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Behaviour of Tropical Residual Soils- Prediction by a Mathematical Model

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Abstract: *Advanced geotechnical design on difficult soils has often been based on finite element analysis using isotropic elasto-plastic soil models, such as Modified Cam clay (Roscoe & Burland 1968). Natural soil deposits, however, tend to be highly anisotropic, due to the deposition process and subsequent loading history. Neglecting the anisotropy of soil behaviour may lead to highly inaccurate predictions of soil response under loading. During the recent times several anisotropic elasto-plastic soil models have been proposed (e.g. Banerjee & Yousif 1986, Dafalias 1987, Whittle & Kavvadas 1994, Newson 1997). Unfortunately some of these models predict unrealistic behaviour for certain stress paths. Others are relatively complex and difficult for practicing engineers to understand or the determination of the model input parameters may require non-standard laboratory tests. As a result, the application of these models to practical geotechnical design is not common. An anisotropic models for geotechnical design which can predict the behaviour of soils in a comprehensive and coherent manner was proposed by Wheeler (1997) and subsequently modified by (Naatanen et al. 1999). The cardinal aim of the present paper is to propose a mathematical model based on critical state framework with easily determinable soil parameters needed to characterise the behaviour for the tropical residual soils available at Thirupati region in the Southern India. An attempt has been made in the present paper to apply proposed mathematical model based on critical state parameters to capture the behaviour of compacted soils and tropical residual soils. A soil samples have been collected from the surrounding areas of Thirupati region located in Southern India. The spectrum of soils considered in the study represents typical soil types encountered in practice in this region. Using the proposed new model and it's predictive capabilities are brought out in comparison to the experimental results on compacted soils and tropical residual soils. It has been shown that the proposed new model which is a minor modification of the models well documented by Wheeler (1997) can effectively predict the behaviour of cemented soils considered in the present investigation*
Keywords: *residual soils; undisturbed soil; critical state parameters; anisotropic models*

I. Introduction

The development of a critical state framework for saturated soils provides a powerful conceptual model based on the generalized principles of the elasto plastic behaviour of frictional materials (Schofield & Wroth, 1968). The model has been modified with time to meet the requirements of more complex applications (Wheeler, 1997). The original Cam clay model assumes the Roscoe surface to be "bullet"- shaped. However the model predicts larger shear deformations than those observed for small levels of shear stress. In order to overcome this limitation a modified version of the Cam clay model was suggested by Burland (1965) replacing the bullet-shaped surface of the Cam clay model with an elliptic shape and subsequently was extended by Roscoe and Burland (1968) to a model, now known as the modified cam clay model (Figure 1). Toll and Ong (2003) presented experimental data from constant water content triaxial tests on a residual soil from Singapore, tested under saturated conditions with measurements of Matric suctions. The functions relating to critical state parameters to degree of saturation have been expressed in normalized form by referring them to saturated state. It has been shown that the normalized forms can be used to predict the experimental data. Baudet and Stallebrass (2004) presented a simple constitutive model for structured clays based on an existing constitutive model for reconstituted clays. Farias *et. al.*, (2006) presents an alternative constitutive model based on classical theory of plasticity and critical state theory for describing the mechanical behaviour of soils particularly at unsaturated states. Despite a large number of elastoplastic models proposed Cam clay models are used in practice owing to simplicity and easily determinable model parameters.

II. General Soil Types Encountered In The Region

The properties of residual soils have received increasing attention from geotechnical engineers in recent years. In particular, the extent to which conventional soil mechanics concepts are applicable to residual soils have been addressed by a number of workers in this field. There appears to be a widely held view that the direct applications of such concepts to residual soils is likely lead to misleading conclusions about the properties of at least some of these soils.

III. Plasticity Models For Soils

3.1 Cam-clay model.

A number of different theories for the prediction of plastic strains in soils have been developed, mostly by research workers at Cambridge, but the essential characteristics of these theories are the same. The present paper focuses on Cam clay models. This theory is the basis for several more advanced theories which, although more complicated, give a better fit to experimental data. One of the key assumptions of Cam clay theory is that the flow rule follows normality condition. Thus, if plastic strain increment vector is everywhere normal to a yield locus, it is only necessary to specify either the shape of the yield curve or the relationship between $\delta\varepsilon_s^p / \delta\varepsilon_v^p$ and the stress state (the flow rule) in order for both the flow rule and the yield curve to be fully specified. A second key assumption, which arises from a consideration of the work dissipated during shear, the flow rule is given by

$$\frac{\delta\varepsilon_v^p}{\delta\varepsilon_s^p} = M - \frac{q'}{p'} \qquad (1)$$

This equation has the consequence that the associated yield curve is given by

$$\frac{q'}{Mp'} + \ln\left(\frac{p'}{p'_X}\right) = 1 \qquad (2)$$

Where p'_x is the value of p', at the intersection of the yield curve with the projection of the critical state line. We should also note that the slope of the yield curve is zero at X, implying that $\delta\varepsilon_v^p / \delta\varepsilon_s^p$ is also zero at the critical state. Of course p'_x will be different for the different yield curves at the top of different elastic walls; indeed there will be a whole family of yield curves at the top of the family of elastic walls. The whole array of yield curves together form a three dimensional surface in $q' : p' : v$ space which will limit possible states of samples, i.e., the array of yield curves will define a boundary surface similar to that found for normally consolidated clays. The equation of the Cam clay state boundary surface can be obtained using the results that the yield curve, and in particular the highest point on it, at $v = v_X$, $p' = p'_X$,
lies on a single swelling line, or

$$v_\kappa = v + \kappa \ln p' = v_X + \kappa \ln p'_X. \qquad (3)$$

and that the highest point X also lies on the critical state line

$$v_X = \Gamma - \lambda \ln p'_X, q'_X = Mp'_X. \qquad (4)$$

Equations (3) & (4) together with equation (2), can be used to eliminate v_X and p'_X to give

$$q' = \frac{Mp'}{\lambda - \kappa}\left(\Gamma + \lambda - \kappa - v - \lambda \ln p'\right) \qquad (5)$$

This is the equation for Cam clay state boundary surface. For the simple Cam clay theory the additional assumption is made that the elastic shear strains are zero. The virtue of the Cam clay theory is that it gives a complete constitutive relationship for soil which can describe deformations and pore pressures during drained and undrained loading for a wide variety of stress paths. The soil constants required $(M, \lambda, \kappa, \Gamma)$ are few and all can be measured in standard laboratory tests.

