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PREDICTION OF THE BREAKING STRESS OF CLAYEY SOILS FROM TCHI DEPRESSION TO BENIN

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ABSTRACT

The phenomena of shrinkage and swelling of clay soils depending on the water content are manifested by disorders affecting mainly individual houses, often not very rigid and superficially founded. The superficial foundations of infrastructures built on swelling soils are subjected to several stresses due to shrinkage and swelling phenomena. These stresses are the cause of damage to the frames in the form of cracks, or even lead to the partial or total breakage of the structure when it is built without special precautions. In order to control these induced stresses and to safeguard these infrastructures, it is necessary to control the breaking stress so that the dimensioned foundations do not cause the structure to break. The objective of this study is to develop a model to estimate the breaking stress thanks to the physical parameters of these soils.

To achieve this, we performed several physical and mechanical tests on swelling soil samples taken from the study area, the results of which we used to use the established non-linear least squares method of swelling pressure prediction models. The models were based on test results from 24 soil samples. The tests were carried out in accordance with the French NF standards.

This study has shown that the shear strength of a soil is a function of several physical parameters, mainly: pre-consolidation stress and plasticity index. We obtained the model qu=(2.9-1.181.IP). σ'p allowing us to predict the shear strength for the study area. This model is obtained with a regression coefficient precision r2 = 98.50%.

KEYWORDS: surface foundations, early degradation, shear strength, prediction model.

1. INTRODUCTION

The allowable soil stress is the limit value of the vertical stress that a soil can mobilize under a given foundation without risk of excessive settlement or failure. It is measured using various procedures. These processes (dynamic penetrometer, soil desiccation, etc.) are applicable to both fine and grained soils and provide accurate results. Some fine soils (clay soils) because of their mineralogy) are subject to the phenomenon of shrinkage - swelling (Amal Medjnoun, 2014) which makes it difficult to access and perform these tests. These phenomena on the clayey surface formations thus cause settling and upheavals which are manifested by the appearance of disorder (A. El Yaakoubi, 2014) such as cracks, affecting mainly the works such as individual houses, or social (school ...) built at shallow depths and without special precautions. Examples of disorders related to the presence of swelling clays are numerous and varied (V. GBAGUIDI et al. 2010), (Yvette S. T. KIKI, 2004). In Benin, these soils are found in the Lama region (Koffi Judicaël Agbéléle, 2016) . It is therefore difficult to understand the constraints of these processes because not only does it vary according to the state of shrinkage or swelling of the soil (Westerberg, B., et al, 2015) but also its determination is very expensive. With this in mind, several authors have set up several empirical models that can be used to estimate the value of the mechanical characteristics of these soils, namely: the swelling pressure (Koffi Judicaël Agbélélé et all, 2020), the undrained shear strength, etc. To the number of authors who have studied the estimation of the stress of ruptures we have: Ching J., and Phoon, K. K. (2012a.), Ching J, Phoon K.K., and Chen C-H. (2014); H.E. Low, T. Lunne, K.H. (2015); Müller, R., Larsson, S., and Spross, J. (2014), who proposes a relationship that links shear strength from the plasticity index and Windisch pre-consolidation stress. And Yong (1990) proposes to determine the stress by a relation associating the pre-consolidation stress.

2. MATERIALS AND METHODS

2.1. Soil identification

For a better appreciation of the deformations observed at the level of the soils supporting the infrastructures in the TCHI depression, we first proceeded with the geotechnical analysis of twenty-four (24) samples taken from the sites in our study area at depths of 0.50 m to 1.00 m; 1.00 m to 2.00 m and 2.00 m to 3.00 m relative to the soil surface.

