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Estimation of Suction Profile and Vertical Deformation in the Indian Expansive Soil Using Thornthwaite Moisture Index

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Abstract **–**Prediction of vertical deformation (heave/ shrink) in the expansive soil, due to change in moisture content is a key focus of geotechnical engineers as it causes major damage to the pavements. Studies have shown that the volume change behaviour of expansive soil is associated with a change in matric suction, which is considered a stress state variable. Thus, the study of suction profiles in the moisture active zone is an important step in the design of pavement resting on the expansive soil. The suction envelope for the wet and dry climate, the depth of the active moisture zone and the value of an equilibrium suction are often evaluated using the Thornthwaite Moisture Index (TMI) of a particular region. The objective of this paper is to develop a suction profile based on the TMI values, considering climatic data for the past 30 years and estimate a total vertical movement of soil mass for Indian expansive soil. To study and compare the vertical movements in the expansive soil for worst-case scenarios, three suction profiles are generated considering minimum (negative), maximum (positive) and mean TMI values for 30 years. To understand the effect of different soil conditions (dry, wet, cracked, equilibrium etc.) on the deformation, analysis is performed with varying lateral earth pressure coefficients at rest. Results show that the predicted total maximum vertical movement is observed for the highest negative value of TMI. Maximum swelling can occur when soil is in wet condition in movement active zone and maximum shrinkage can happen when soil is in cracked condition.

***Keywords*: Indian expansive soil, matric suction, swell, shrink, pavement, Thornthwaite Moisture Index, volumetric strain

1. Introduction

Many countries such as the United States, Australia, India, South Africa, Israel, China, Spain, Venezuela etc. have reported damage to the pavements due to differential movement caused by swell/shrink behaviour of the expansive soil. In India, the expansive soil is locally called Black Cotton Soil or BC Soil as it is black in colour and good for cotton crops. The Indian expansive soil has originated by decomposition of a parent igneous rock (such as basalts in Deccan Plateau) with montmorillonite as the most predominant mineral[1]. This soil is very hard in dry conditions showing a lot of cracks on the surface but loses its strength when comes in contact with water showing swelling at the surface.

Expansive soils being unsaturated, deals with negative pore water pressure (suction) [2]. Lightly loaded structures such as pavements are prone to get affected by the volume change behaviour of the soil. The matric suction under pavements is controlled by the climatic conditions and material characteristics than the depth of the groundwater table [3].

Thornthwaite Moisture Index (TMI) is a climate indicator, mainly a function of rainfall and evapotranspiration, which represents moisture conditions in the subgrade soil of a particular area [4]. Many researchers [5]–[10] have been working to correlate TMI with suction parameters of subgrade soil to understand the moisture conditions in the soil. The suction profile represents boundaries of suction variation i.e minimum suction for wet conditions, maximum suction for dry conditions and the equilibrium suction in the moisture active zone. Vann and Houston [10] developed the latest suction profile model based on the TMI values. This model is useful where the direct measurements of suction are not available from the field. Lytton et al. [11] presented a methodology to estimate a vertical movement in the soil considering index properties of soil, change in suction and initial and final stresses at various layers of the soil.

The main objectives of this paper are to generate suction envelopes based on the model developed by Vann and Houston[10] and to estimate a vertical movement (swell/ shrink) of a typical expansive soil at village Ravet, Pune, Maharashtra, in India using a suction-based approach suggested by Lytton et. al [11]. A two-fold comparative study is performed, one for evaluating the maximum vertical movement caused by the soil in a worst-case scenario considering suction profiles with the extreme TMI values and yearly average TMI value and second to understand the effect of lateral earth pressure coefficient for varying soil conditions such as drying, wetting, at equilibrium and cracked on the prediction of movement in the soil.

