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MODELS TO ESTIMATE SOIL MOISTURE RETENTION LIMITS AND SATURATED HYDRAULIC CONDUCTIVITY

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ABSTRACT

In-situ determination of soil water retention limits and saturated hydraulic conductivity is a time taking cumbersome procedure with intensive manpower requirement and heavy expenses. Therefore, it is essential to determine these properties by indirect approach. In the present study, models were developed to estimate soil moisture retention limits and saturated hydraulic conductivity for the sandy soil of paddy fields situated in the vicinity of Nirjuli, District Papumpare of Arunachal Pradesh (India). The simple correlation coefficient was determined among soil physical properties, moisture retention at field capacity, wilting point,. Furthermore, correlation was also determined among saturated hydraulic conductivity, porosity, voids ratio and effective size (D_{10}) and saturated moisture content. There was significant correlation between moisture retention at field capacity ($cm^3\ cm^{-3}$) and porosity at all depths. Significant correlation between moisture retention at field capacity ($cm^3\ cm^{-3}$) and void ratio was observed from 15 to 60 cm depth of the soil. Multiple linear regressions were developed for moisture retention at field capacity, wilting point and saturated hydraulic conductivity using different independent variables.

***Keywords**: Regression models; Soil moisture retention limits; Saturated hydraulic conductivity*

INTRODUCTION

Knowledge of soil moisture limits at field capacity and permanent wilting point is the prerequisite for irrigation and hydrological application related to agriculture. Studies of water retention characteristics of soils are necessary for better utilization of rainwater and irrigation water for optimum crop production. The knowledge is also useful for providing information on the ability of soils for storing water in the root zone and its subsequent availability to the crops. Retention and release of water from soil depends on same soil properties such as depth, texture, bulk density, organic carbon and cation exchange capacity (Walia *et al.*, 1999). All the water present in the soil is not available for plant use. Laboratory or in-situ determination of soil moisture characterstics is a time taking cumbersome procedure with intensive manpower requirement and heavy expenses. Therefore, it is essential to determine these limits by indirect estimation by relating them to commonly measured physical properties.

The saturated hydraulic conductivity is also used in the design of irrigation and drainage systems, canals and reservoirs, and as inputs for water balance models. Several methods are available in the literature for the estimation of saturated hydraulic conductivity. Saturated hydraulic conductivity is determined in the laboratory by constant and falling head permeameter methods (Punamia, 1988). Laboratory or in-situ determination is a time taking and cumbersome procedure. The estimation of saturated hydraulic conductivity is also possible from soil properties, namely soil texture and porosity by empirical formulae (Hazen formula, Brooks- Corey relationship) and graphical methods viz Johnson graph. For indirect estimation, it is essential to determine saturated hydraulic conductivity by relating them with commonly measured physical properties, viz porosity, void ratio, effective size (D_{10}) and saturated soil moisture content.

Das *et al.* (2005) studied the water retention characteristics of four typical soil series belonging to inceptisols of Damodar catchment, West Bengal (India). The study showed that water retentivity at 33kPa and 150kPa tension was significantly and positively corrected with clay, silt+clay, cation exchange capacity (CEC), exchangble Ca^{+2} + Mg^{+2} and negativity correlated with sand, bulk density and per cent pore space. An empirical model was developed through multiple linear regression equation using different soil parameters viz. sand, clay, CEC, exchchangble Ca^{+2} + Mg^{+2}, bulk density and per cent pore space which can be efficiently used to predict the water content of different soils. Kar and Singh (2004) studied soil water retention and transmission properties and established empirical relationship for determining soil water diffusivity, unsaturated hydraulic conductivity and metric potential based on retention-transmission properties. Singh and Kundu (2005) predicted profile water storage capacity of major soil groups of Orissa (India). Out of 21 soils sub groups, 2 were found to be low, 3 medium and 11 very high in water storage capacity. Simple correlation showed that moisture retention at field capacity, wilting point and available water in these was positively influenced by silt, clay, organic carbon, calcium carbonate and cation exchange capacity, whereas negatively influenced by sand and bulk density. Step wise regression analysis was carried out to test the effectiveness of the influence of variables namely sand, silt, clay, bulk density, organic carbon, calcium carbonate and cation exchange capacity on water retention, field capacity and wilting point. They concluded that soil water retention at field capacity and wilting point can be predicted by using easily measured soil properties like sand, silt and cation exchange capacity data with satisfactory level of accuracy. Pandey *et al.* (2006) developed a simple power function to estimate the soil water limits based an soil survey data such as texture for Chhattisgarh (India). Nikam *et al.*(2006) carried out study for water retention characteristics of shallows soils of basaltic origin in Nagpur district (India). They observed that clay content was positively correlated with the moisture held at field capacity (R^2=0.70) and permanent wilting (R^2=0.89). Kumar and Singh (2008) developed a linear relationship to predict water retention at field capacity and permanent wilting point as a function of some physical properties such as clay

