Chapter

Swelling Clay Parameters Investigation Using Design of Experiments (A Case Study)

Yacine Berrah, Serhane Brahmi, Nouar Charef and Abderrahman Boumezbeur

Abstract

The present paper aims to investigate geotechnical parametric effects on the expansion behavior of clayey soils in Tebessa province northeast of Algeria using the Design Of Experiments (DOE) methodology. It has been used as powerful tools based on physical and mechanical properties, data results obtained within laboratory soil mechanics testing. This statistical tool methodology presents the factor screening design to determine the effect of different parameters such as dry unit weight, saturation degree, water content, plasticity index, etc., on the swelling pressure parameter which can be used as expansion behavior of clay indicator. All data previously collected in the studied prone area allows the ability of detailed analysis using design of experiment and parametric optimization process with response surface methodology (RSM). Each variable that present effects on swelling pressure is also discussed. Besides, the obtained models and equations related the factors affecting the expansion process have been determined. At the output process; the response desirability of the screening design methodology can be optimized by maximization or minimization of the optimal values affecting the swelling behavior. This process allows us to find the best describing models, whereas output results may be compared to empirical laboratory tests results to assess the RSM models.

Keywords: design of experiments (DOE), response surface methodology (RSM), laboratory tests, geotechnical parameters, swelling soil, parametric optimization process

1. Introduction

The Design of Experiments theory DOE is detailed and covered in many fundamental books [1–3]; its application to machining studies is discussed by various researches [4–7]. However, they have yet to make any inroads in engineering geology except for environmental engineering areas. In fact, geological and geotechnical engineering researchers, especially those who never heard about it and continue to use different inefficient methods and techniques. Moreover, in DOE there are many commercial software packages as, for example, Design-Expert by Stat-Ease, Minitab by Minitab, R Packages powered by R foundation for Statistical Computing, S-Plus by Mathsoft. A great literature and online sources combined are readily available as commercial software packages that apparently make DOE almost effortless.

Though, the simplicity of DOE is really pseudo-simplicity or masked complexity.

That is, in the first stage of DOE requires the formulation of clear objectives study on the swelling pressure of clayey soils as mentioned in this paper. The statistical model selected in DOE requires the quantitative formulation of the objective(s). A response is considered as objective, which is the result of the process under study presented in **Figure 1**. In satisfying these constraints, the software allowed us to establish minimum criteria for the response variables, then view both feasible and unfeasible regions of specific portions of the design space. The process under study may be characterized by several important output parameters but only one of them should be selected as the response. The response must satisfy certain requirements. It should be the effective output in terms of desirable final aim of the study, also easily measurable, preferably quantitatively and a single-valued function of the chosen parameters (dry unit weight $\gamma_d\left(kN/\mathrm{m}^3\right)$, water content $\mathrm{w}(\%)$, Clay fraction Cf (%), plasticity index $\mathrm{I_p}(\%)$, Limite of liquidity (%), Saturation degree (%), the preconsolidation pressure $\mathrm{P_c}(kPa)$ and the swelling pressure Ps (kPa) as the output parameter).

Basically, swelling soil experiments is one or a series of tests in which purposeful changes are made to dependent or independent input factors or variables of a system, so we may observe and identify the reasons for changes observed in the output response.

Expansive soil has extensively been found in all over the world and cover especially arid and semi-arid regions, literatures and studies investigate deeply the swelling soils behavior and assume that physical properties, geological facies, mechanical and mineralogical characteristics present the main governs parameters dependency [8–13]. Swelling pressure parameter (Ps) or potential was presented in enormous conducted studies as the indicator of phenomenon that can be used in infrastructure sustainable and geotechnical design [14–19]. The output parameter (Ps) is defined in many ways and depend on the testing procedure, to assess the degree of swell, many procedures including laboratory methods determining swell pressure have been developed by geotechnical researchers and engineers [20–22]. Though swelling pressure methods have been developed by