2. Research Methodology

The following steps are adopted to compute the deformation (swell/ shrink) in the Indian Expansive soil

2.1 Identification of weather station near village Ravet and collection of climate data
2.2 Computation of TMI for 30 years to get minimum, maximum and average TMI value based on climate data
2.3 Generation of suction profiles and other suction parameters using TMI values based on Vann and Houston Model [10]
2.4 Laboratory testing to get index properties of a typical expansive soil at village Ravet.
2.5 Computation of deformation (swell/ shrink) in the soil based on the method suggested by Lytton et al. [11]

2.1. Identification of weather station and collection of climate data

The village Ravet (Lattitude and Longitude coordinates-18.660° N, 73.732° E) is situated in the northwest outskirts of Pune, the western part of India. The climate data from the nearest weather station (18.50° N, 73.85° E) is collected from the Indian Metrological Department Pune [16]. A data set consists of a daily gridded rainfall data at a high spatial resolution (0.25° × 0.25°, latitude × longitude) and daily gridded temperature data at a high spatial resolution (1° × 1°, latitude × longitude) from the year 1991 to 2020. (30 years). The daily available data is sorted for the month and year.

2.2. Computation of TMI

The year-by-year method is used to calculate a monthly average TMI for 30 years. Fig.1 shows a flow-chart for the TMI calculation [12]

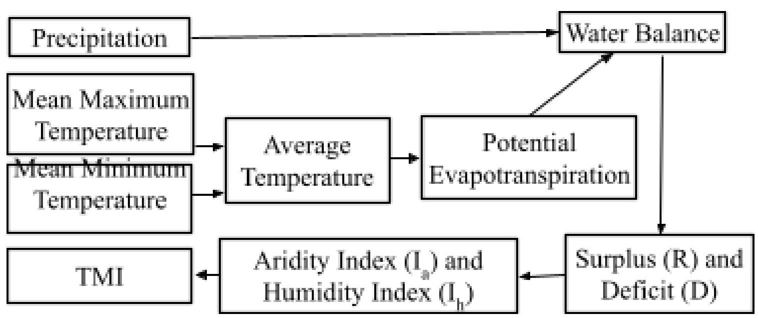


Fig.1 Flow-chart for the TMI calculation [12]

Thornthwaite[4] defined the TMI considering two separate climate-related indices. The humidity index (I_h) and the aridity index (I_a) as given by Eqs. (1)- (3)

$$I_h = 100\left(\frac{R}{PE_i^{'}}\right) \quad (1)$$

$$I_a = 100\left(\frac{D}{PE_i^{'}}\right) \quad (2)$$

$$TMI = I_h - 0.6 I_a \quad (3)$$

R is the moisture surplus (or runoff), D is the moisture deficit and $PE_i^{'}$ is the adjusted potential evapotranspiration.
At first unadjusted potential evapotranspiration is determined using Eq.(4) as below

$$PE_i = 1.6\left(\frac{10t_i}{H_y}\right)^a \tag{4}$$

Where,
PE_i = Unadjusted Potential evapotranspiration (cm) for month i

h_i = Heat Index for month i, $h_i = (0.2t_i)^{1.514}$,
ti = Mean monthly temperature in °C, calculated as the average of *tmax* and *tmin*,
H_y = Annual heat index, determined by summing the 12 monthly heat index and

$$a = 6.75 \times 10^{-7} \times H_y^3 - 7.71 \times 10^{-5} \times H_y^2 + 0.017921 \times H_y + 0.49239$$

The value of PE_i obtained from Eq. (4) represents potential evapotranspiration in cm of water per month for a 30-day month of 12-hour days. Hence it is adjusted depending on the latitude and the month of the year as Eq.(5)

$$PE_i^{'} = \sum_{i=1}^{12} PE_i \frac{D_i N_i}{30} \tag{5}$$

$PE_i^{'}$ = adjusted potential evapotranspiration for month i (cm),
Di = Day length correction factor for month i,
Ni = Number of days in month i.
The climate data is processed in the Microsoft Excel worksheet, to calculate the TMI values for village Ravet. Fig.2 shows yearly mean TMI values, from the years 1991-2020.