3.2 Modified Cam-Clay Model

It is assumed that recoverable changes in volume accompany any changes in mean effective stress p' according to the expression

$$\delta\varepsilon_v^e = \kappa \frac{\delta p'}{vp'} \qquad (6)$$

It is assumed that recoverable shear strains accompany any changes in deviator stress q according to the expression

$$\delta\varepsilon_s^e = \frac{\delta q}{3G} \qquad (7)$$

with constant shear modulus G. The combination of above two equations implies a variation of Poisson's ratio with mean effective stress but to assume instead a constant value of Poisson's ratio would be equally acceptable.

It is convenient to make it always pass through the origin of effective stress space, though this is not essential: it seems reasonable to propose that unless the soil particles are cemented together, a soil sample will not be able to support an all-round tensile effective stress and that irrecoverable volumetric deformations would develop if an attempt were made to apply such tensile effective stresses.

3.3 New Proposed Model

An alternative mathematical model for tropical residual soils was proposed, which is an extension of Wheeler. The main objective in developing the model was to provide a realistic representation of the influence of plastic anisotropy, whilst still keeping the model relatively simple, so that there would be a realistic chance of widespread application in geotechnical design.

This model is an extension of the critical state models, with anisotropy of plastic behaviour represented through a rotational component of hardening. The model is applicable to compacted soils and tropical residual soils, where plastic deformations dominate. For simplicity, isotropy of elastic behaviour is therefore assumed, and hence the elastic increments of volumetric and deviatoric strains are calculated as

$$d\varepsilon_v^e = \frac{\kappa dp'}{vp'}, \qquad d\varepsilon_v^e = \frac{dq}{vG'} \tag{8}$$

Where κ is the slope of the swelling line, ν is specific volume, G is the elastic shear modulus and p' and q are the mean effective stress and deviatoric stress respectively.

The yield curve for the proposed model is,

$$f = (q - \alpha p')^2 - ((M + c/p)^2 - \alpha^2)(p'_m - p')p' = 0 \tag{9}$$

where M is the critical state value of stress ratio η (where η = q/p') and the parameters p_m' and α define the size and the inclination of the yield curve respectively. The parameter α is a measure of the degree of plastic anisotropy of the soil. The parameter ‘c’ is the intercept made by the critical state line on q-axis (deviatoric axis) which is a common phenomenon in the residual soils of Thirupati region . For the case of normal soils the value of intercept ‘c’ assumes the value of zero and the proposed model reduces to Wheeler model.

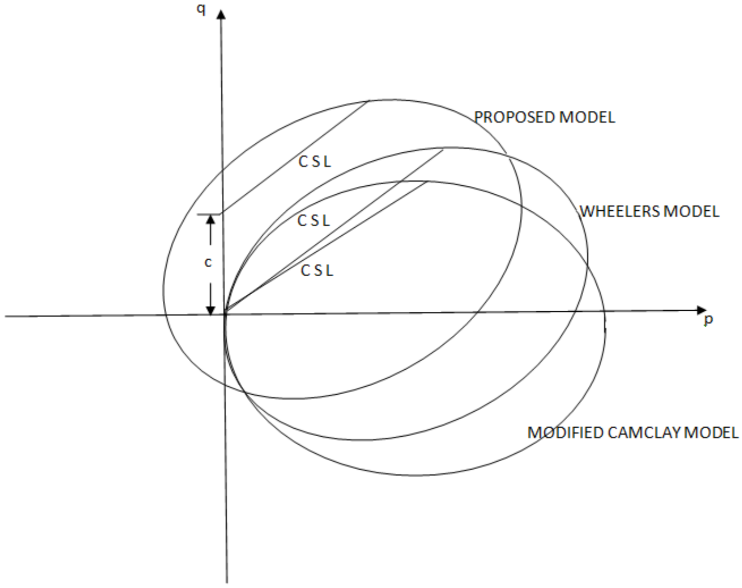

Fig 1. Comparative Yield Curve

In the interests of simplicity, an associated flow rule is assumed, and hence:

$$\frac{d\varepsilon_d^p}{d\varepsilon_v^p} = \frac{2(\eta - \alpha)}{(M + c/p)^2 - \eta^2} \tag{10}$$

The greatest advantage of assuming an associated flow rule is that numerical implementation of the model is far simpler than with a non-associated flow rule, this assumption is reasonable for many residual soils. The model incorporated with two hardening laws. The first one describes changes in size of the yield .

$$dp'_m = \frac{vp'_m d\varepsilon_v^p}{\lambda - \kappa} \tag{11}$$

$dp_m = dp + d\{ (q-\alpha p)^2/p((M+c/p)^2-\alpha^2) \}$ (12)

The second hardening rule predicts the change of inclination of the yield curve produced by plastic straining, representing the development of anisotropy with plastic strains. It is assumed that plastic volumetric strain attempts to drag the value of α towards an instantaneous target value $\chi_v(\eta)$ that is dependent on the current value of η, whereas plastic shear strain is simultaneously attempting to drag α towards a different instantaneous target value $\chi_d(\eta)$ (also dependent on η).

$$d\alpha = \mu\left[\left(\chi_v(\eta) - \alpha\right)d\varepsilon_v^p + \beta\left(\chi_d(\eta) - \alpha\right)d\varepsilon_d^p\right] \qquad (13)$$

The overall current target value for α will lie between $\chi_v(\eta)$ and $\chi_d(\eta)$. Constants μ and β control, respectively, the absolute rate at which α heads towards its current target value and the relative effectiveness of plastic shear strains and plastic volumetric strains in determining the current target value.