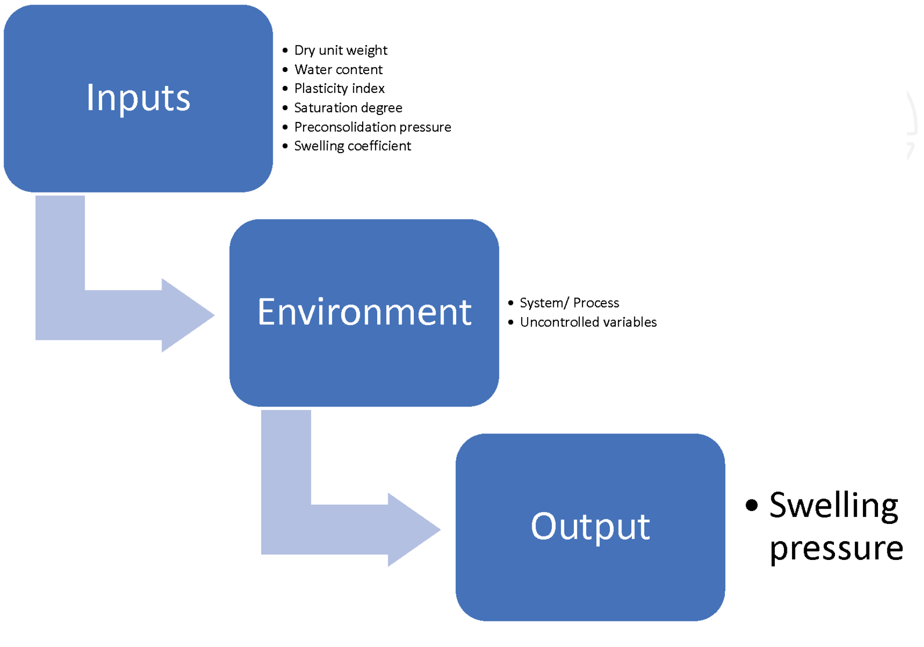

Figure 1.
Visualization of DOE intent.

various researchers, only three methods are standardized and also popularly used as documented in the literature.

The swelling is a complicated phenomenon and the different parameters effects cannot be predictable, used methods for estimating the swelling pressure of clayey soil can be direct or indirect. Direct methods are based on tests, experiences and the basic soil mechanics parameters and provide quick and useful identification, various authors in literature present some empirical relationships with indirect methods [23, 24].

The Tebessa area (Algeria) is the case study of the present work, in point, the weathered geological facies in this arid region has primarily created cover soils in a large basin with very plastic behavior. However, expansive soils exist and well identified litigation and reports high difficulties to infrastructure stability.

In the present research the concept of design of experiments (DOE) has been introduced to study the swelling behavior of the clayey soils with about 121 samples collected and tested in soil mechanics laboratory identification (LTPE).

In various engineering branch, the DOE method is largely used especially in manufacturing and chemical research, it is a powerful approach in experimentations; it seeks to determine the factors affecting a process in relationships with an output of our choice. This research aims to study the swelling pressure as an output parameter affected by several of physical and mechanical parameters as dependent or independent input parameters. Sequential application of DOE plan is used to find the optimal parameter and propose mathematical models to predict the swell pressure generated by clayey soil in Tebessa area and provide recommendations in the quality control measures.

2. Material and methods

The experimentation strategy is an approach to conduct and planning. The best-guess approach, combined, mixture and one-factor-at-a-time approach and factorial experimentation are the main approach used. One-factor-at-a-time for each factor consists of baseline level selected as reference, then varying successively factor in its range remaining and fixing the other factors in the goal to analyze the representative or abstruse factors joint effect on the response.

In this strategy, experiments are conducted by simultaneously varying six factors over two levels (namely low level and high level). The two levels are so chosen that they cover the practical range of the parameters under consideration **Table 1**. This case study presents an example of using the response surface for the modeling of the swelling pressure $P_s(\mathbf{kPa})$ and the analysis of results with

Factor	Name	Unit	Level	Low Level	High Level	Std. Dev.	Coding
A	γd	kN/m^3	1.72	1.16	2.06	0.0000	Actual
B	*w*	%	13.21	11.71	38.24	0.0000	Actual
C	Cf	%	69.31	57.00	98.18	0.0000	Actual
D	WL	%	109.79	36.00	160.00	0.0000	Actual
E	IP	%	54.90	22.00	85.00	0.0000	Actual
F	P	*kPa*	224.52	79.50	270.00	0.0000	Actual

Table 1.
Factors for response surface study.