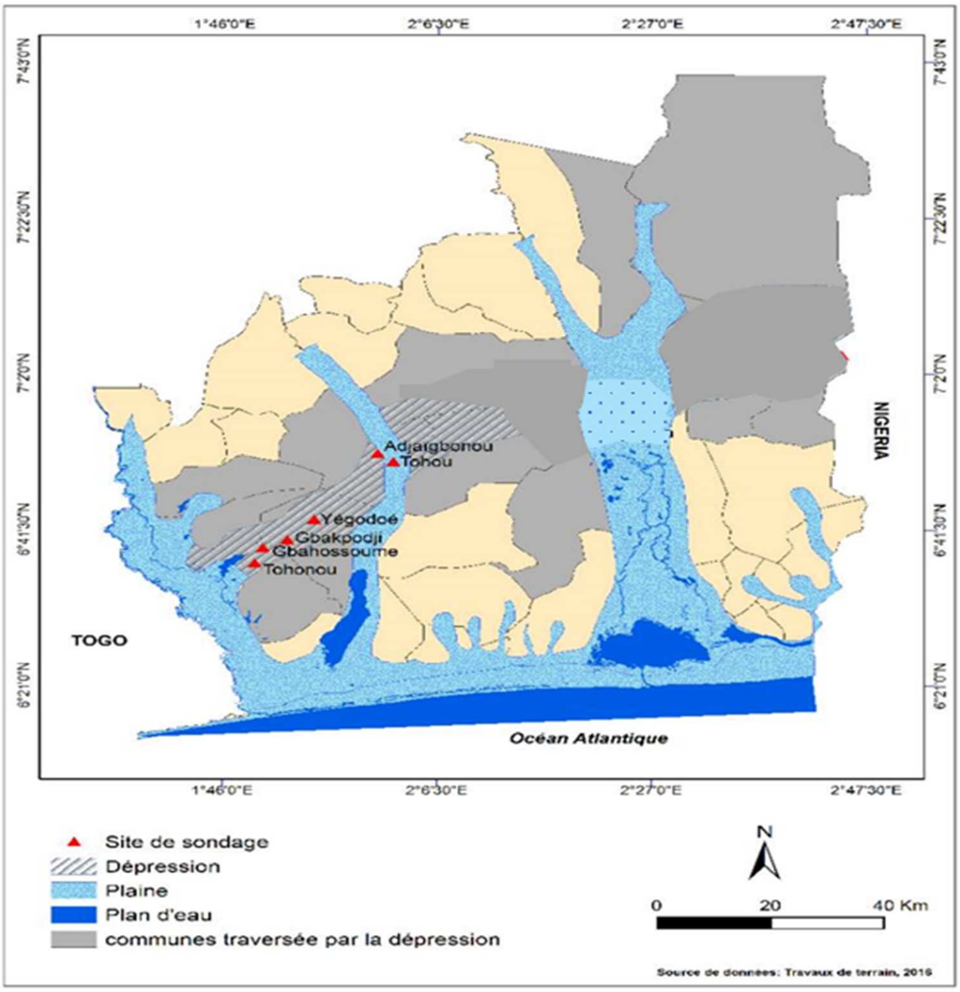

Fig. 1: Sample collection card

The Centre National des Essais et Recherches en Travaux Publics (CNERTP) of Benin and the Laboratoire des Travaux Publics (LAB-TP) of Togo served as the framework for the various tests.

2.2 Methodology for estimating the breaking stress

The breaking stress was evaluated using Terzaghi's formula :

$$q_u = c.N_c + q.N_q + \frac{1}{2}.\Upsilon.B.N_\Upsilon \qquad (i)$$

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Where Nc, Nq, and Nϒ are the lift factors and are only a function of the angle of ground friction, φ.

$$Nc = \cot\varphi.(Nq-1);\ Nq = \frac{e^{2\left(3\pi/\left(4-\frac{\varphi}{2}\right)\right)\tan\varphi}}{2.\cos^2\left(45+\frac{\varphi}{2}\right)};\ N\Upsilon = \frac{1}{2}\left(\frac{K_{p\Upsilon}}{\cos^2\varphi}-1\right)\tan\varphi \qquad \text{(ii)}$$

It must be said that the calculation method initiated by Terzaghi, (1951) for the evaluation of the bearing capacity of a foundation is currently adopted by most geotechnicians and has been used for the determination of the ultimate tensile stress in this document.

2.3 Methodology for estimating the breaking stress

Many authors have worked on the empirical equations in order to find values for the breaking stress (Pg) from simple realization tests such as Atterberg limits, shrinkage limit, percentage of clay fraction (< 2 µm). The approach of these authors consists in establishing correlations between the breaking stress and some geotechnical parameters of identification A. Usmani; G. V. Ramana; and K. G. Sharma (2010). From these empirical equations it is possible to determine the characteristics of the swollen soil immediately after completion of the identification tests and to estimate or quantify the swelling characteristics that may develop under water and/or mechanical soil variations. Many of these correlations are listed by Ching, J., and Phoon, K. K. (2014b).