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content, sand content, silt content and bulk density. Saha *et al.* (2013) had done evaluation of soil water retention characterstics using pedotransfer functions of *Alfisols* in Meghalya. Kumar *et al.*(2014) had done a statistical assessment of curve fitting to soil-water retention curve for two different types of soil viz., Kharaghpur sandy loam (four lyers) and black clay soil of Akola. The closed form equation describing soil water retention function of van Genuchten [VG(m,n) and VG(n)] and Brooks Corey was fitted using RETC software. Results indicated that all three models were found to perform reasonably well.

In the present study, regression models were developed to estimate moisture retention limits and saturated hydraulic conductivity for the sandy soil of paddy fields existing in the vicinity of Nirjuli (Itanagar), India. The main objectives of the study are as follows:

1. To find out the simple correlation coefficients among soil properties, moisture retention at field capacity and wilting point.
2. To find out the simple correlation coefficients among saturated hydraulic conductivity, porosity, void ratio, effective size (D_{10}) and saturated moisture content.
3. To develop multiple linear regression models for moisture retention at field capacity and wilting point by taking different soil parameters in different combinations.
4. To develop multiple linear regression models for saturated hydraulic conductivity by taking different soil parameters in combinations.

MATERIALS AND METHODS

Collection of data

Pandey *et al. (*2009) collected sixty four soil samples at selected paddy fields (Nirjuli village, Modern village, Doimukh and Banderdewa) in the vicinity of Nirjuli, Papumpare district of Arunachal Pradesh (India). Soil samples were collected from the depths (0-15 cm, 15-30 cm, 30-45 cm, 45-60 cm) using auger from paddy fields at four selected grid points at equal interval (Fig. 1).

After that selected point samples mixed thoroughly and half the sample was again mixed in the same way until about one kg representative sample was obtained. Bulk density, dry density, void ratio, porosity of the soil was determined by the methods suggested by Punmia (1988). Soil texture (sand, silt and clay percentage) was determined using the hydrometer method. Particle size was determined using sieve analysis method. A graph was drawn between per cent fineness and particle size. From that curve certain particle size D_{10} was also determined (Table 1).