ANOVA. For the presented implementation of DOE technique, Design-Expert10 software was employed to obtain the appropriate functional equations. The right tools at knowledge of research take in account mathematics and statistics to solve the problem considering each potential of the approximation.

The response surface methodology RSM in DOE techniques is widely used for machining processes. Experiments based on RSM technique relate to the determination of response surface based on the general equation [25]:

$$\mathbf{y = A_0 + A_1x_1 + \ldots + A_ix_i + A_{12}x_1x_2 + A_{13}x_1x_3 + A_{11}x_1^2 + A_{ij}x_i^2} \qquad (1)$$

Where A_0, A_i, A_{ij} are respectively interaction, linear, quadratic and intercept coefficients. x_i input independent variables. Continuous factors affect the quantitative response which is analyzed by response surface methodology (RSM), this later best fitting representative critical factors, commonly chosen in the screening phase of the experimental program. The final obtained results using RSM are polynomial models display the true response surface in the best approximation over a region of factors.

2.1. Definition of the input variables and the output responses

In this study, the effects of input parameters (dry unit weight $\boldsymbol{\gamma_d}\left(\mathbf{kN/m^3}\right)$, water content $\mathbf{w}(\%)$, plasticity index $\mathbf{I_p}(\%)$ Liquidity limits **Wl** (%) Saturation degree $\mathbf{Sr}(\%)$, the preconsolidation pressure $\mathbf{P_c}\left(\mathbf{kPa}\right)$ and the clay fraction **Cf** (%)) on the output response the swelling pressure $\mathbf{P_s}\left(\mathbf{kPa}\right)$. The levels for each factor are tabulated in **Table 1**.

Significant factors are identified using two-level factors as the first technique permit to compare the obtained results in full factorial design, where lower numbers of runs are required in this identification.

Results of the full factorial design are then compared to the results of two-level fractional factorial design, in which much lower number of runs are required to identify the significant factors. Explicitly, the half-fraction design can be also compared to the two-level factorial design.

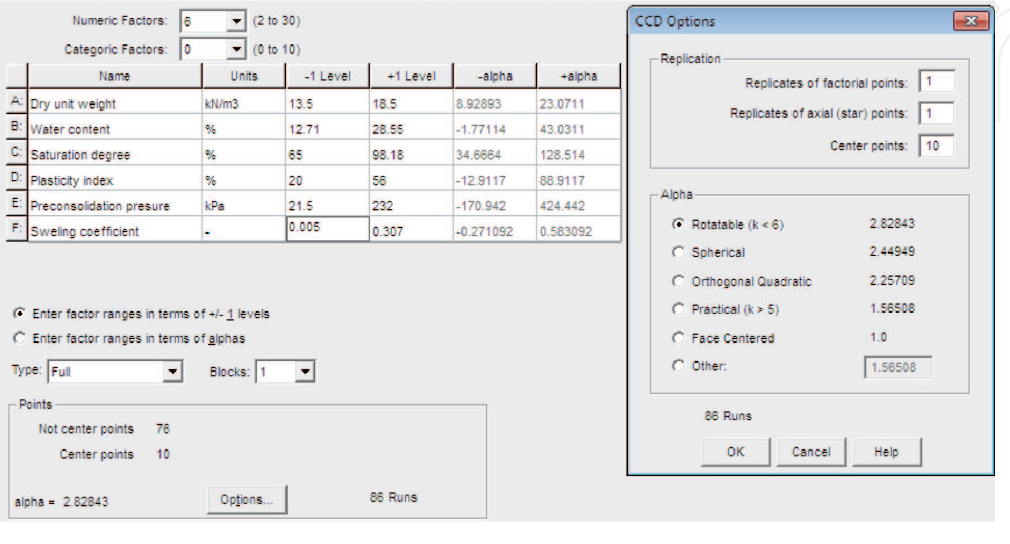

Figure 2.
Definition of different parameters as numeric factors in design-expert, and the dialog box for definition replication points and "alpha" parameter.