Larsson Rolf (1980), is one of these authors who proposes to determine the ratio of the breaking stress to the pre-consolidation stress:

$$\frac{qu}{\sigma' p} = 0{,}08 + 0{,}55\, IP \qquad (iii)$$

Windisch. And Yong (1990) proposes to determine the constraint :

$$qu = 2{,}32 + 0{,}260\, \sigma' p \qquad (iv)$$

- ***Choice of the prediction model***

The reliability of the models listed above will be verified by means of statistical tests, namely the Fisher test and the comparison of the R2 determination coefficients, from the test data obtained per site studied in order to make a choice which will then be contextualized so that it is applicable to our site .

- ***Definition of the suitability test***

The measurement of the adequacy of a model is essentially based on the calculation of the coefficient of determination (R2) and the analysis of the residuals. The formula used to evaluate the coefficient of determination for a non-linear regression is that of Kvalseth *(*1985) .

- ***Parameter identification approach***

The parameters of the inflation pressure prediction model were determined, by the non-linear least squares method, using the statistical tool STATA 2014.

By this fact, the coefficients are determined and the model is known. After fitting the model, statistical tests were carried out to assess the reliability of the fitted model. Among these tests we have: the significance test of the model, the determination of the R2 coefficient and the analysis of the residuals.

- **Meaning of the model :**

The analysis of the significance of the model will be performed using the Fisher test at a 1% risk. It will confirm the test carried out using the R2 coefficient. In statistics, the test of equality of two variances, is a hypothesis test that allows to test the null hypothesis that two normal laws have the same variance, thus verifying if the law described by the model has the same variance as the one described by the results of the laboratory tests.

- **Coefficient of determination R2**

The measurement of the adequacy of a model is essentially based on the calculation of the coefficient of determination (R2) and the analysis of the residuals. According to *Kvalseth (*1985) , the appropriate formula for evaluating the coefficient of determination for a non-linear regression is of the form :

$$R^2 = 1 - \frac{CRDD}{SSE} \quad [12]\text{With} \qquad (v)$$

$$SSR = \sum_{i=1}^{n}(y_i - \bar{y})^2 et\ SSE = \sum_{i=1}^{n}(y_i - \ddot{y_i})^2 \qquad (vi)$$

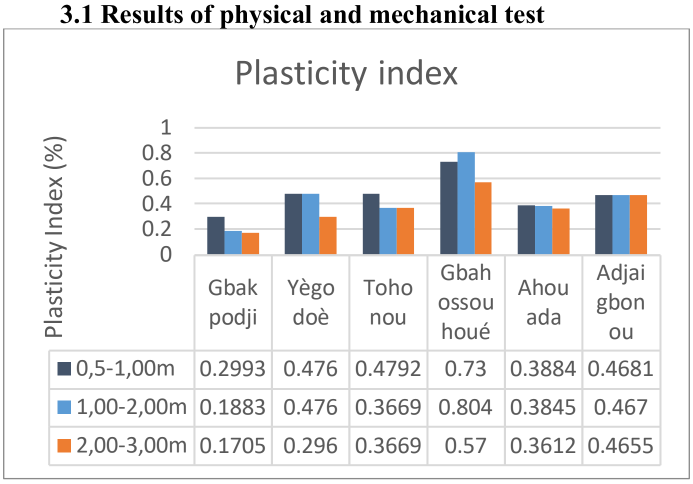
$\ddot{y}_i$: value of the inflation pressure predicted by the model
y_i : Value of the inflation pressure obtained by test
$\bar{y}$: Average of the values of the inflation pressure obtained by test
From this model we have moved to its adjustment by numerical approach to identify the parameters.

Residue analysis
It is an essential part of the study of the adequacy of any model. The review of residuals will take place in two distinct stages: model validity and model quality. The validity study is based primarily on the statistical test of the normality of the residuals.

2.4 Equipment
The equipment used for the physical and mechanical parameters of the soils in our study area is: a Casagrande apparatus for the determination of Atterberg limits, a set of sieves for the determination of the passageways to the different sieves including the 2 µm sieve, an oven for drying the materials, balances for weighing the samples and an oedometric apparatus for the determination of the swelling pressure.