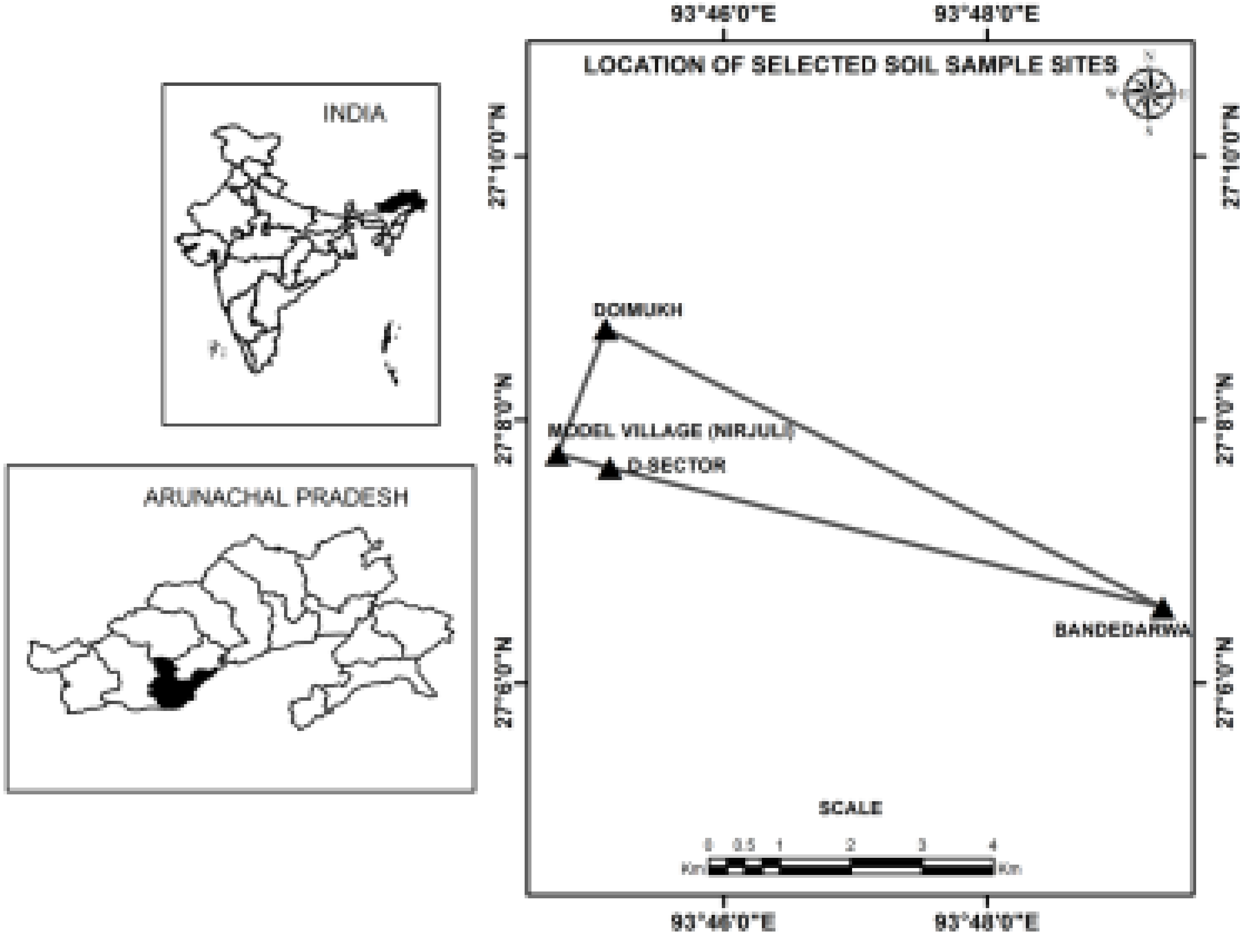

Fig. 1: Location map of selected soil samples sites

Table 1: Soil physical properties of at various depths at different sites

Name of Site	Soil Depth (cm)	Bulk Density (gcm^{-3})	Void Ratio	Porosity (%)	Sand (%)	Silt (%)	Clay (%)	D_{10} (mm)
D-SECTOR	0-15	1.83	0.93	48	99.715	0.002	0.238	0.13
	15-30	1.61	0.95	49	99.730	0.003	0.264	0.08
	30-45	1.60	0.96	49	99.719	0.004	0.277	0.06
	45-60	1.86	0.96	49	99.728	0.002	0.270	0.10
MODEL VILLAGE (NIRJULI)	0-15	1.52	0.97	49	99.727	0.003	0.269	0.10
	15-30	1.57	0.96	49	99.720	0.003	0.274	0.21
	30-45	1.57	0.96	49	99.700	0.002	0.289	0.08
	45-60	1.60	0.97	49	99.721	0.008	0.270	0.14
DOIMUKH	0-15	1.43	0.91	48	99.761	0.003	0.236	0.13
	15-30	1.61	0.85	46	99.774	0.005	0.222	0.20
	30-45	1.82	0.60	37	99.781	0.002	0.218	0.24
	45-60	1.49	0.94	48	99.771	0.006	0.223	0.10
BANDERDEWA	0-15	1.56	0.93	48	92.354	0.001	7.645	0.12
	15-30	1.60	0.85	46	88.450	0.002	11.548	0.10
	30-45	1.66	0.80	45	91.585	0.001	8.414	0.15
	45-60	1.61	0.93	48	88.450	0.001	11.549	0.23

