio = 1; Natural (U) C-2 = Unstabilized Soil C-2 under capping zone at void ratio = 1; OMC+2 (LS) C-1 = Lime Stabilized Soil C-1 at OMC+2%;

γ_b = Bulk density; c = cohesion; ϕ = angle of friction; ψ = Angle of Dilatancy; E = Young's Modulus; E_{OED} = Oedometer Modulus; G = Shear Modulus; ν = Poisson's ratio.

Unconfined Compressive Strength (UCS) values for the soils mentioned in Table 2 are presented in Table 3.

Tests were performed on soil samples in unstabilized and in lime stabilized states with curing periods of 0, 3, 7, 14, 28, 45 and 90 days. After molding the samples were sealed in air and water tight polythene bags and wrapped with moist cloth to maintain the humidity surrounding the bags in order to prevent the moisture loss. It was observed that, the UCS values of stabilized soils were more than 5 times after 45 days and 10 times after 90 days compared to unstabilized state. However, to keep the work on hold for 90 days for curing may not be practicable. Due to this reason, curing of 45 days is considered and corresponding strength is presented above.

The properties of components of models used as an input parameter are presented in Table 2. The modulus is estimated from Thompson's equation [14] giving correlation between UCS (psi) and Elastic Modulus (ksi). The UCS obtained in laboratory in units of kg/cm^2 is converted to psi and the modulus 'E' obtained in ksi as per the original equation is then again converted to kN/m^2. The same correlation used for both unstabilized and stabilized expansive soils is presented below in SI units: -

$$E(\text{kN/ m}^2) = 68810 + 124\ (\text{UCS, kN/ m}^2) \tag{1}$$

In Table 2, bulk unit weights (γ_b) are based on the field densities obtained by using core cutter method. Modulus of Elasticity is obtained from Thompson's Equation (Eq. (1)) based on UCS values of soils. Other Moduli are calculated by PLAXIS on entering the 'E' values. Volume strains in Table 2 for expansive soils are estimated from the laboratory consolidation tests. In this test the samples are allowed to swell under seating load of 5 kN/m^2 and increase in thickness of the sample due to swelling is recorded. The ratio of this increase in thickness of sample to original thickness expressed as a percentage is swelling strain. The values of swelling strain obtained are expressed as volumetric strain for the respective expansive soil. Embankment and Sandy Murom are simulated using Hardening Soil Model. Typical values are considered for the parameters for Hardening Soil Model.

3. Methodology

3.1. *Methodology for constructing lime stabilized 'C'-shaped capping*

The authors suggest that the capping should be constructed well before monsoon say at least two months before monsoon when the expansive subgrade is in its shrinkage phase of swell-shrink cycle. Considering the above construction methodology, two different states of model are considered for numerical analysis. One is when the embankment rests directly on expansive subgrade without any capping. This state is called as unstabilized state of model and is referred as Unstabilized Road Model (URM). The other state is when the 'C'-shaped capping is provided under the pavement embankment. This state is called as stabilized state and the model is referred as Stabilized Road Model (SRM). In this dry state, properties of soil namely unsaturated and saturated densities, volumetric strain, permeability, modulus and void ratio which is also a function of swelling pressure are taken corresponding to Shrinkage Limit (S.L.) of the expansive soil as input parameters in PLAXIS. After the start of monsoon, the moisture in the soil due to infiltrating rain water goes on increasing and the process of swelling starts with increase in void ratio. The most crucial state will

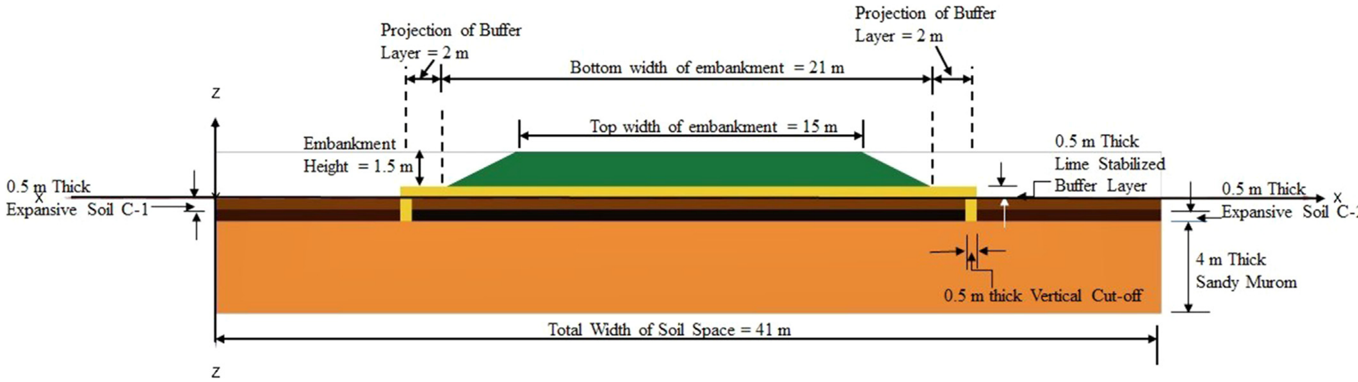

Fig. 1. Geometry of the model.