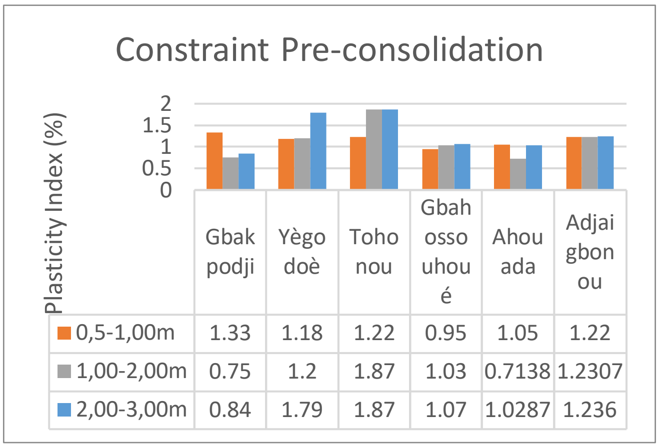
3. RESULTS AND DISCUSSION

3.1 Results of physical and mechanical test



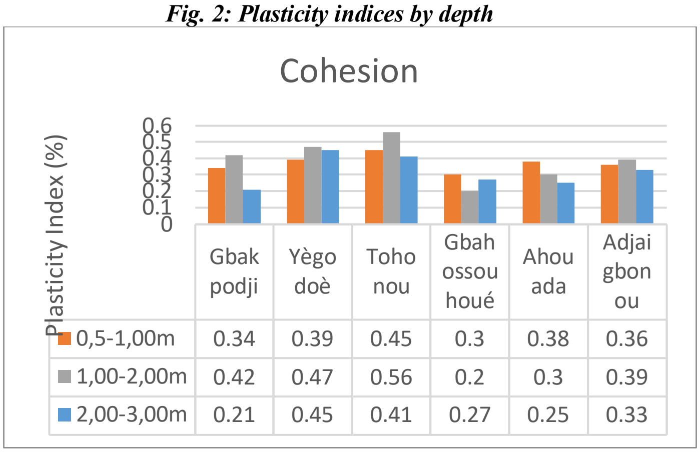
	Gbakpodji	Yègodoè	Tohonou	Gbahossouhoué	Ahouada	Adjaigbonou
0,5-1,00m	0.2993	0.476	0.4792	0.73	0.3884	0.4681
1,00-2,00m	0.1883	0.476	0.3669	0.804	0.3845	0.467
2,00-3,00m	0.1705	0.296	0.3669	0.57	0.3612	0.4655

Fig. 2: Plasticity indices by depth



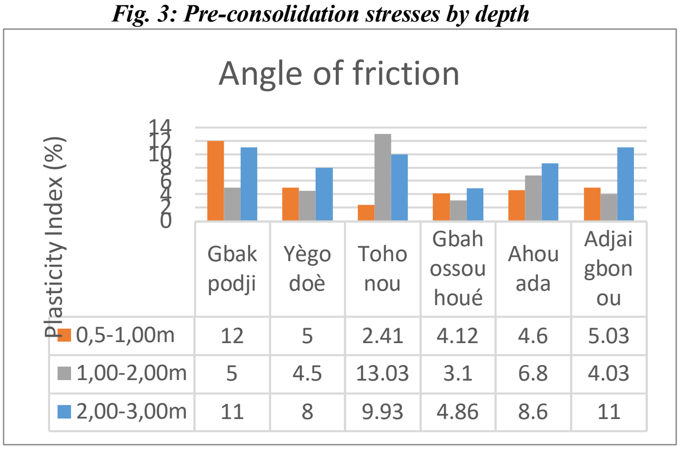
	Gbakpodji	Yègodoè	Tohonou	Gbahossouhoué	Ahouada	Adjaigbonou
0,5-1,00m	1.33	1.18	1.22	0.95	1.05	1.22
1,00-2,00m	0.75	1.2	1.87	1.03	0.7138	1.2307
2,00-3,00m	0.84	1.79	1.87	1.07	1.0287	1.236

Fig. 3: Pre-consolidation stresses by depth



	Gbakpodji	Yègodoè	Tohonou	Gbahossouhoué	Ahouada	Adjaigbonou
0,5-1,00m	0.34	0.39	0.45	0.3	0.38	0.36
1,00-2,00m	0.42	0.47	0.56	0.2	0.3	0.39
2,00-3,00m	0.21	0.45	0.41	0.27	0.25	0.33

Fig. 4: Cohesion by depth



	Gbakpodji	Yègodoè	Tohonou	Gbahossouhoué	Ahouada	Adjaigbonou
0,5-1,00m	12	5	2.41	4.12	4.6	5.03
1,00-2,00m	5	4.5	13.03	3.1	6.8	4.03
2,00-3,00m	11	8	9.93	4.86	8.6	11