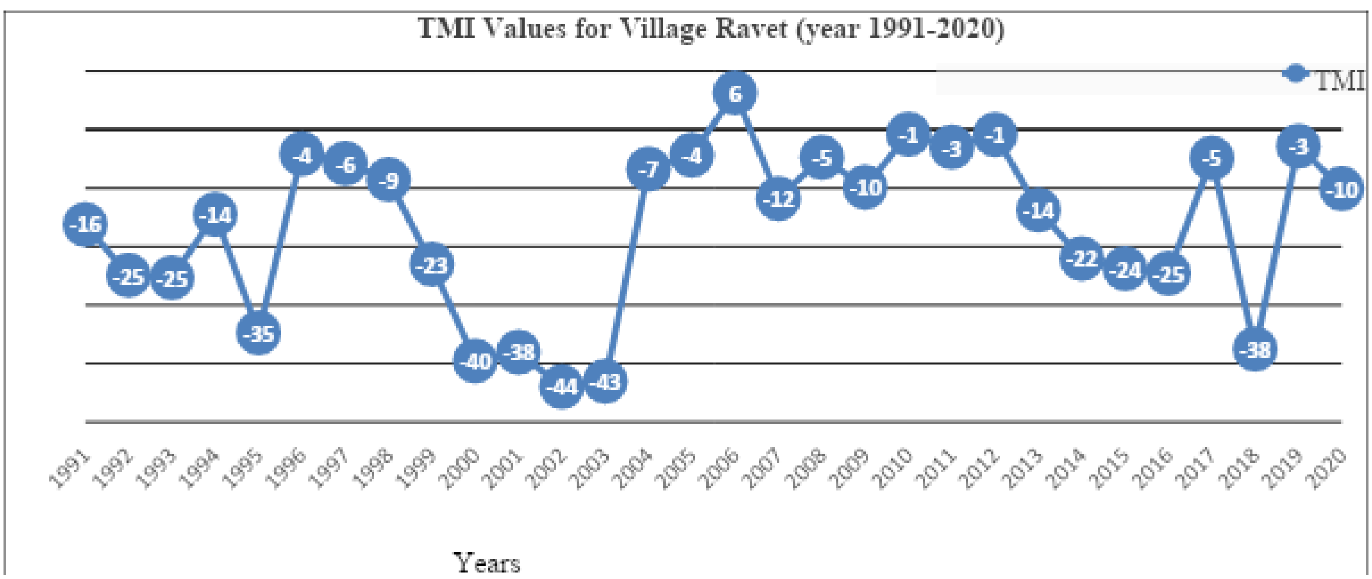


Fig.2 Yearly mean TMI values for village Ravet

Discussion

1. Fig.2 show that the TMI value ranges between -1 to -44 (The only exception is TMI=+6 for the year 2006) in the past 30 years, which classifies village Ravet in the region of a dry sub-humid to semiarid climate. [4]
2. It is observed from the fig.2 that the maximum value of TMI is +6 (year 2006), whereas the minimum value is -44 (year 2002). The average TMI value for 30 years is found to be -16.55.

2.3. Generation of Suction Profile for the typical expansive soil at village Ravet

The various suction parameters required to generate suction envelopes are derived based on the maximum, minimum and mean TMI Values using Eqs. (6)-(9) and presented in Table1. [10]