2.2. DOE and response data implementation

The two sides unit's length of the cube rang between −1 to +1. "Alpha" is the distance out of cube area measured in levels of coded factors, statistically it is always been a point of discussion view. A variety of Alpha options is presented in the Design-Expert software (**Figure 2**).

3. Statistical results analysis and the model properties

Regression model and test for coefficients significance on individual model achieved using ANOVA method. **Table 2** show summary statistics of the model, values of "Adjusted and Predicted R^2" are higher for quadratic model which is suggested for the present analysis; experimental data analysis was performed to identify statistical significance of the aim's parameters. The dry unit weight, degree of saturation, water content, plasticity index, preconsolidation pressure and the swelling index on the measured response swelling pressure Ps. The model was developed for 95% confidence level with $R^2 = 0.9155$, and the results are summarized in **Table 2**.

In **Table 2** the value of 0.2 between **Predicted and Adjusted R^2** indicate the reasonable agreement.

Adeq Precision is the SNR, greater than 4 is desirable, so the obtained model can be used to delineate a design space.

Std. Dev.	47.60	**R^2**	**0.9155**
Mean	228.75	**Adjusted R^2**	0.8913
C.V. %	20.81	**Predicted R^2**	0.8391
		Adeq Precision	27.2634

Table 2.
Model summary fit statistics.

Source	Sum of squares	df	Mean square	F-value	p-value	
Mean vs. Total	6.384E+06	1	6.384E+06			
Linear vs. Mean	2.082E+06	6	3.470E+05	90.65	< 0.0001	
2FI vs. Linear	**2.048E+05**	**15**	**13653.28**	**5.80**	**< 0.0001**	**Suggested**
Quadratic vs. 2FI	22389.69	6	3731.62	1.65	0.1429	
Cubic vs. Quadratic	1.448E+05	56	2585.61	1.44	0.1180	
Quartic vs. Cubic	68206.19	32	2131.44			Aliased
Residual	0.0000	6	0.0000			
Total	8.906E+06	122	72998.07			

Table 3.
Sequential model sum of squares [type I].

ANOVA for Quadratic model						
Response 1: R1						
Source	**Sum of squares**	**df**	**Mean square**	**F-value**	**p-value**	
Model	2.309E+06	27	85524.15	37.74	< 0.0001	significant
A-γd	17098.00	1	17098.00	7.55	0.0072	
B-W	5782.26	1	5782.26	2.55	0.1135	
C-Cf	7180.22	1	7180.22	3.17	0.0783	
D-WL	684.43	1	684.43	0.3020	0.5839	
E-IP	11086.62	1	11086.62	4.89	0.0294	
F-P	52922.74	1	52922.74	23.36	< 0.0001	
AB	829.09	1	829.09	0.3659	0.5467	
AC	1752.67	1	1752.67	0.7735	0.3814	
AD	414.75	1	414.75	0.1830	0.6698	
AE	12761.47	1	12761.47	5.63	0.0197	
AF	2534.55	1	2534.55	1.12	0.2929	
BC	221.88	1	221.88	0.0979	0.7550	
BD	1146.40	1	1146.40	0.5059	0.4787	
BE	2240.01	1	2240.01	0.9885	0.3227	
BF	244.95	1	244.95	0.1081	0.7431	
CD	4177.66	1	4177.66	1.84	0.1778	
CE	1458.91	1	1458.91	0.6438	0.4243	
CF	2057.89	1	2057.89	0.9082	0.3430	
DE	4307.25	1	4307.25	1.90	0.1713	
DF	403.89	1	403.89	0.1782	0.6739	
EF	10128.29	1	10128.29	4.47	0.0371	
A^2	1219.99	1	1219.99	0.5384	0.4649	
B^2	8073.28	1	8073.28	3.56	0.0622	
C^2	8255.06	1	8255.06	3.64	0.0594	
D^2	1668.27	1	1668.27	0.7362	0.3931	
E^2	2479.02	1	2479.02	1.09	0.2983	
F^2	578.87	1	578.87	0.2555	0.6144	
Residual	2.130E+05	94	2265.96			
Lack of Fit	2.130E+05	88	2420.46			
Pure Error	0.0000	6	0.0000			
Cor Total	2.522E+06	121				