Fig. 5: Angle of friction by depth

The choice of the prediction model was guided by various statistical tests including the Fisher Test and the R2 coefficient of determination. The tests were carried out for the different existing models.
For each of the sites studied in the TCHI depression and for all depths, the results of the Fisher test and the model regression coefficient are as follows :

Table 1: Fisher test results and R2 coefficient results

Depression	Model	Coefficient R²	Fisher Test
TCHI, KHO and ISSABA	Windisch EJ., Yong RN	0,4736	The model does not fit the data correctly.
	Larson Rolf	0,5438	

The previous results show that none of the models fit the data correctly and therefore cannot be used to predict the breaking stress of the studied sites. It will therefore be necessary to establish an appropriate prediction model for these sites.

Although these two models **- Larson Rolf and Windisch EJ., Yong RN -**, according to Fisher's test, do not correctly fit the data for all the sites studied, Larson Rolf's model (1980), on the other hand, has a better calculated R2 coefficient of determination (0.5438 compared to 0.4736 for Windisch EJ., Yong RN, 1990). Thus, within the framework of our research work, we appropriate this model and adjust it.

3.2 Détermination of model parameters

The adjustment of the function was done by the non-linear least squares method. This method minimizes the squared difference between the experimental values and those given by the function of **Larson Rolf, (1980)** . Table 2 below summarizes the values of the parameters found :

$$\frac{qu}{\sigma' p} = a + b * IP \qquad \text{(vii)}$$

Table 2: Coefficients a and b determined using the method of least squares

Depression	Depth (m)	A	b
TCHI	0,00 – 0,50	3,489	0,424
	0,50 – 1,00	-0,812	2,72
	1,00 – 2,00	-1,10	2,89
	2,00 – 3,00	**-1,09**	**2,9**

The different parameters "a" and "b" allowed us to write the different models for the prediction of the inflation pressure.

3.3 Standardization of the established models

The analysis of the different models established led us to look for similarities between the different models in order to determine a single model for depression at any depth. To this end, we have :
-established a single model for the depression from 0.50 m to 3.00 m depth (the 0.00 m to 0.50 m interval was not considered because generally the anchorage depth for any structure is at least greater than 0.50 m) ;
-verified the adequacy of the unified models established ;
-appreciated the efficiency (accuracy) of the different unified models established for the different depths (at intervals).

3.4 Determination of unified models

The values of the parameters "a", and "b" of **Larson Rolf**'s model (1980) regardless of depth are summarized in the following table:

Table 3: Coefficients a, b, c, and d of established models based on Larson Rolf's model, 1980.

Depression	Depth (m)	a	b
TCHI	0,50 – 3,00 m	-1,181	2,9

These coefficients allowed us to rewrite the adjusted models and then to proceed with the fit tests.

Significance testing of each model

The following table shows the results of the Fisher test.

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Table 4: Fisher's test results for the unified models.

Depths (m)	Depression	Fcalc	Flue
0,50-3,00	TCHI	133,00	26,98

Statistical tests show that for all sites and regardless of the model, Fcal is superior to Flu, according to Montgomery and Runger (2003). We can conclude that the different numerical models developed fit the experimental data well.

- **Residue Normality**

Table 5 Residual normality test results on unified models

Depth	Depression TCHI	
	What Predicts	qu Calculated
0,50-1,00m	3,3869	3,3508
	2,7587	2,7525
	2,8476	2,8068
	1,9360	2,0395
	2,5634	2,4964
	2,8636	2,9374
1,00-2,00m	2,0082	1,9934
	2,8054	2,9823
	4,6127	4,5723
	2,0090	2,0205
	1,7459	1,7452
	2,8903	2,9147
2,00-3,00m	2,2669	2,2860
	4,5653	4,5710
	4,6127	4,6834
	2,5091	2,5443
	2,5444	2,6245
	2,9049	2,9741

Looking at the previous table, we see that none of the residues are outside the interval [2; -2]. We can admit, according to Montgomery and Runger (2003) [11], that the estimated residuals (errors) are normally distributed. The following table presents the results of the adequacy tests carried out :

Table 6: Residual normality test result for unified models

Tests Depressions	Coefficient R2	Fisher suitability test	Outlier searches	Error normality
TCHI	0,9950	Correctly adjusts the data	None	OK

In order to better appreciate the quality of the different models, the following curve allows to observe the differences between the laboratory data, the fitted and non-fitted model.