Table 2
Mohr-Coulomb model properties.

Layer and soil details	γ_b (kN/m^3)	C (kN/m^2)	Φ (Degrees)	Ψ (Degrees)	E (kN/m^2)	E_{OED} (kN/m^2)	G (kN/m^2)	ν (ratio)	Volume strain representing swelling strain (%)	Type of analysis
Dry (U) C-1	19.82	44.89	6	0	7.994×10^4	1.076×10^5	3.075×10^4	0.3	5.63	Undrained 'A'
Dry (U) C-2	19.82	47.60	6	0	8.061×10^4	1.085×10^5	3.101×10^4	0.3	1.91	Undrained 'A'
OMC (U) C-1	20.01	47.07	6	0	8.048×10^4	1.083×10^5	3.096×10^4	0.3	3.23	Undrained 'A'
OMC (U) C-2	19.91	52.96	7	0	8.194×10^4	1.103×10^5	3.151×10^4	0.3	1.81	Undrained 'A'
Natural (U) C-1	18.64	33.89	5	0	7.721×10^4	1.039×10^5	2.970×10^4	0.3	0.16	Undrained 'A'
Natural (U) C-2	18.15	33.89	5	0	7.721×10^4	1.039×10^5	2.970×10^4	0.3	0.10	Undrained 'A'
OMC+2 (LS) C-1	19.52	258.41	7	0	1.329×10^5	1.789×10^5	5.111×10^4	0.3	0.08	Undrained 'A'

arrive if the void ratio becomes equal to that corresponding to MDD and moisture content will reach a value equal to OMC if rain falls continuously for a long duration. Because at this situation swelling pressures have maximum magnitude [10]. To simulate this crucial state during monsoon, properties of expansive soils are applied which correspond to this crucial state that is corresponding to density and moisture content equal to MDD and OMC respectively. Therefore, for unstabilized expansive subgrade soil, apart from densities, volumetric strain representing swelling, void ratio, permeability and modulus of expansive soils corresponding to OMC and MDD are considered in monsoon phase. As the lime stabilized capping material will be compacted to MDD and OMC+2%, all the corresponding properties mentioned above are applied to this lime stabilized expansive soil used in capping.

3.2. Basis for numerical modelling

In stabilized state, the horizontal lime stabilized layer in 'C'-shaped capping will act as buffer layer between expansive subgrade soil and base of embankment and vertical cut-offs below buffer layer are provided at its either end for controlling the moisture ingress in expansive subgrade below embankment during monsoon. In the two types of models namely unstabilized and stabilized models, two layers of expansive soils C-1 (from G.L. to 0.5 m depth below it) and C-2 (from 0.5 m depth to 1.0 m depth below G.L.) are simulated with properties corresponding to S.L. to represent summer phase. To simulate monsoon phase, the two expansive subgrade soils C-1 and C-2 are assigned properties corresponding to MDD and OMC. Two Ground Water Conditions have been simulated in the numerical analysis viz, dry or summer conditions with water table at -12 m and wet or monsoon condition with water table at -3m as per known field data. Outside capping zone maximum swelling pressure would be attained at MDD and OMC causing maximum swelling. This state of swelling outside capping zone is simulated by applying positive volume strain in expansive soils C-1 and C-2 as well as in lime stabilized expansive soil used in capping.

3.3. Boundary conditions

In the present work, a near 2-D analysis has been implemented by considering 1 m length of embankment rather than Plane-strain approximation. There are two types of boundary conditions in PLAXIS. Boundary conditions for displacements and boundary conditions for ground water flow. As the vertically upward swelling displacements are intended to be assessed, the boundary conditions specified for displacements are as follows (Fig. 2): -

X_{min} = Horizontally fixed, X_{max} = Horizontally fixed, Y_{min} = Horizontally fixed, Y_{max} = Horizontally fixed, Z_{min} = Vertically fixed, and Z_{max} = Free

Along Y_{min} and Y_{max} directions the boundary conditions for moisture movements are considered as 'Closed' All other boundaries, that is, X_{min}, X_{max}, Z_{min}, and Z_{max} are considered as 'Open' to moisture movements.

4. Results and discussion

The main objective of this study is to assess the effect of the lime stabilized 'C'-shaped capping on swelling displacement and suctions in expansive soils. Therefore, the results of swelling displacements and suctions are compared between unstabilized model and stabilized models by considering the different types of stabilized models and values are compared at specific nodes. The nodes and the stress points considered at level of center of each subgrade soil layer. Nodes are considered outside embankment on either side at X = 5 m and X = 36 m, that is, 5 m away from toe of embankment on either side. The nodes are also considered under both the toes that is at X = 10 m and X = 31 m and at mid-point of soil medium under the embankment, that is, at 20.5 from either end of soil medium (Fig. 3).