Factor coding is ***Coded.***
Sum of squares is ***Type III - Partial.***
F-value *of 37.74 indicates a significant model. Only a 0.01% chance that F-value could occur due to noise.*
P-values *< 0.0500 implies significant terms model. A, E, F, AE, EF are the chosen terms. Values >0.1000 implies a not significant model term. The other terms may be used to reduce the improved model require to support hierarchy* ***Table 4.***

Table 4.
ANOVA response surface quadratic model, analysis of variance table [Partial sum of squares - Type III].

Select the highest order polynomial where the additional terms are significant and the model is not aliased.

The F-Value of 90.65–5.80 indicates a significant model with P- value <0.0001 that provide the suggested one 2FI vs. linear with 5.80 F-value, out of the cited condition the models are aliased (**Table 3**). In this case A, B, C, BC are significant model terms where P- Values >0.10 as mentioned in **Table 4**.

Normal plot of residuals, shown in **Figures 3–8**, should be in a straight line, in the residuals the errors distribution is normal regards the strait line form. Whereas the nonlinear patterns such as S-curve form implies a non-normality of the error term and can be corrected by a transformation. Residuals versus predicted response should be randomly scattered without pattern as shown in **Figure 8**. Other analysis can be provided in other cases.

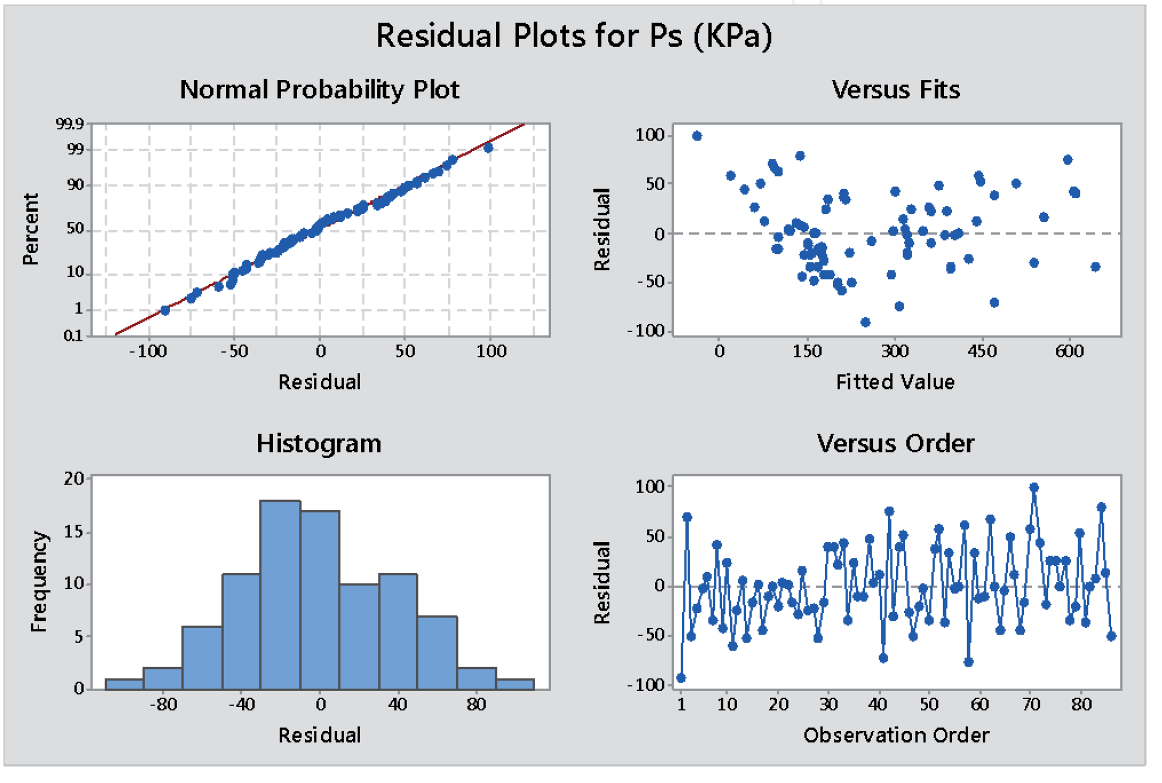

Figure 3.
Residual plots for the swelling pressure of the study soil case.

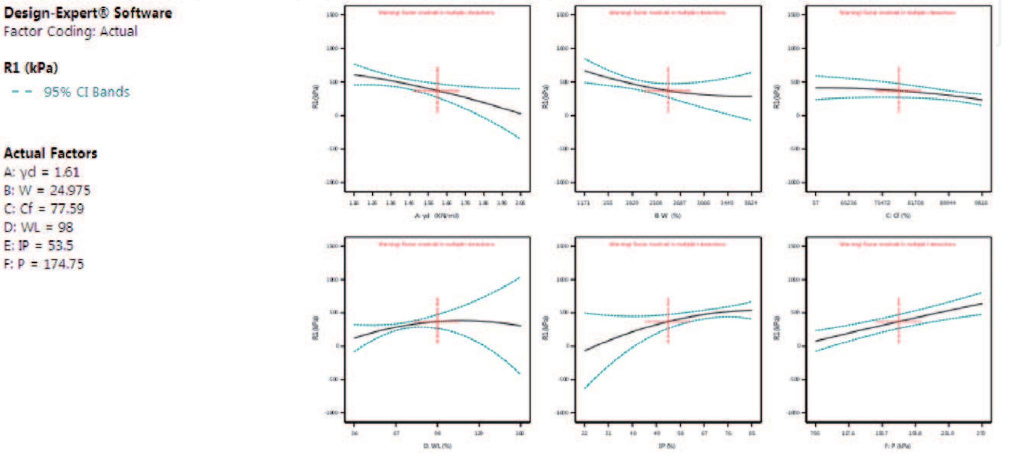

Figure 4.
All factors contribution and effects on the response output for the swelling pressure of the study soil case.

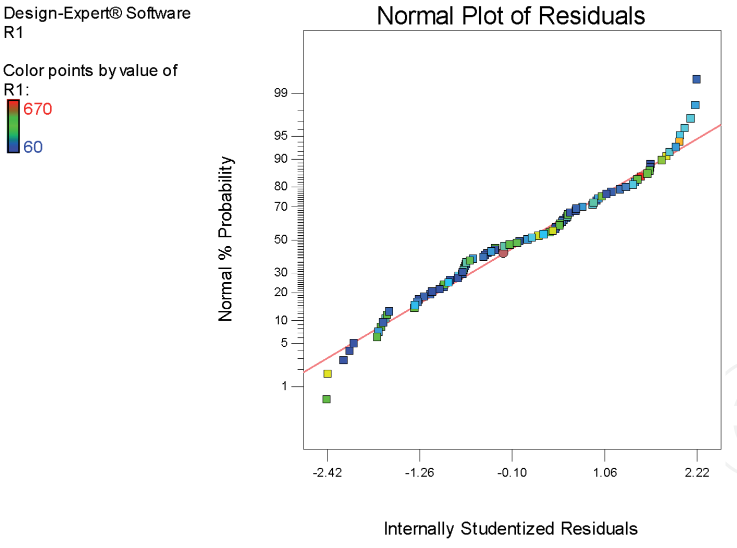

Figure 5.
Normal probability plot of residuals for swelling pressure.