Based on initial yield curve, Naatanen et al., proposed the following expressions for $\chi_v(\eta)$ and $\chi_d(\eta)$:

$$\chi_v(\eta) = \frac{3\eta}{4} \qquad (14)$$

$$\chi_d(\eta) = \frac{\eta}{3} \qquad (15)$$

In practice the expression for $\chi_v(\eta)$ in Equation 14 means that plastic volumetric strains attempt to align the yield curve approximately about the current stress point. The proposal for $\chi_d(\eta)$ in Equation 15 corresponds to a significant degree of anisotropy at critical states (α = M/3 at η= M), as suggested by Naatanen et al.,

IV. Soils Tested

Undrained tests were conducted on compacted soils and undisturbed tropical soils. The soils are from eight different chosen locations, keeping in view variation in the grain size characteristic and other basic properties of soil. The tests have been conducted both on compacted soils and natural soils, which are collected from the surrounding areas of Thirupati, in Andhra Pradesh. The spectrum of soils considered in the study represents typical soil types encountered in practice. Using the Proposed new model the predictions of this model are brought out in comparison to the experimental results on compacted soils and also on undisturbed tropical residual soils.

Table 1. Index properties of compacted soils of Thirupati area

property	Soil1	Soil 2	Soil 3	Soil 4
% Gravel	1.6	0.52	0.4	0
% Sand	24.0	13.88	4.2	45.6
% Silt + Clay	74.4	85.6	95.4	54.4
% passing 425μ (F)	85.0	93.8	95.8	94.6
Liquid limit (%)	49	66	55	28.5
Plastic Limit (%)	20	28	28	18
Plasticity Index (%)	29	38	27	10.5
IS Classification	CI	CH	CH	CL
Modified liquid limit,WLM (%)	41.6	61.9	52.7	26.7

Table 2. Details of CU Triaxial shear tests on compacted soils considered

Test	w_f (%)	□d (kN/m³)	S_i (%)	□3 (kPa)	(□1' - □3')max / 2 (kPa)	(□1'+□3')max / 2 (kPa)
A-1	21.4	17.2	84.5	50	54.3	76.8
A-2	21.0	17.3	85.8	200	59.85	215
A-3	21.7	17.4	87.4	300	90.2	337.8
B-1	27.5	16.5	82.3	50	44.7	81.4
B-2	24.3	16.7	85.9	300	122.0	404
B-3	19.7	16.8	85.8	400	157	538
C-1	25.9	16.3	80	25	31.98	49.2
C-2	23.7	16.4	80.7	300	79.85	345
C-3	24.8	16.3	80	400	94.95	449.4
D-1	16.7	18.2	78.8	25	46.45	104
D-2	15.5	18.3	79.6	300	163.8	347
D-3	14.2	18.7	85.9	400	217.5	472

A-Soil 1
B-Soil 2
C-Soil 3
D-Soil 4

Table 3. Properties of Tropical Soils considered

S.No	Location	Depth of Sampling (m)	γ_b (kN/m^3)	σ_O kPa	e_o	W_L (%)	% <425μm	$(W_L)_m$ %	e_{LM}	e_O/e_{LM}
1	Soil 5	2.7	16.78	46	0.61	42	68	28.56	0.77	0.79
2	Soil 6	3.5	16.86	59	0.61	33	79	26.00	0.70	0.87
3	Soil7	2.5	16.37	42	0.62	92	32	29.44	0.79	0.78
5	Soil 8	2.7	17.00	47	0.55	55	50	27.50	0.74	0.74

V Determination of Cam-Clay Model Parameters

The critical state parameters viz. N, λ, κ, Γ and M can be evaluated based on two test results. The slope of isotropic compression is λ and swelling path is κ. The specific volumes corresponding to 1 kPa on normal compression line and critical state line in v-lnp' space indicate N and Γ respectively. The value of M is obtained as a ratio of deviatoric stress to mean principal stress at critical state line in q-p' space. Only two test results are required to evaluate the critical state parameters which are useful in understanding the soil behaviour under different loading conditions. The Wheeler model involves 7 soil constants: 5 conventional parameters from Modified Cam clay (λ, κ, M, G' (or ν) and Γ) and two additional parameters relating to the rotational hardening (β and μ). In addition, the initial state of the soil is defined by the stress state and the initial values of the parameters p_m' and α defining the initial size and inclination of the yield curve. If the initial value of specific volume v is also defined, this replaces the requirement to define a value for the parameter Γ (the intercept of the critical state line in the v : ln p' plane).

Values of the soil constants λ, κ, M, Γ and G can be measured in laboratory tests using relatively standard procedures. This section therefore concentrates on procedures for evaluating the remaining two soil constants (β and μ) and the initial values of the parameters p_m' and α.

This inclination will be calculated using the equation

$$\alpha_{K_o} = \frac{\eta_{K_o}^2 + 3\eta_{K_o} - M^2}{3} \qquad (15)$$

Initial size of yield curve will be calculated as If the initial inclination α of the yield curve can be estimated, using the procedure outlined above, then only one point on the yield curve is required in order to calculate an initial value for the parameter p'_m, which defines the size of the curve. Ideally this, single yield point would be identified by either isotropic or K_o consolidation in a triaxial apparatus. Alternatively, one-dimensional consolidation in an oedometer would be possible, but this would require either measurement or estimation of radial stress, in order to fully define the stress state. Estimation of a point on the yield curve without the performance of any laboratory tests, from a knowledge of the maximum overburden stress applied to the soil deposit, would rarely be satisfactory, because of uncertainties about the depositional history and because of the possibility of an increase in the yield stress above the maximum pressure previously applied, due to the effects of ageing or inter-particle bonding (Burland).

5.1 Soil Constant □

$$\beta = \frac{3(M^2 - \eta_{K_0}^2 - 3\eta_{K_0}/4)}{2(\eta_{K_0}^2 - M^2 + 2\eta_{K_0})} \qquad (16)$$

5.2 Soil constant □

The model parameter μ controls the rate, at which α tends towards its current target value. It is difficult to devise a simple and direct method for experimentally determining the value of μ for a given soil. The only solution would appear to be to conduct model simulations with several different values of μ and then to compare these simulations with observed behaviour in order to select the most appropriate value for μ. The type of experimental test required would be one involving significant rotation of the yield curve. Comparisons of observed and predicted behaviour could then be made in terms of both the degree of rotation of the yield curve (identified experimentally by unloading and then reloading along a different stress path) and the observed pattern of straining. In practice, performing suitable laboratory tests and then undertaking model simulations with different values of μ may not be feasible in a practical design scenario. In such a situation, the best course of action may be simply to select a standard default value for μ.