4.1. Effect of volumetric strain in representing swelling of expansive soil

The role of volume strain feature in PLAXIS was studied to assess its effect in simulating swelling.

It can be observed from Fig. 4a and b that, at both 0.25 m and 0.75 m depths when volume strain is not applied displacements are almost same in magnitude in URM and SRM.

On the contrary, it can be observed from Fig. 4c and Fig. 4d that displacements differ at 0.25 m and 0.75 m depth respectively and they are observed to reduce in SRM compared to URM when volume strain is applied.

Similarly, if volume strain is not applied, there is no difference in suctions in unstabilized and stabilized models at depths 0.25 m (Fig. 5a). However, at this depth when volumetric strain is applied (Fig. 5c) then

Table 3
UCS (kN/m^2) after 45 days of curing for different types of soils used in model.

Layer and soil details	Dry (U) C-1	Dry (U) C-2	OMC (U) C-1	OMC (U) C-2	Natural (U) C-1	Natural (U) C-2	OMC+2 (LS) C-1
UCS (kN/m^2)	89.78	95.20	94.14	105.91	67.78	67.78	516.81

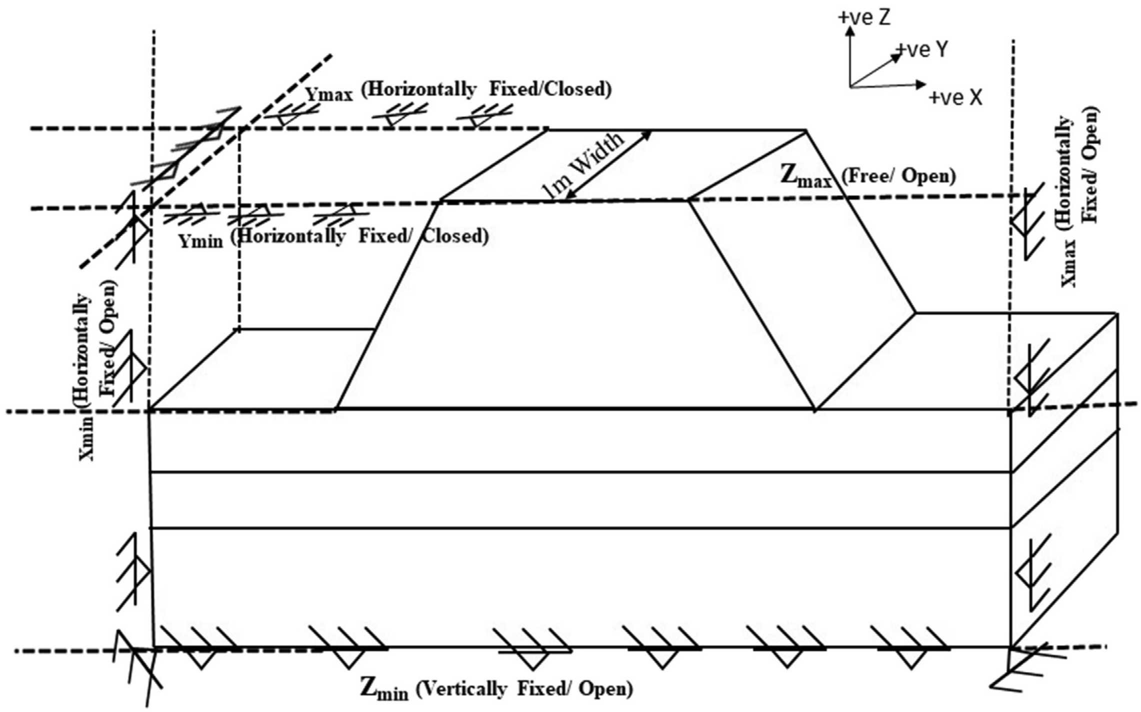

Fig. 2. Boundary conditions.