Depth of equilibrium suction

$$D_{\varphi_e} = 1.617 + \frac{2.617}{1+e^{(2.36+0.1612TMI)}} \tag{6}$$

Change in suction at the ground surface

$$\Delta\varphi = 1.2109e^{-0.005TMI} \tag{7}$$

Equilibrium suction

$$\varphi_e = 0.00002(TMI)^2 - 0.0053(TMI) + 3.9771 \tag{8}$$

Climate Parameter

$$r = 0.3725e^{-0.009TMI} \tag{9}$$

Table 1 Suction Envelope parameters for typical expansive soil at village Ravet

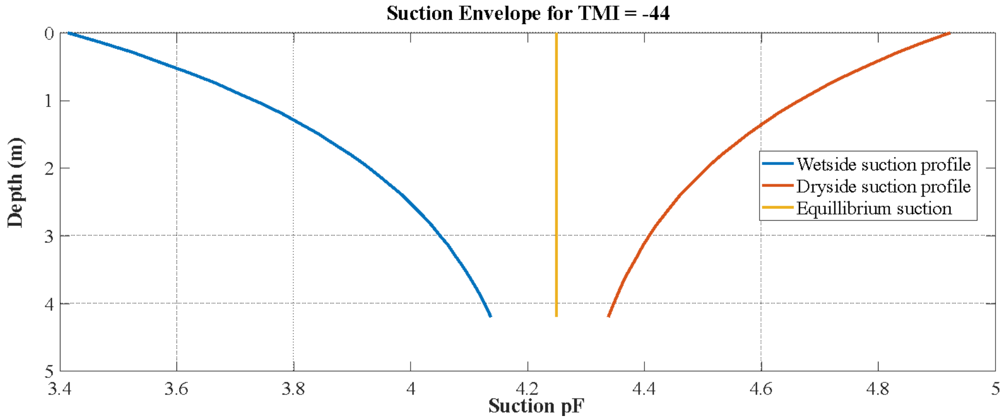
Parameters	Symbol	TMI = -44	TMI = -16.55	TMI = +6
Depth of equilibrium suction (m)	$D\varphi_e$	4.21	3.13	1.71
Change in suction at the surface (pF)	$\Delta\varphi$	1.51	1.32	1.18
Equilibrium suction (pF)	φ_e	4.25	4.07	3.95
Climate parameter	r	0.55	0.43	0.35

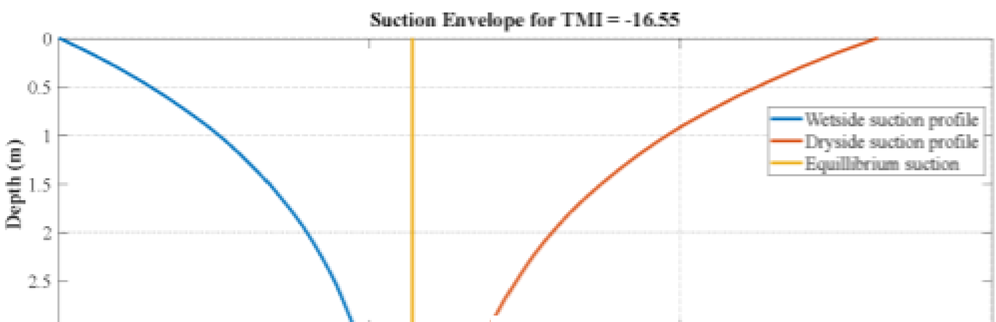
It is assumed that there is a homogeneous expansive soil layer up to the depth of equilibrium suction and the water table is much below this depth. For the calculation purpose, the soil layer is divided with an equal thickness of 30 cm each, keeping the upper layer as 15 cm thick, and suction profiles are generated applying Eqs. (10) and (11) as recommended by Vann and Houston [10] for varying TMI values.

$$\varphi_{wet} = \varphi_e - r\Delta_\varphi e^{\left(\frac{-zln\left(\frac{0.2}{\Delta\varphi}\right)}{-D\varphi_e}\right)} \tag{10}$$

$$\varphi_{dry} = \varphi_e + (1 - r)\Delta_\varphi e^{\left(\frac{-zln\left(\frac{0.2}{\Delta\varphi}\right)}{-D\varphi_e}\right)} \tag{11}$$