Table 4. Material parameters

Parameter	Description	Procedure
λ	Slope of the hydrostatic loading curve of soil in v-ln p space	Evaluated from an oedometer consolidation test on compacted soil.

κ	Average slope of the hydrostatic unloading curve of soil	
M	Stress ratio (η = q/p) at critical state in triaxial compression	Evaluated from triaxial compression test on tropical soil
K,G	Nonlinear elastic constants of the remoulded soil used in modified Cam clay	Functions of effective mean principle stress evaluated by $K= p\,(1+e_o)/\,\kappa$ $G = [3(1-2\upsilon)(\,1+e_o)p]\,/[2\,(1+\upsilon)\,\kappa]$ e_o = initial void ratio υ = Poisson's ratio
c	Intercept on deviator stress axis on p'-q plot	Obtained from triaxial compression tests on tropical soils under different confining pressures

Table 5. Model parameters for the compacted soils

Location	λ	κ	M	N
Soil 1	0.147	0.015	0.85	2.3
Soil 2	0.194	0.028	1.20	2.9
Soil 3	0.156	0.017	0.95	2.7
Soil 4	0.08	0.004	1.40	1.84

Table 6. Model Parameters of Tropical Soils Considered

Location	λ	κ	M	α	β	e_o	p_m	σ_3	μ	ν
Soil 5	0.0944	0.0236	1.52	0.84	0.36	0.61	71	50	60	0.3
Soil 6	0.0777	0.0194	1.42	0.78	0.5	0.63	73	50	70	0.3
Soil7	0.0958	0.0239	1.44	0.89	0.55	0.61	84	50	60	0.3
Soil 8	0.071	0.0178	1.47	0.89	0.5	0.48	84	50	60	0.3

V. Predictions of Soil Behaviour based on the Proposed New model

It may be seen that the Proposed New Model predicts the behaviour of natural soils and compacted soils. Based on these modifications effected to the wheelers model, the elastic and plastic strains have been evaluated for the stress increments and the model predictions are presented in Fig 2. To Fig 16., for the soils tested under the present investigation. The predicted behaviour and observed behaviour are qualitatively in agreement with each other. However, there are some minor deviations noticed, which could be due to the approximations involved in the determination of model parameters.