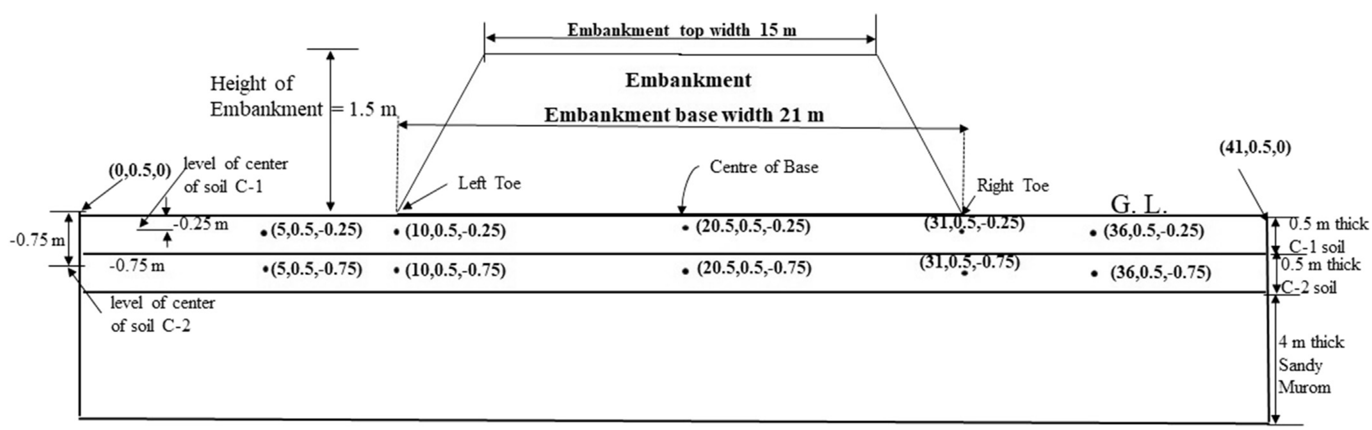

Fig. 3. Coordinates of nodes for value of swelling displacements and suctions.

suction is seen to increase under the toes in capping zone. Similar behavior is observed when suctions are compared at 0.75 depth (Fig. 5b and Fig. 5d). This indicates that, volume strain feature needs to be applied to simulate the swelling.

4.2. Effect of buffer layer on swelling displacements and suctions

For studying the effect of horizontal buffer layer, two cases were compared. Fig. 6a shows the comparison between URM and SRM results for swelling displacements at 0.25 m depth from G.L. when buffer layer is **absent** and **only** vertical cut-offs are provided under the toe of embankment. Fig. 6b shows the comparison between URM and SRM results for displacements at 0.25 m depth when the buffer layer and the cut-off are both present. Fig. 6c and Fig. 6d show similar comparisons for displacements at 0.75 m depth.

The results indicate that, in the absence of buffer layer (Fig. 6a), if only vertical cut-off is provided under the toe then there are negative displacements or settlements of small magnitude (refer displacements in SRM series). These settlements are observed at both 0.25 m depth (in soil C-1) (Fig. 6a) and at 0.75 m depth (in soil C-2) (Fig. 6c). This may be due to the reason that, under the overburden of embankment, the compressible clay subgrade is settling in the absence of buffer layer. However, in the presence of buffer layers due to its increased stiffness, buffer layer provides cushioning effect immediately under the embankment and neither swelling nor settlement is observed at depth 0.25 m (Fig. 6b, SRM series). Similar behavior is observed at 0.75 m depth.

Fig. 7a shows the comparison of suction results between URM and SRM at 0.25 m depth when buffer layer is **absent** and **only** vertical cut off of 1 m depth is provided under the toe of embankment. Fig. 7b shows this comparison when buffer layer is provided along with vertical cut-offs. Similar results are observed at 0.75 m depth as indicated by Fig. 7c and Fig. 7d. It can be observed from SRM series in Fig. 7a and c that, when buffer layer is absent, the suctions are reducing as compared to URM series indicating increase in saturation in the capping zone. Whereas, if results of SRM series in Fig. 7b and Fig. 7d are compared, when buffer layer is present the suctions are increasing indicating reduction in saturation in capping zone. Whereas, under the toe of embankment suctions are observed to increase when buffer layer is