(Source: Pandey *et al*., 2009)

Table 2: Soil moisture content (%) vs tension and saturated hydraulic conductivity at various depths

Name of Site	Soil Depth (cm)	Moisture Content (%)			Saturated hydraulic conductivity ($cm\ s^{-1}$)
		At saturation	At 1/3 bar pressure	15 bar pressure	
D-SECTOR	0-15	40.7	29.6	22.2	7.20×10^{-5}
	15-30	30.3	19.0	18.8	3.19×10^{-4}
	30-45	27.4	21.1	17.0	5.96×10^{-4}
	45-60	28.7	13.0	14.6	7.43×10^{-4}
MODEL VILLAGE (NIRJULI)	0-15	40.7	29.6	10.4	8.94×10^{-5}
	15-30	31.3	22.8	10.0	4.38×10^{-5}
	30-45	30.3	19.0	6.9	2.18×10^{-5}
	45-60	29.8	12.5	3.9	8.74×10^{-5}
DOIMUKH	0-15	40.7	28.2	11.4	1.831×10^{-4}
	15-30	40.1	27.7	11.3	1.831×10^{-5}
	30-45	39.2	26.8	11.1	1.831×10^{-6}
	45-60	41.7	28.4	10.9	1.831×10^{-7}
BANDERDEWA	0-15	50.7	35.1	16.7	1.721×10^{-4}
	15-30	43.9	29.2	15.4	1.721×10^{-5}
	30-45	38.3	28.3	13.3	1.721×10^{-6}
	45-60	39.4	24.0	12.2	1.721×10^{-7}

(Source: Pandey *et al*., 2009)

Saturated hydraulic conductivity of soil samples at various depths was determined using the constant head method (Table 2). Water retention property of soil was determined using pressure plate apparatus. Pressure was maintained at 1/3 bar and 15 bar respectively, for 24 hours and then the moisture content of the soil samples was determined by gravimetric method (Table 2).

Conversion of gravimetric moisture content to volumetric moisture content

Gravimetric moisture content data were converted into volumetric moisture content data by multiplying with bulk density. This was done to make model sensitive to bulk density.

Determination of correlation coefficient

The simple correlation coefficient was determined among soil physical properties, moisture retention at field capacity, wilting point. Simple correlation was also determined among saturated hydraulic conductivity, porosity, void ratio and effective size (D_{10}). t test was carried out to determine significance of correlation at 5% significance level using the following:

$$t = \{r \sqrt{(n-2)}\} / \sqrt{(1 - r^2)} \quad \ldots\ldots\ldots\ldots(1)$$

where, t= calculated value of t-test, r= correlation coefficient, and n= no. of observations.

Development of regression models

The following regression relationships were developed using SPSS software.

a) Multiple linear regression models were developed taking volumetric soil water content (cm^{3}cm^{-3}) at soil water limits as a dependent variable and sand (%) , clay (%), bulk density, porosity, void ratio etc. as independent variables.

b) Multiple linear regression models were developed taking hydraulic conductivity (m day^{-1}) as dependent variable and void ratio, porosity, D_{10} (mm), volumetric saturated moisture content (cm^{3}cm^{-3}) as independent variables.

Qualitive evaluation of model performance

The qualitative performance of the models was ascertained by estimating the value of coefficient of multiple determination (R^2) , root mean square error (RMSE) and mean absolute percentage error (MAPE). The general acceptable limits for R^2, RMSE and MAPE were taken as close to 1, 0 and 20% respectively in the study.

RESULTS AND DISCUSSION

Correlation among soil properties, moisture retention (volume basis) at soil water limits

Table 3 presents simple correlation between soil properties (sand (%), silt (%), clay(%), bulk density and porosity) and moisture retention (volume basis) at field capacity and wilting point for the soil depths 0-15, 15-30, 30-45 and 45-60 cm respectively.

There was significant correlation between moisture retention at field capacity (cm^3 cm^{-3}) and porosity at all depths. Significant correlation between moisture retention at field capacity (cm^3 cm^{-3}) and void ratio was also observed from 15 to 60 cm depth of the soil.