6.1 Compacted soils

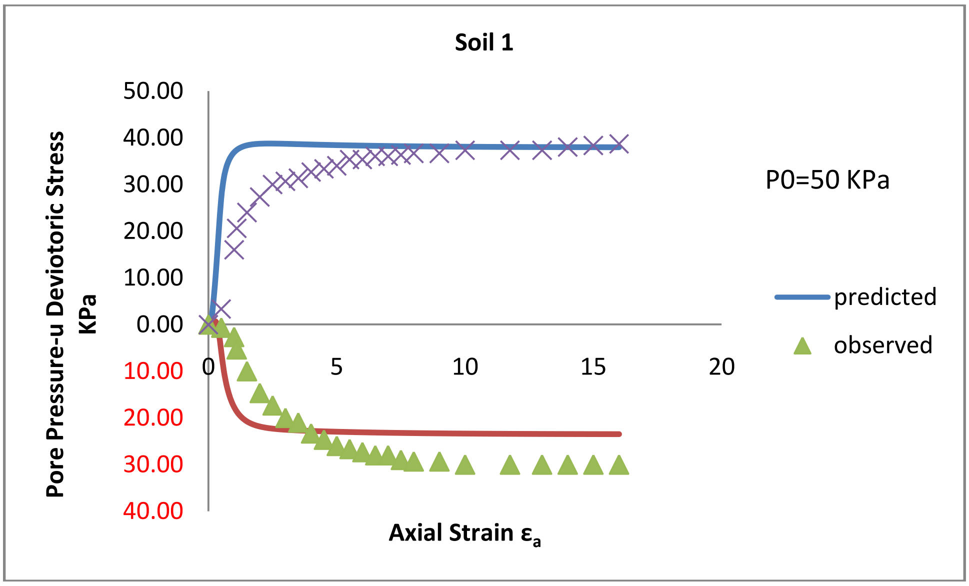

Fig 2. Stress-Strain- Pore Pressure Response of Soil 1

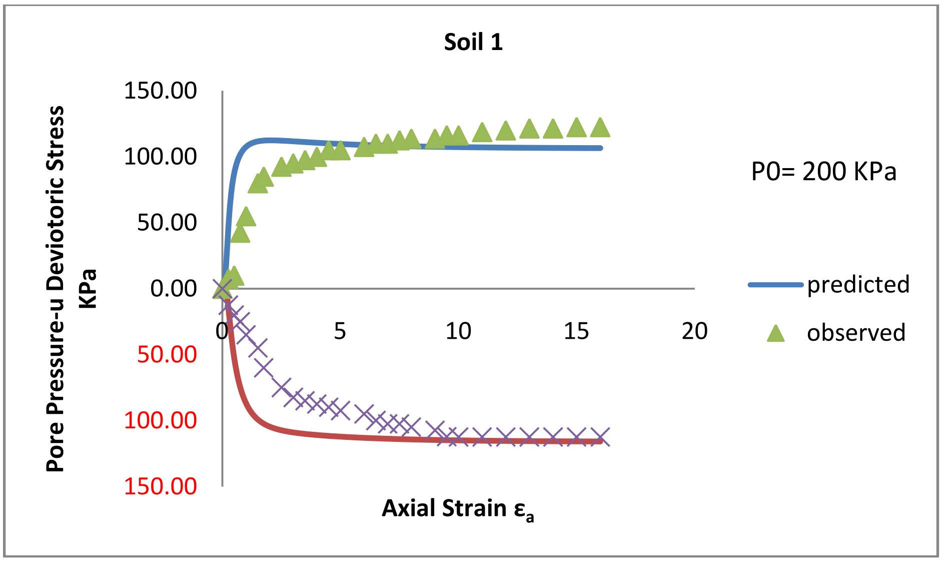

Fig 3. Stress-Strain- Pore Pressure Response of Soil 1

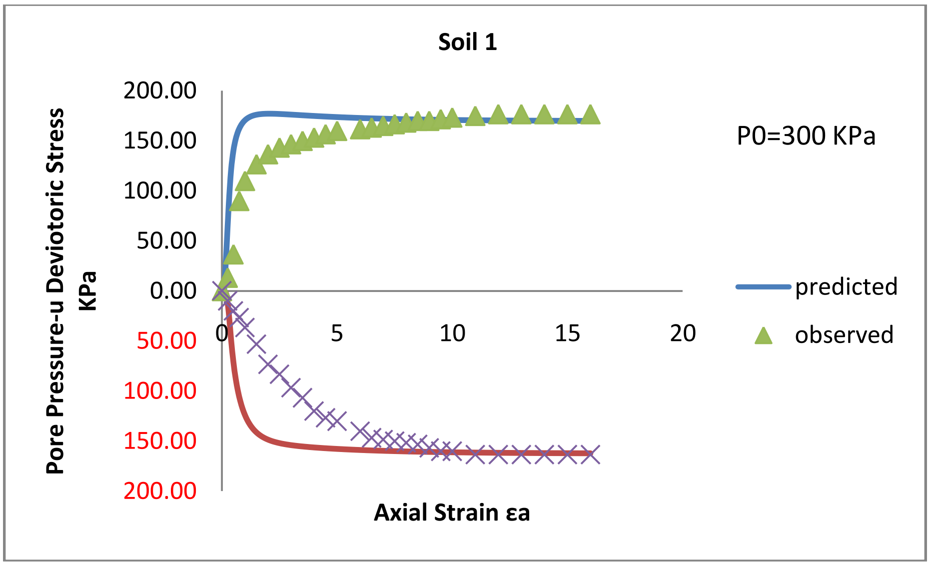

Fig 4. Stress-Strain- Pore Pressure Response of Soil 1

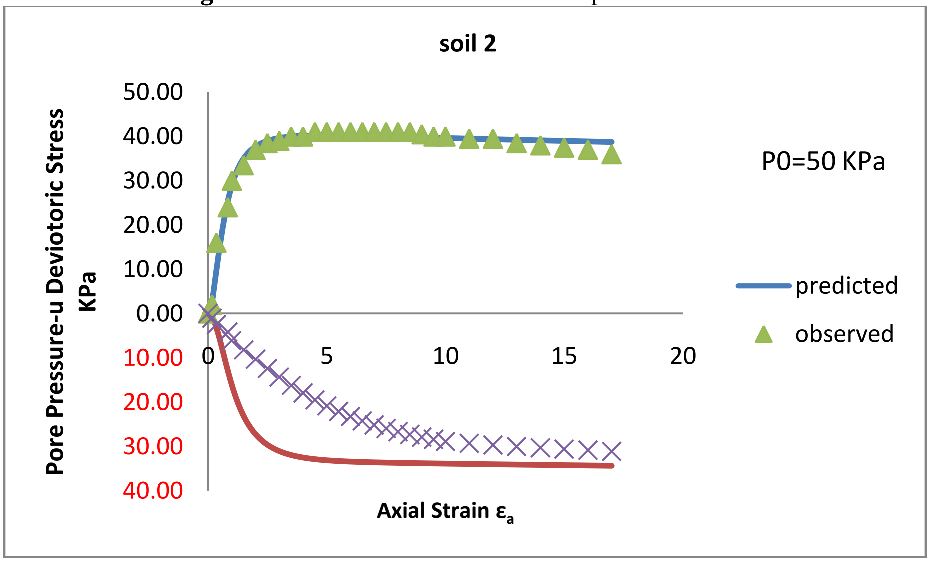

Fig 5. Stress-Strain- Pore Pressure Response of Soil 2

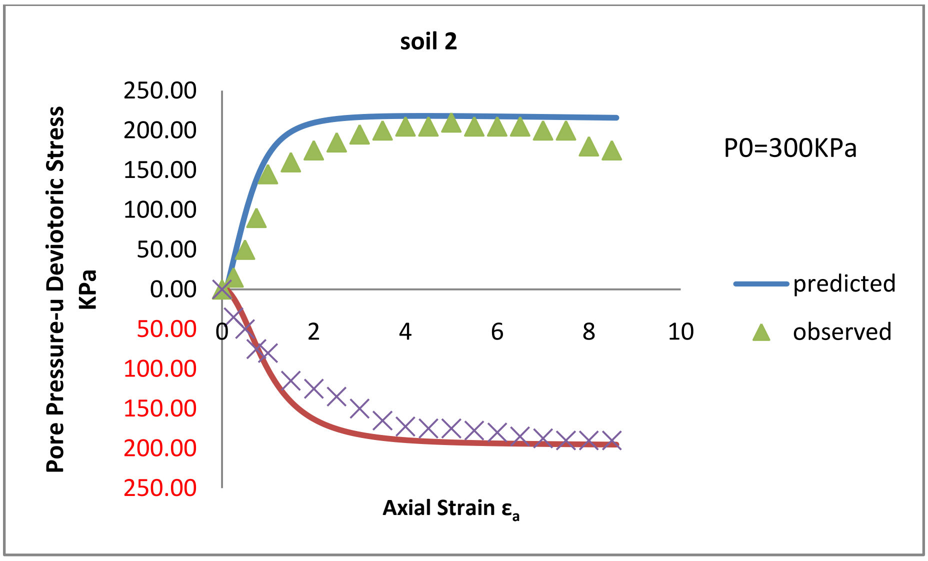

Fig 6. Stress-Strain- Pore Pressure Response of Soil 2

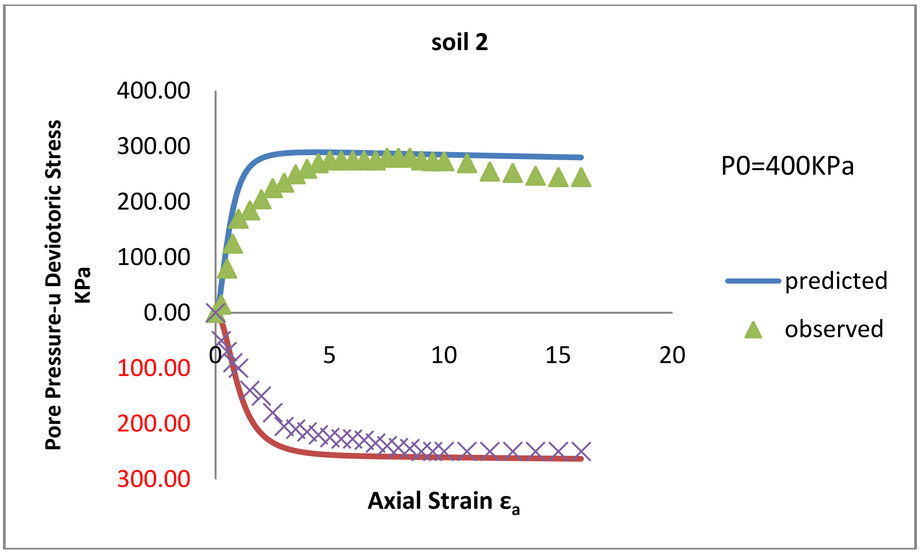

Fig 7. Stress-Strain- Pore Pressure Response of Soil 2

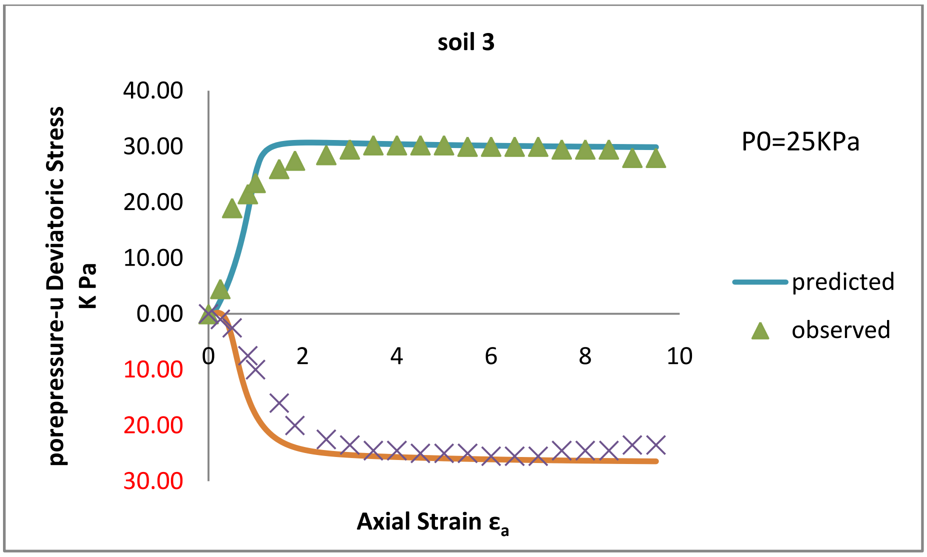

Fig 8. Stress-Strain- Pore Pressure Response of Soil 3