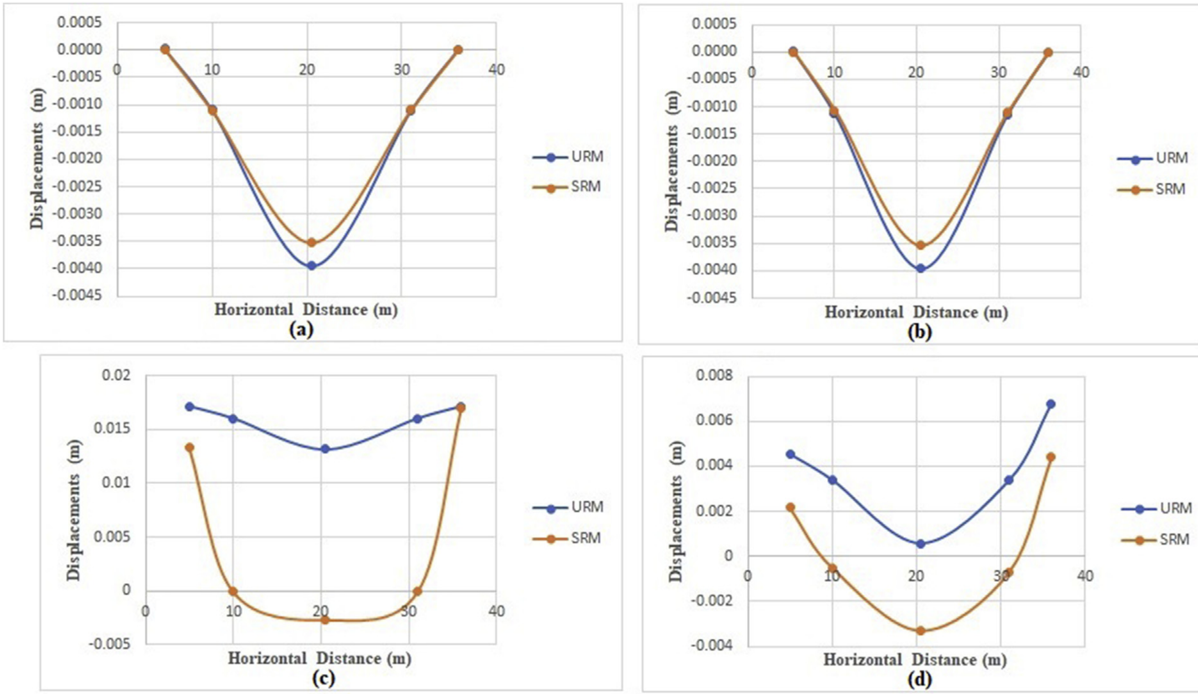

Fig. 4. Effect of volumetric strain on displacements. (a) at depth 0.25 m without volumetric strain (b) at depth 0.75 m without volumetric strain (c) at depth 0.25 m with volumetric strain (d) at depth 0.75 m with volumetric strain.

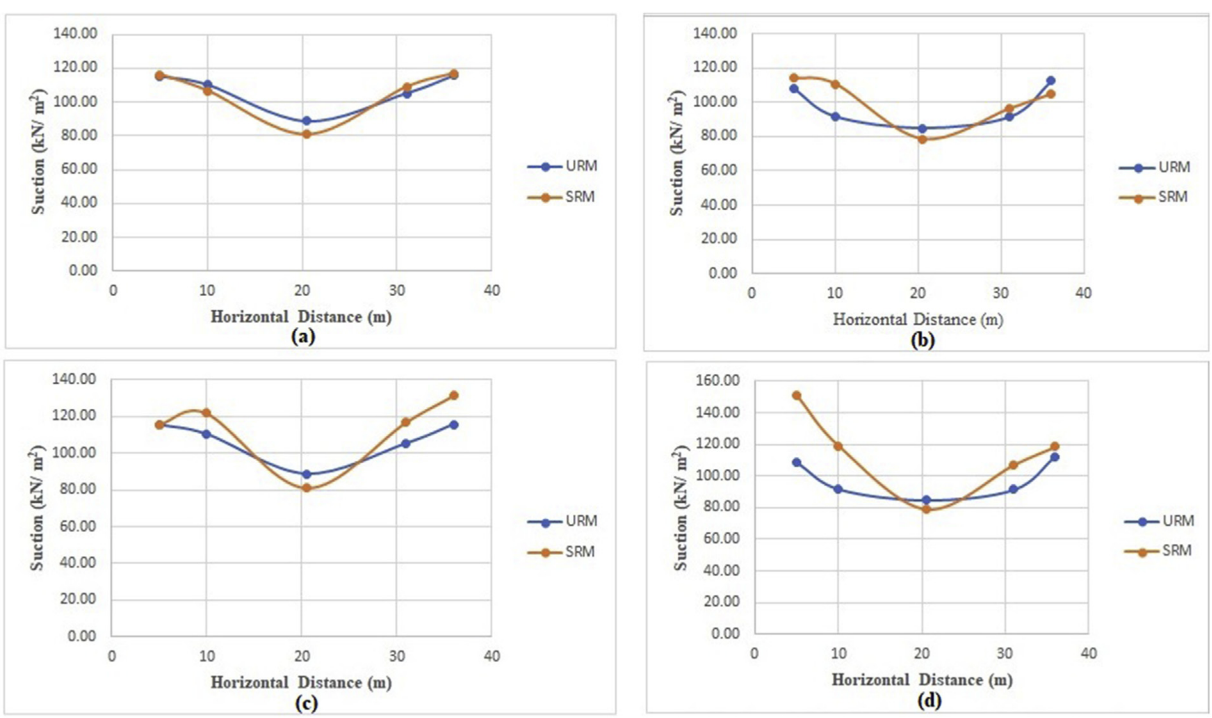

Fig. 5. Effect of volumetric strain on suctions. (a) at depth 0.25 m without volumetric strain (b) at depth 0.75 m without volumetric strain (c) at depth 0.25 m with volumetric strain (d) at depth 0.75 m with volumetric strain.

provided along with vertical cut-offs. Therefore, for restraining the entry of moisture within the enclosed capping zone, it is expedient to use the buffer layer.