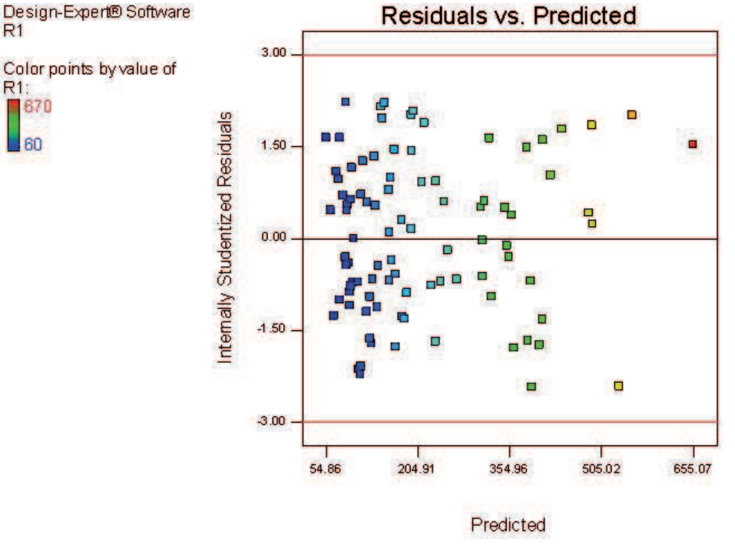

Figure 6.
Residuals versus predicted response for swelling pressure.

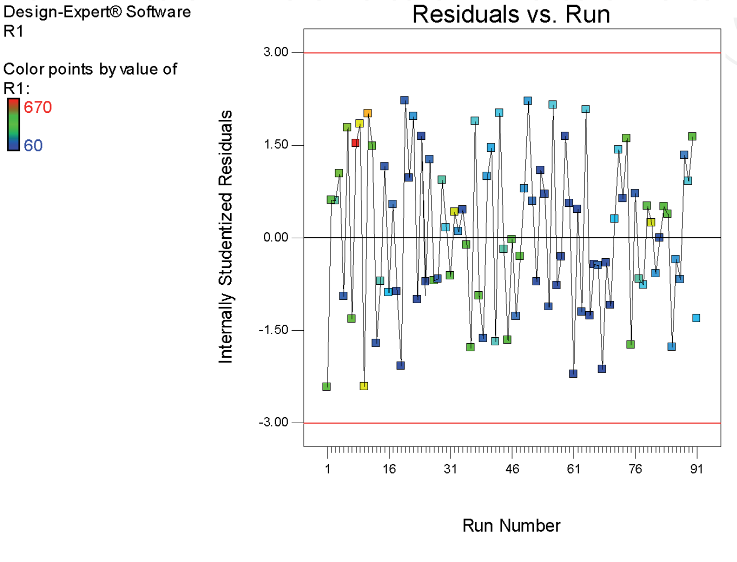

Figure 7.
Residuals versus run for swelling pressure.

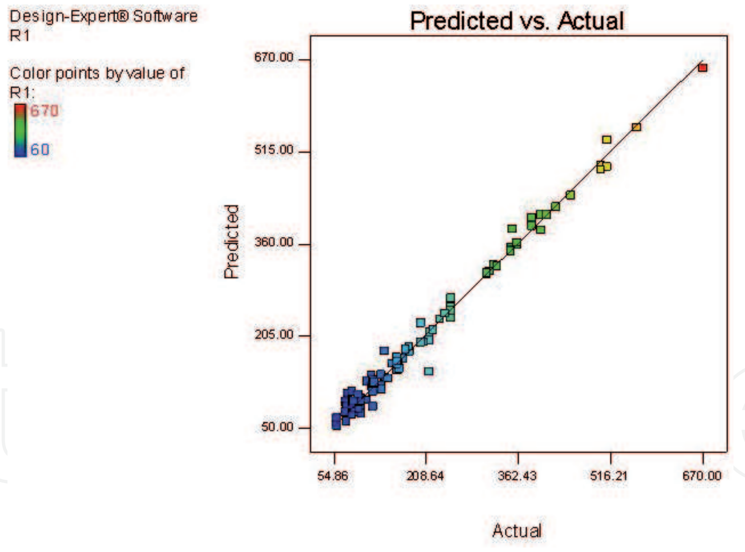

Figure 8.
Predicted response versus actual for swelling pressure.