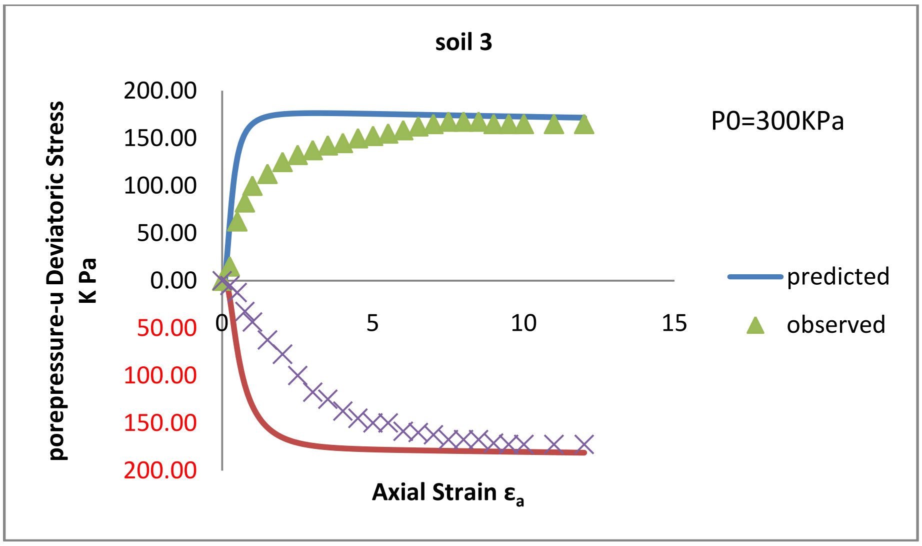

Fig 9. Stress-Strain- Pore Pressure Response of Soil 3

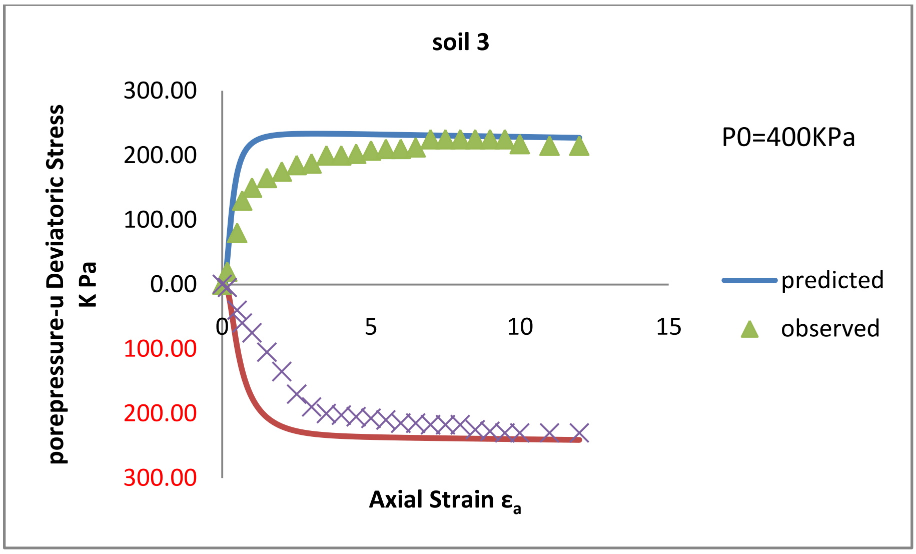

Fig 10. Stress-Strain- Pore Pressure Response of Soil 3

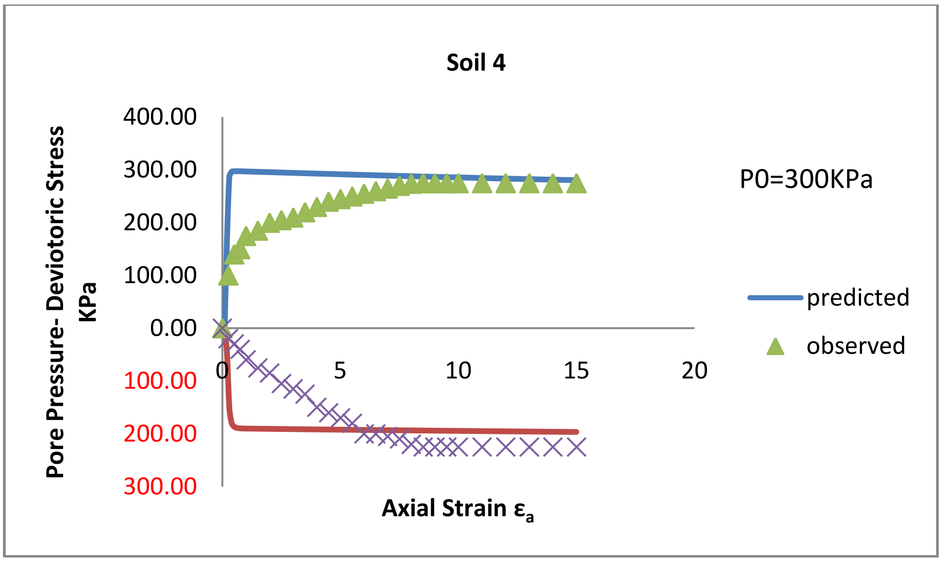

Fig 11. Stress-Strain- Pore Pressure Response of Soil 4

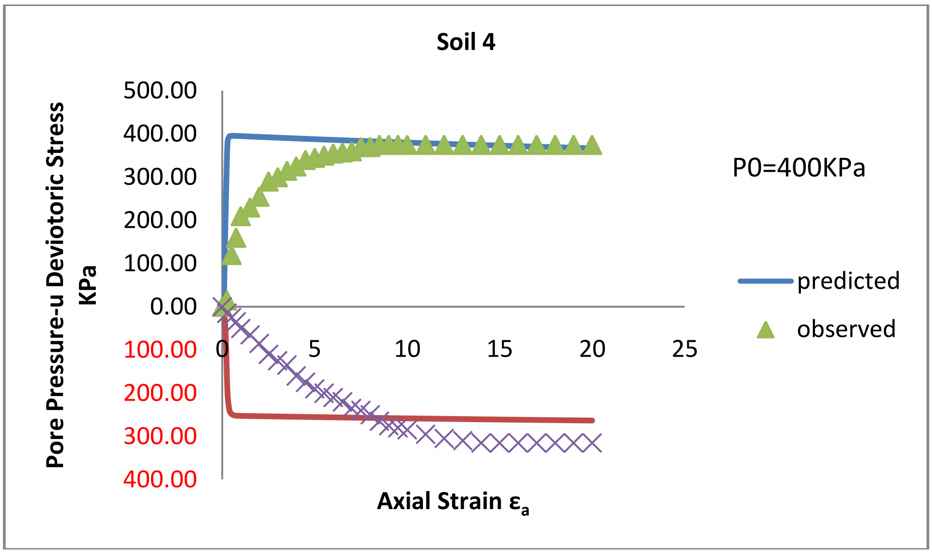

Fig 12. Stress-Strain- Pore Pressure Response of Soil 4

6.2 Tropical natural soils

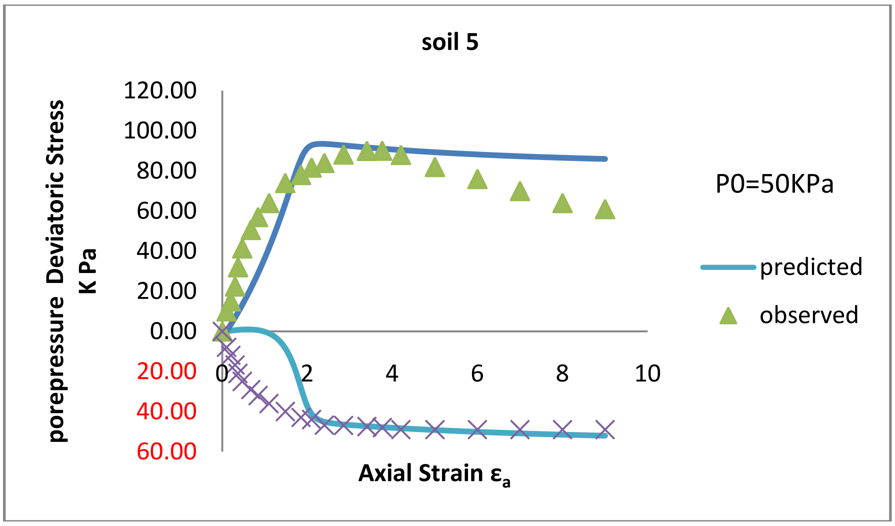

Fig 13. Stress-Strain- Pore Pressure Response of Soil 5

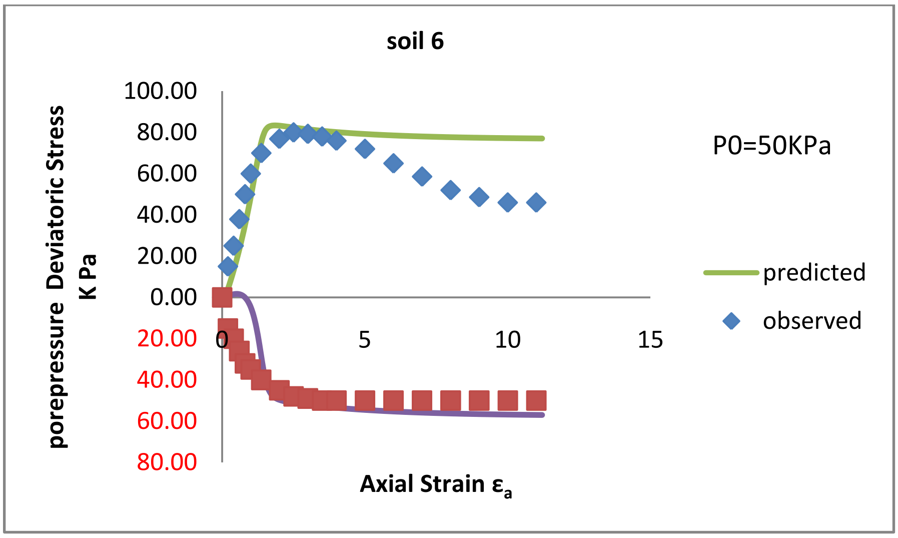

Fig 14. Stress-Strain- Pore Pressure Response of Soil 6

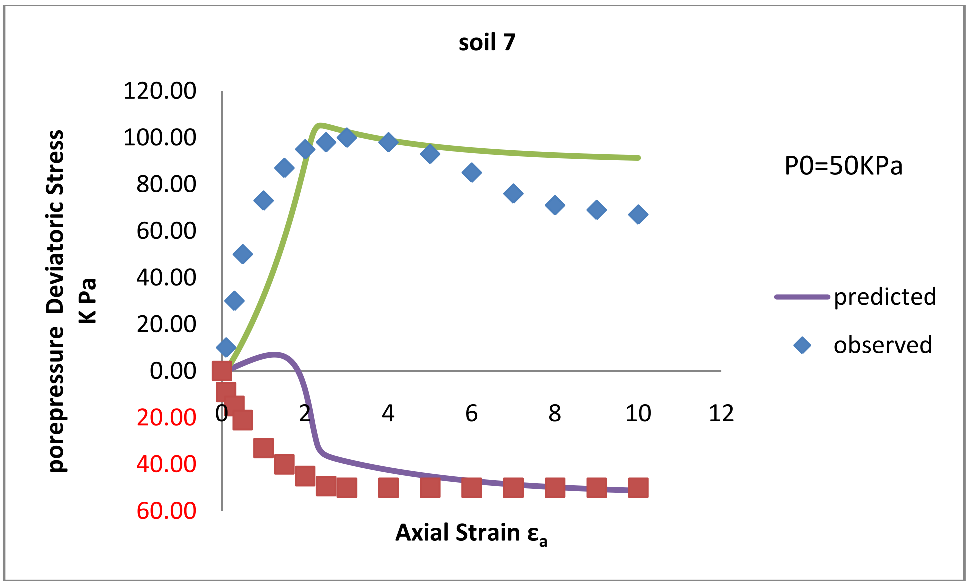