4.3. *Effect of vertical cut-offs on swelling displacements and suctions*

The results showing effect of vertical cut-off on swelling displacements are shown in Fig. 8 and the results showing effect of cut-off on suctions are shown in Fig. 9. Fig. 8a shows the results of vertical displacements at 0.25 m depth (in soil C-1) for different cases of vertical cut-off. There are three such cases of SRM. In first case, **only** buffer layer is provided **without** vertical cut-off. In second case vertical cut offs are provided **up to 0.5 m depth** and in third case the cut-offs are considered **up to 1 m depth**, that is up to the bottom of second expansive soil layer.

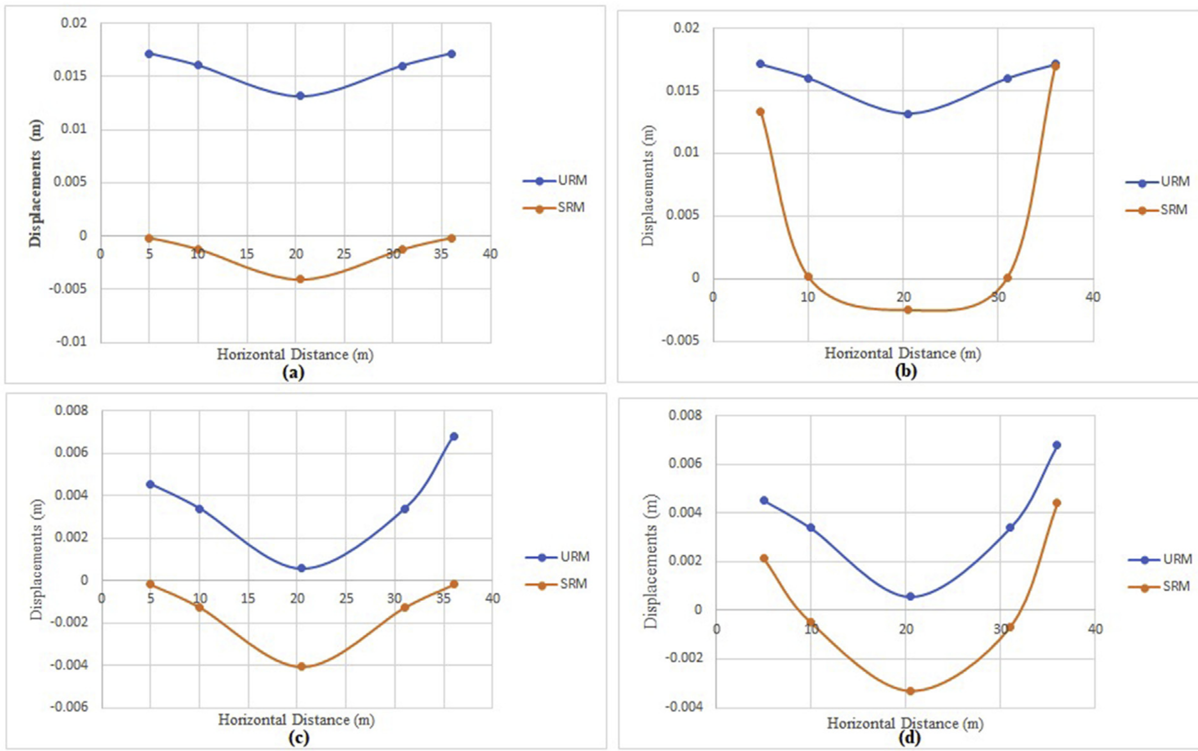

Fig. 6. Effect of buffer layer on displacements. (a) at 0.25 m depth without buffer (b) at 0.25 m depth with buffer (c) at 0.75 m depth without buffer (d) at 0.75 m depth with buffer.