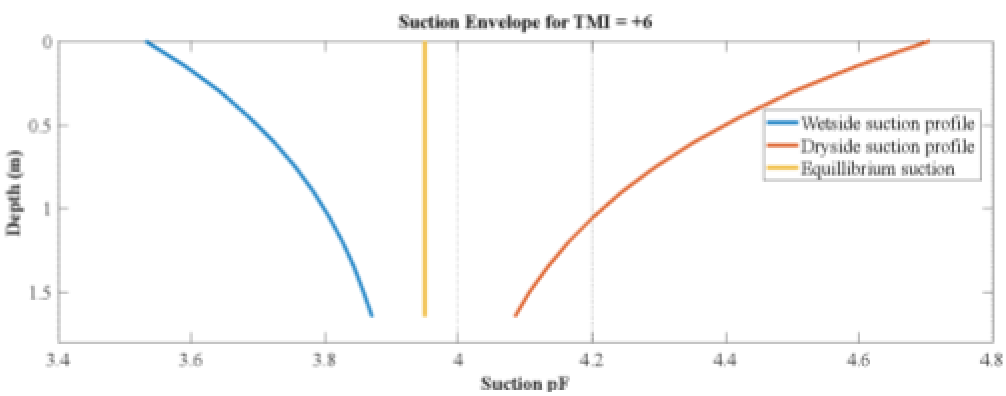
Fig.3 (a), (b) and (c) shows wet, dry and equilibrium suction profiles for TMI -44, -16.55 and +6 respectively, for the typical expansive soil in village Ravet. The formulation and plotting is carried out using MATLAB software.





(a)

(b)



(c)

Fig. 3 Suction Envelopes of a) TMI= - 44 b) TMI= -16.55 and c) TMI= +6 for the expansive soil at village Ravet Discussion

1. It is observed from Table 1 and Fig.3 that the value of depth of the moisture active zone, change in suction at the surface, equilibrium suction and climate parameter increase as TMI become more negative.

2.4. Laboratory Test Results

Laboratory tests are conducted to get index properties of the soil sample from the site at village Ravet, using relevant Bureau of Indian Standards (BIS) codes. Results of the laboratory tests are presented in Table 2(a). Other soil parameters are tabulated in Table 2(b), which are calculated using charts provided by Covar and Lytton [13]

Table 2(a) Basic properties of a typical expansive soil at village Ravet

Sr. No.	Soil Properties	Value	Reference
1.	Liquid Limit (LL)	85	From Lab test [14], [15]
2.	Plastic Limit (PL)	36	
3.	Plasticity Index (PI)	49	
4.	% clay <0.002mm	30.16	
5.	Fines content % passing #No.200 ASTM sieve (IS 75µ sieve)	83.26	

Table 2(b) Soil Parameters derived from index properties of soil at village Ravet

Sr.No	Soil Parameters	Value	Reference
1.	%fine clay (%fc) ((% −2µ) /(% passing #200)	33.5 %	[13]
2.	LL / %fc	2.54	
3.	PI / %fc	1.46	
4.	γ_0	0.22	
5.	γ_h	0.0737	
6.	$\gamma_{h\ swell}$	0.0793	[11]
7.	$\gamma_{h\ shrink}$	0.0685	

Discussion –

1. Index properties from laboratory data in Table 2 (a) show that the typical expansive soil at village Ravet is of CH type (High plasticity clay) as per the Unified Soil Classification System.

2. Soil parameters derived in Table 2 (b) indicate that the candidate soil at village Ravet lies in Zone III [13].

2.5. Computation of Deformation in the Soil

Once the suction envelope and index properties of soil are determined, then volumetric strain in the soil is calculated as per Eq.(12) developed by Lytton et al. [11]. Note that the net normal stress portion of equation 1 is added if the soil is wetting (swelling) and subtracted if the soil is drying (shrinking).

$$\frac{\Delta V}{V} = -\gamma_h log_{10}\frac{h_f}{h_i} \pm \gamma_\sigma log_{10}\frac{\sigma_f}{\sigma_i} \qquad (12)$$