Fig 15. Stress-Strain- Pore Pressure Response of Soil 7

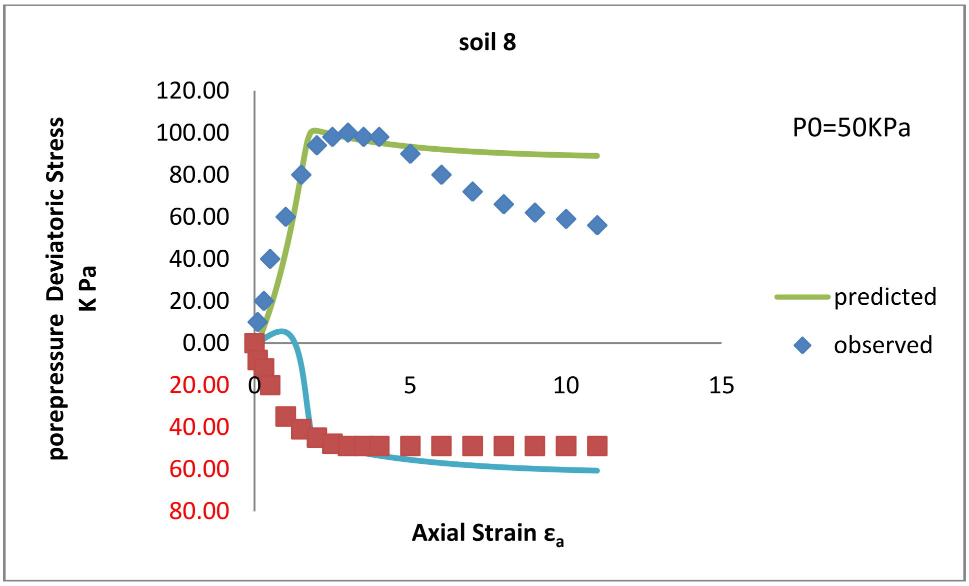

Fig 16. Stress-Strain- Pore Pressure Response of Soil 8

VI. Conclusions

Based on the analysis of test results of different soils considered in the present investigation and the proposed model predictions, the following concluding remarks may be made.

(1) The model proposed is a minor modification to the yield curve equation to proposed by Wheeler.

(2) The additional parameter incorporated in the model is the factor 'c' which is an intercept on deviatoric stress axis, which is due to interlocking of soil particle groups and particle associations in compacted soils.

(3) In case of normally compacted soils and reconstituted soils the factor 'c' reduces to zero and the yield curve becomes Wheelers model.

(4) The behaviour of soils both compacted and in-situ are predicted satisfactorily by the proposed model.

(5) The observations made on above are based on experimental work on soils considered in this paper, which can be further reinforced by elaborate experimental investigations involving different stress paths or loading conditions.

(6) The additional parameter ' c ' can be determined easily from routine soil tests, the other parameters are determined from the procedures defined by Wheeler.

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