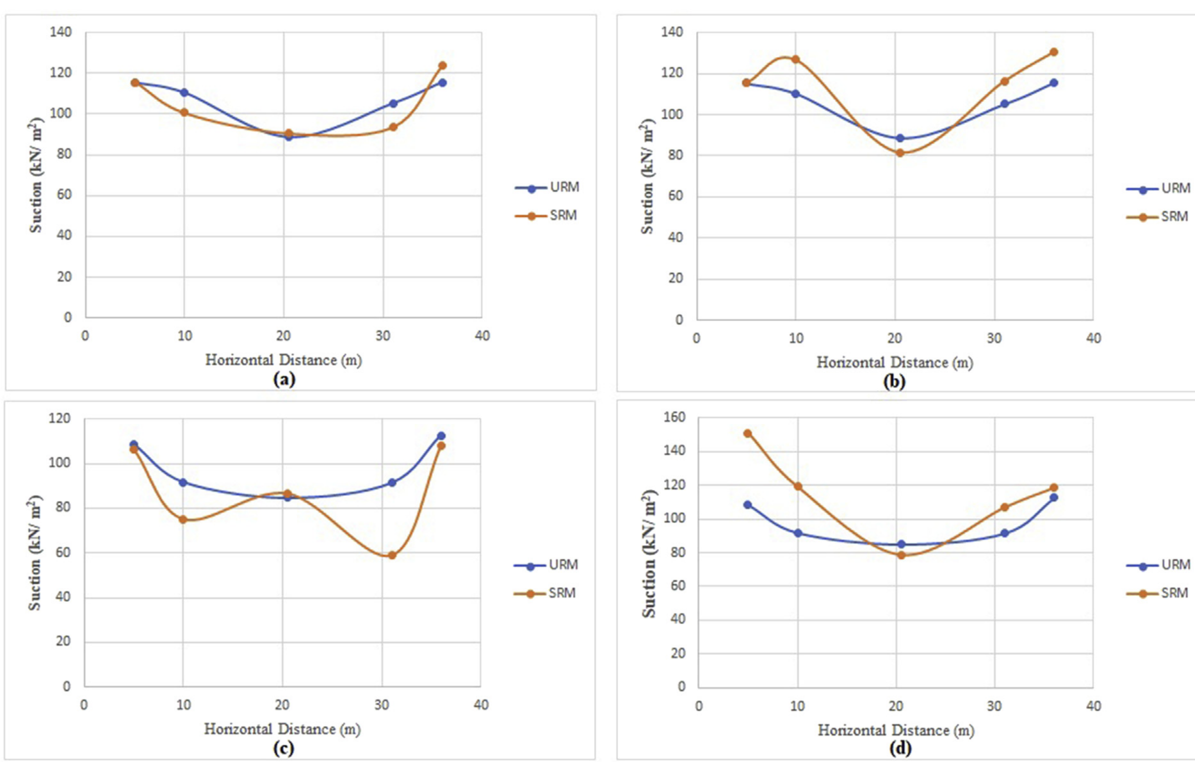

Fig. 7. Effect of buffer layer on suctions. (a) at 0.25 m depth without buffer (b) at 0.25 m depth with buffer (c) at 0.75 m depth without buffer (d) at 0.75 m depth with buffer.

It is observed that the swelling displacements are almost same in case of unstabilized and stabilized models having only buffer layer (refer the top two series of Fig. 8a). However, the swelling displacements go on reducing as depth of cut-off increases to 1 m depth (refer bottommost series of Fig. 8a). This implies that, vertical cut-offs are providing the required control on moisture ingress which causes swelling

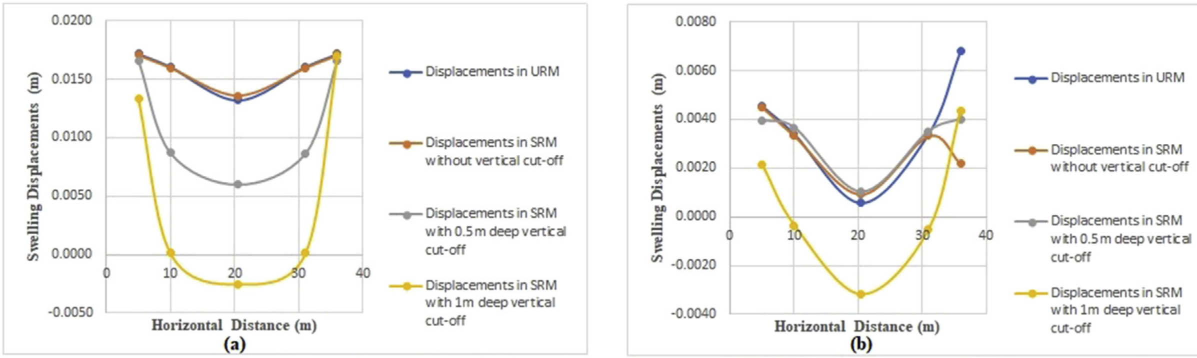

Fig. 8. Effect of vertical cut-off on vertical displacements with buffer layer present in all SRMs. (a) at 0.25 m depth (b) at 0.75 m depth.