Correlation among saturated hydraulic conductivity (K), void ratio, porosity, D_{10} and saturated soil moisture content (volumetric basis) at 0-60 cm of soil depth

Table 4 presents simple correlation among saturated hydraulic conductivity (K), void ratio, porosity, D_{10} and saturated soil moisture (volumetric basis) for the soil depths 0-15, 15-30, 30-45 and 45-60 cm respectively. Correlation coefficient between hydraulic conductivity and porosity at depths 0-15 cm, 15-30 cm, 30-45 cm and 45-60 cm were observed -0.468, 0.644, 0.492 and 0.67 respectively. However, saturated hydraulic conductivity was not found statistically significant correlated with void ratio, porosity, D_{10} and saturated soil moisture content (volumetric basis) at all depths.

Regression models for moisture retention at field capacity

Table 5 presents the linear regression models for moisture retention (cm^{3}cm^{-3}) at field capacity at soil depths of 0-15, 15-30, 30-45 and 45-60 cm.

At 0-15 cm depth, multiple linear regression model resulted in the coefficient of multiple determination 0.88 when

Table 3: Correlation coefficient between various parameters at various soil depths

Physical Parameters	θ_{FC} (cm3 cm^{-3})				θ_{WP}(cm3 cm^{-3})			
	0-15 cm	15-30 cm	30-45 cm	45-60 cm	0-15 cm	15-30 cm	30-45 cm	45-60 cm
BD(gcm^{-3})	-0.41	0.28	0.47	-0.59	0.84	0.63	0.52	0.66
Void ratio(e)	0.69	-0.97**	-0.97 **	-0.93**	-0.22	0.08	-0.10	-0.33
Porosity(η) (%)	0.99 **	-0.98**	-0.96**	-0.98**	-0.51	0.14	-0.08	-0.08
Sand(%)	-0.05	-0.65	-0.09	-0.45	-0.52	-0.25	-0.19	-0.18
Silt(%)	-0.57	0.12	-0.26	-0.29	0.91	-0.42	0.47	-0.85
Clay(%)	+0.02	0.65	0.09	0.45	0.55	0.25	0.19	0.18

**= Significant at 5 % level

Table 4: Correlation coefficient between K and various soil physical parameters at various depths

	K(mday^{-1})			
Physical Parameters	0-15 cm	15-30 cm	30-45 cm	45-60 cm
Void ratio(e)	-0.562	0.614	0.524	0.52
Porosity (η)(%)	-0.468	0.644	0.492	0.67
D_{10} (cm)	0.318	-0.632	-0.615	-0.481
θ_S(cm^{3}cm^{-3})	-0.92	-0.636	-0.674	-0.41

independent variables were taken porosity and clay. At 15-30 cm depth, multiple linear regression model resulted in the coefficient of multiple determination 1.0 when independent variables were taken bulk density, porosity and clay. At 30-45 cm depth, multiple linear regression model resulted in the coefficient of multiple determination 1.0 when independent variables were taken porosity, silt and clay. At 45-60 cm depth, multiple linear regression model resulted in the coefficient of multiple determination 1.0 when independent variables were taken bulk density, void ratio and clay. The values of R^2, RMSE and MAPE of all these models were found within permissible limit. Hence, models can be used for predicting moisture retention at field capcity in the study area.

Table 5: Regression models for moisture retention (cm^3cm^{-3}) at field capacity at various soil depths

Soil Depth (cm)	Regression model	R^2	RMSE (cm^3cm^{-3})	MAPE (%)
0-15	$\theta_{WP=}$ 8.367-0.0190 η(%)+ 4.139Clay(%)	0.883	0.037	15.53
15-30	θ_{WP}= -7.535+3.645BD(gcm^{-3}) + 0.040 η(%)+0.009 Clay %)	1.00	0.0065	3.105
30-45	θ_{WP} = 0.327-0.008 η(%)+81.970 Silt(%)+0.020Clay(%)	1.00	0.0043	2.44
45-60	θ_{WP} = 4.446+0.593BD(gcm^{-3})-5.496 e-0.008 Clay(%)	1.00	0.0008	0.660