Where

$\frac{\Delta V}{V}$ is a volumetric strain in the soil

γ_h is suction compression index

γ_σ is mean principal stress compression index. (For analysis value of γ_σ is considered equal to γ_h)

h_i *and* h_f are initial and final matric suction values

σ_i is initial overburden stress calculated at depth of 80cm as a constant

σ_f is final overburden stress as given in Eq.(13)

$$\sigma_f = \left[\frac{(1+2K_0)\sigma_z}{3}\right]$$

σ_z is vertical overburden stress at depth z

K_0 is 1D at-rest lateral earth pressure as given in Eq (14)

$$K_0 = e\left(\frac{1-sin(\phi')}{1+sin(\phi')}\right)\left(\frac{1+dsin(\phi')}{1-ksin(\phi')}\right)^n \qquad (14)$$

Where $\phi' = 0.0016PI^2 - 0.3021PI + 36.208$

PI *is a plasticity Index.*

The values of parameters *e, d, k, n* varies as per the soil conditions. The value of K_0 is calculated considering these parameters and *PI* of candidate soil as mentioned in Table 3.

Table 3 Value of K_0 considering different soil conditions for village Ravet

Soil Condition	**Parameters for soil conditions**				K
	e	**d**	**k**	**n**	
Cracked	0	0	0	0	0
Drying	1	0	0	1	0.4
Equilibrium (at rest)	1	1	0	1	0.57
Wetting (within movement active zone)	1	1	0.5	1	0.727
Wetting (below movement active zone)	1	1	1	1	1
Swelling near the surface (passive earth pressure)	1	1	1	2	2.5

The total vertical movement (heave/ shrinkage) of soil is calculated as a sum of the products of the vertical strains and the increment of depth to which they apply, Δz_i as given in Eq.(15)

$$\Delta H_{total} = \sum_{i=1}^{n} f\left(\frac{\Delta V}{V}\right)_i \Delta z_i \qquad (15)$$

Where

ΔH_{total} is a sum of vertical movements of all the layers for swelling/ shrinkage conditions of soil

Δz_i is the thickness of the soil layer

f is a crack fabric factor (0.5 for drying and 0.8 for wetting)

3. Result

Detail calculation is carried out as per the procedure explained in the above sections, using an excel worksheet, for computation of vertical movement based on suction profiles, index properties, suction parameters of soil and varying K_0 (soil conditions). The result is summarized in Table No.4

Table 4 Predicted vertical movement in the expansive soil at Village Ravet Pune

Type of deformation	Value for K_0	Expected Vertical Movement (ΔH) in cm		
		TMI = -44	TMI= -16.55	TMI= +6
Swelling	0.727	3.36	2.90	2.6
	1	2.34	2.06	1.85
	2.5	0.66	0.52	0.46
Shrinkage	0	-3.18	-3.18	-2.92
	0.4	-1.6	-1.61	-1.55
	0.57	-1.29	-1.3	-1.26
Maximum $\lvert \Delta H_{swelling} \rvert + \lvert \Delta H_{Shrinkage} \rvert$		**6.54**	**6.08**	**5.52**

Note- Negative sign shows downward movement of soil

Discussion-

1. It is observed from Table 4 that both maximum swelling and shrinkage is at the highest negative TMI Value (TMI= -44).
2. Deformation is maximum when $K_0 = 0$, for drying condition and when $K_0 = 0.727$ for the wetting condition of the soil.

4. Conclusion

1. The TMI value of village Ravet ranges between -1 to -44 (except TMI= +6, for the year 2006), and the average TMI value is found to be -16.55 for the years 1991 to 2020.

2. The predicted total maximum vertical movement in the typical expansive soil at village Ravet, is found to be 6.54cm, with the TMI value equal to -44.

3. The maximum swelling occurred when the soil condition is wetting within the movement active zone (K_0 is 0.727), and maximum shrinkage in the soil happened when soil is in cracked condition (K_0=0) for all TMI values.

4. The prediction of total vertical movement in the typical expansive soil at village Ravet, is useful for the further analysis and design of pavement.

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