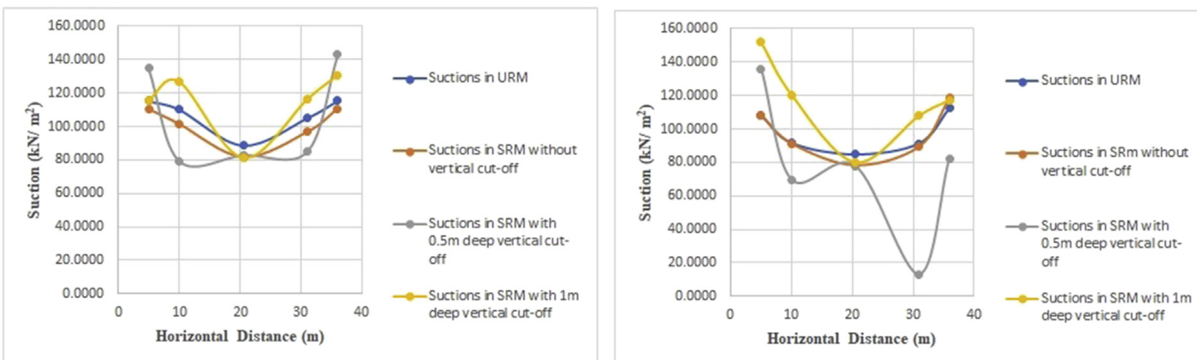

Fig. 9. Effect of vertical cut-off on suctions with buffer layer present in all SRMs. (a) at 0.25 m depth (b) at 0.75 m depth.

displacements. Fig. 8b showing displacement results at 0.75 m depth also indicate the similar trends in results. Fig. 9a shows the results of suction at 0.25 m depth in subgrade soil C-1, and in Fig. 9b, results of suction are shown at 0.75 m depth in subgrade soil C-2. Results of suctions of URM series are compared with these three possible cases of SRM series (with no vertical cut-off, 0.5 m deep vertical cut-off and 1 m deep vertical cut-off), in both Fig. 9a and Fig. 9b. They indicate that, suctions under the toe are increasing to their maximum (refer SRM series with 1m deep cut-off) when depth of cut-off is 1m that is, up to the bottom of expansive soil layers. However, there is reduction in suction under the toes in other two cases that is when cut-off is absent and it is up to 0.5 m depth.

From the above discussion, regarding effects of buffer layer and vertical cut-off it is can be inferred that, both these components of capping are essential and the depth of vertical cut-offs should be up to the complete depth of expansive subgrade. Similarly, buffer layer should also project horizontally for sufficient length beyond the width of embankment. Then the swelling displacements are observed to be reduced and the suctions are observed to be increased indicating the corresponding reduction in saturation under the embankment, which is normally responsible for swelling and associated volume changes.

Therefore, it can be summarized from the results and discussions that, when 'C'-shaped lime stabilized expansive soil capping is provided under the embankment, the swelling displacements in expansive subgrade are reduced and the suctions in such soils are increased under the toes of the embankment in capping zone. The method uses the locally available soil required for lime stabilization. Such stabilization can be done by mixing soil on site by using usually available equipment in road construction projects. Therefore, no costly material like cement or geosynthetics is required as used for moisture barriers in some earlier studies. It can therefore be concluded that, the methodology suggested in the present study can be used as an economical solution to control the distress caused in embankments founded on expansive clay subgrade. This will in turn help to reduce the distress in flexible pavements constructed on such embankments and will also help to enhance the performance of flexible pavements.

The conclusions drawn from the above discussions are presented in the subsequent section.

5. Conclusions

1) It was observed from the Finite Element Analysis carried out using PLAXIS 3D that; the swelling displacements in expansive subgrade soil are reduced by 100 % within the protected capping zone under toe of embankment in top layer (C-1) of expansive subgrade. This indicates that, capping is effective in reducing swelling displacements in expansive subgrade immediately under the embankment.
2) It is observed from the results that, there is increase in suction values of 11 % and 15 % under the toes within the capping zone in top layer C-1 at depth 0.25 m, in case of Stabilized Road Model (SRM) as compared to Unstabilized Road Model (URM). However, there is not much change in the suction values in this layer outside the capping zone. That means the 'C'-shaped capping is controlling the moisture ingress and therefore, swelling displacements are also observed to reduce by about 100 %.
3) The models were tested with and without horizontal buffer layer and keeping the vertical cut-offs in both the cases. In the absence of buffer layer, the model is subjected to settlements under the overburden of embankment and suctions are reducing indicating ingress of moisture. Therefore, it is evident that, the presence of stiffer lime stabilized buffer layer provides a levelled surface and also resists the volume changes caused by strains generated due to swelling of expansive subgrade.
4) The reinforced models are studied with different depths of vertical cut-off and providing buffer layer in all the cases. However, only when cut-offs are provided up to complete depth of expansive soil

layers, swelling is observed to reduce by 100 % and there is increase in suction by 11 %–15% indicating reduction in moisture ingress.

5) Therefore, it can be concluded that, compared to the traditional approach of lime stabilization up to complete active zone depth or use of CNS material suggested by earlier studies, the 'C'-shaped capping proposed in the present study is a cost-effective solution for reducing the distress in embankments. It reduces swelling of expansive subgrade soils by controlling saturation in these soils.

Declarations

Author contribution statement

Manoj Anaokar: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Sharad Mhaiskar: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors would like to thank Dr. G. Venkatachalam, Professor Emeritus (Adjunct), NMIMS, Mumbai and retired Professor IIT Bombay, India for his constructive comments and suggestions for improving quality of the manuscript.

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