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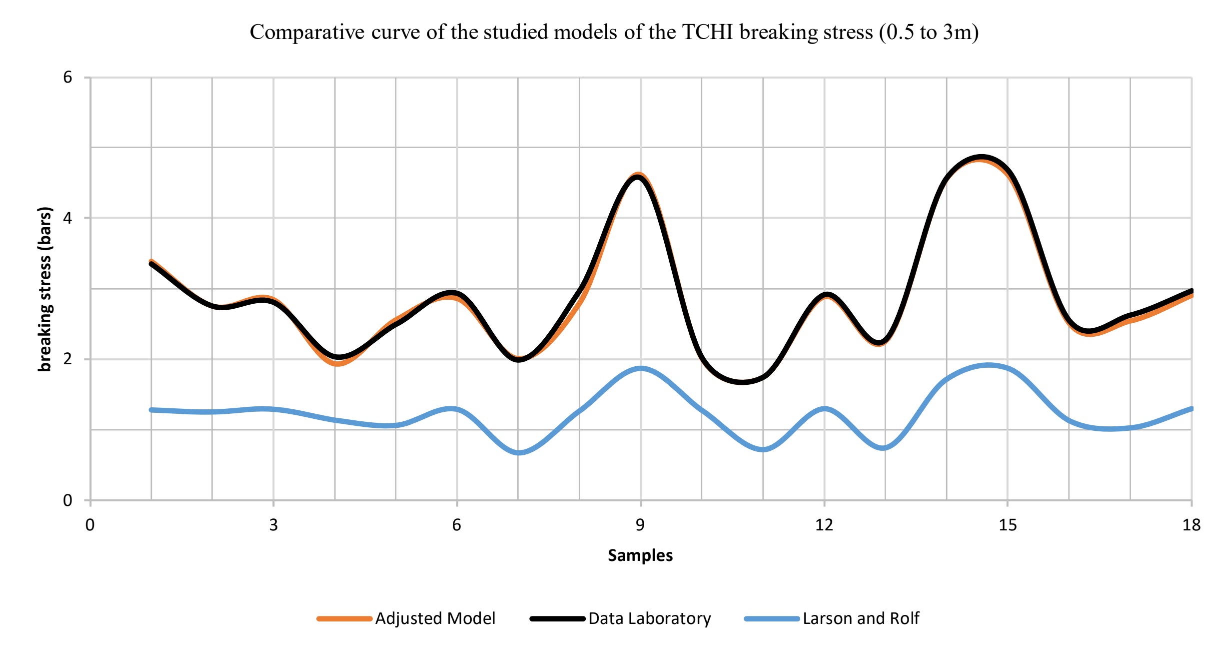

Figure 6: Evolution of the constraint of as a function of the sites of the TCHI depression

We note that the curves "fitted model" and "fitted model" are $qu = (2{,}9 - 1{,}181.IP).\sigma'p$ and 'Laboratory Data" are similar except for a few differences. This then justifies the accuracy of the model close to 99% and differs very well from the model of **Larson Rolf**, (1980).

3.5. Verification of the effectiveness of the unified models for the different depths

To check the accuracy of the different models, the regression coefficient was determined for each model with interval data. With a regression rate greater than 95% according to Montgomery and Runger (2003), the model is considered viable for the selected interval.

Table 7: Reliability test results of the unified models by depths

Depths	Depressions	Coefficient R2	Fisher Test
0,50-1,00	TCHI	0,9837	The model adjusts the data correctly
1,00-2,00	TCHI	0,9940	The model adjusts the data correctly
2,00-3,00	TCHI	0,9977	The model adjusts the data correctly

Through this table, we notice that the R2 coefficient is higher than 95% (0.95) for all depths. The unified models therefore fit the studied data perfectly and can be used for the determination of the breaking stress from 0.50 m to 3.00 m depth for the sites studied without having to resort to the various mechanical tests of non-drained shear.

4. CONCLUSION

In the Lama Depression, in particular the TCHI Depression, the experimental study carried out on intact soils collected at different depths concluded that these soils are clays and that correlations can be established. The study of the modelling of the breaking stress is of paramount importance. It has allowed the identification of predictive models of fracture stress as a function of physical parameters. The unified model based on the model of **Larson Rolf, (1980)** can be used to predict the breaking stress of soils in the localities studied in the TCHI Depression. This model will make it possible to predict the breaking strength of these soils and others by helping to safeguard and ensure the good performance of the works that are carried out in these risk areas

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