Regression models for moisture retention at wilting point

Table 6 presents the linear regression models for moisture retention (cm^3cm^{-3}) at wilting point at 0-15, 15-30, 30-45 and 45-60 cm soil depths. At 0-15 cm soil depth, multiple linear regression models resulted in the coefficient of multiple determination 1.0 when independent variables were taken porosity and clay. At 15-30 cm soil depth, multiple linear regression model resulted in the coefficient of multiple determination 1.0 when independent variables were taken bulk density and porosity. At 30-45 cm depth, multiple linear regression model resulted in the coefficient of multiple determination 1.0 when independent variables were taken porosity, silt and clay. At 45-60 cm depth, multiple linear regression model resulted in the coefficient of multiple determination 1.0 when independent variables were taken bulk density, void ratio and clay. The values of R^2, RMSE and MAPE values of of all these models were found within permissible limit. Hence, models can be used for predicting moisture retention at wilting point in the study area.

Table 6: Regression models for moisture retention (cm^3cm^{-3}) at wilting point at various soil depths

Soil Depth (cm)	Regression model	R^2	RMSE (cm^3cm^{-3})	MAPE (%)
0-15	θ_{FC} = -4.166+0.098η(%)-0.718 Clay(%)	0.80	0.1021	16.61
15-30	$\theta_{FC=}$ 3.886-0.802 BD(gcm^{-3})-0.047 η(%)	1.00	0.0140	3.68
30-45	θ_{FC} = 1.065-0.017 η(%)+ 27.546 Silt(%)+0.008 Clay(%)	1.00	0.0069	1.872
45-60	θ_{FC} =7.192-0.109 BD(gcm^{-3})-7.026e-0.008 Clay(%)	1.00	0.0018	0.299

In a similar type of study Singh and Kundu (2005); Kumar and Singh (2008) concluded that multiple regression model could be developed using soil physical characteristics for predicting soil moisture retention limit. Patil *et al*. (2007) also favoured to develop site specific pedo-transfer functions to predict soil moisture retention limits.

Multiple linear regression models for saturated hydraulic conductivity

Table 7 presents multiple linear regression models for saturated hydraulic conductivity at 0-15, 15-30 and 45-60 cm soil depths. multiple linear regression models resulted in the highest coefficient of multiple determination (1.0) when independent variables were taken saturated moisture content,void ratio and D_{10}. At 30-45 cm soil depth, multiple linear regression model resulted in the highest coefficient of multiple determination (1.0) when independent variables were taken saturated moisture content, void ratio , porosity and D_{10}.

At 45-60 cm soil depth, multiple linear regression model resulted in the highest coefficient of multiple determination(1.0) when independent variables were taken saturated moisture content, void ratio and D_{10}. The values of R^2, RMSE and MAPE of all these models were found within permissible limit. Hence, models can be used for predicting saturated hydraulic conductivity in the study area.

Table 7: Multiple linear regression models for hydraulic conductivity at various soil depths

Soil depth (cm)	Regression model	R^2	RMSE (m day^{-1})	MAPE (%)
0-15	K(m day^{-1})= 4.945- θ_S -4.385e-6.120 D_{10}(mm)	1	0.0007	0.693
15-30	K(m day^{-1})= 4.396-3.484 θ_S-3.154e-0.730D_{10}(mm)	1	0.0005	2.14
30-45	K(m day^{-1})= 2.620 + 4.948 θ_S -0.063 η(%)-11.203 D_{10}(mm)	1	0.0151	10.78
45-60	K(m day^{-1}=70.821-11.190 θ_S-69.399e-8.506D_{10}(mm)	1	0.0004	13.71

CONCLUSION

There was significant correlation between moisture retention ($cm^3\ cm^{-3}$) at field capacity and porosity at all depths. Similarly, significant correlation between moisture retention ($cm^3\ cm^{-3}$) at field capacity and void ratio was observed from 15 to 60 cm depth of the soil. The values of R^2, RMSE and MAPE of multiple linear regression models for moisture retention at field capacity and wilting point were found within permissible limit. Hence, moisture retention at field capacity and wilting point can be predicted at various soil depths by using easily measured soil properties like bulk density, porosity, void ratio, silt (%) and clay(%) data for the study area. Saturated hydraulic conductivity at various soil depths can also be predicted by using developed multiple linear regression models easily from the soil properties like saturation moisture content, void ratio, porosity and effective diameter (D_{10}) for the study area.

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