4. Equations and models graphs

For the analyzed example the final equation in terms of actual factors was determined, which determines the swelling pressure (Ps) from the input factors for the linear model:

$$P_S = 2604 - 10412 * A - 11440 * B + 4034 * C - 2568 * D + 1420 * E + 133 * F \qquad (2)$$

And it can be represented by another suggested model of Quadratic form.

The equation can be used to predict the response for each factor levels, that should be specified by their original units. Because the coefficients are scaled to accommodate the factor units and the intercept is not at the center of the design space; this equation is not able to be used in determining relative impact.

Figures 9–**11** shows the response surfaces describing the swelling pressure Ps dependence on, the Dry unit weight (kN/m^3) and the water content w (%), plasticity index (%) and Dry unit weight (kN/m^3) and the degree of saturation (%) respectively. Plasticity index (IP) and water content (w) and the preconsolidation pressure, the dry unite weight and the swelling index for this case study.

Figures 12 and **13** represent the factors that affect the (Ps) where the plasticity index is fixed common parameter, saturation degree and the preconsolidation pressure varied respectively.

5. Response surface methodology and optimization process

The response surfaces method is a set of mathematical techniques that use experimental design to determine the range of independent input variables [26]. This method makes it possible, thanks to empirical mathematical models, to determine an approximation relation between the output responses (Y) the swelling pressure $\mathbf{P_s}(\mathbf{kPa})$, and the input variables (dry unit weight $\boldsymbol{\gamma_d}(\mathbf{kN/m^3})$, water content $\mathbf{w}(\%)$, plasticity index $\mathbf{I_p}(\%)$ Saturation degree $\mathbf{Sr}(\%)$, the preconsolidation pressure $\mathbf{P_c}(\mathbf{kPa})$ and the Plasticity Index $(\mathbf{I_p})$ and limite of plasticity WL) to

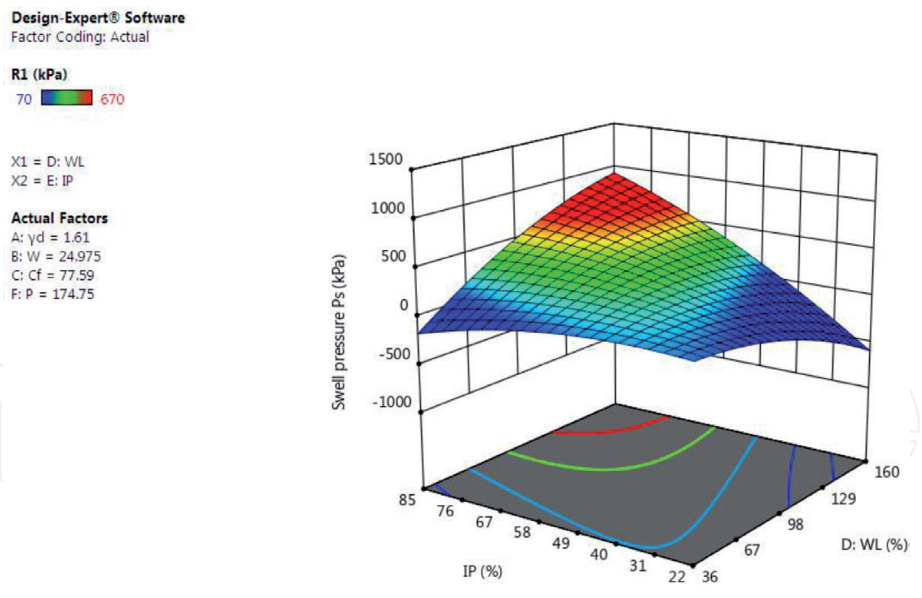

Figure 9.
Response surface 3D representing the swelling pressure dependence on the plasticity index % and the limit of liquidity (%).

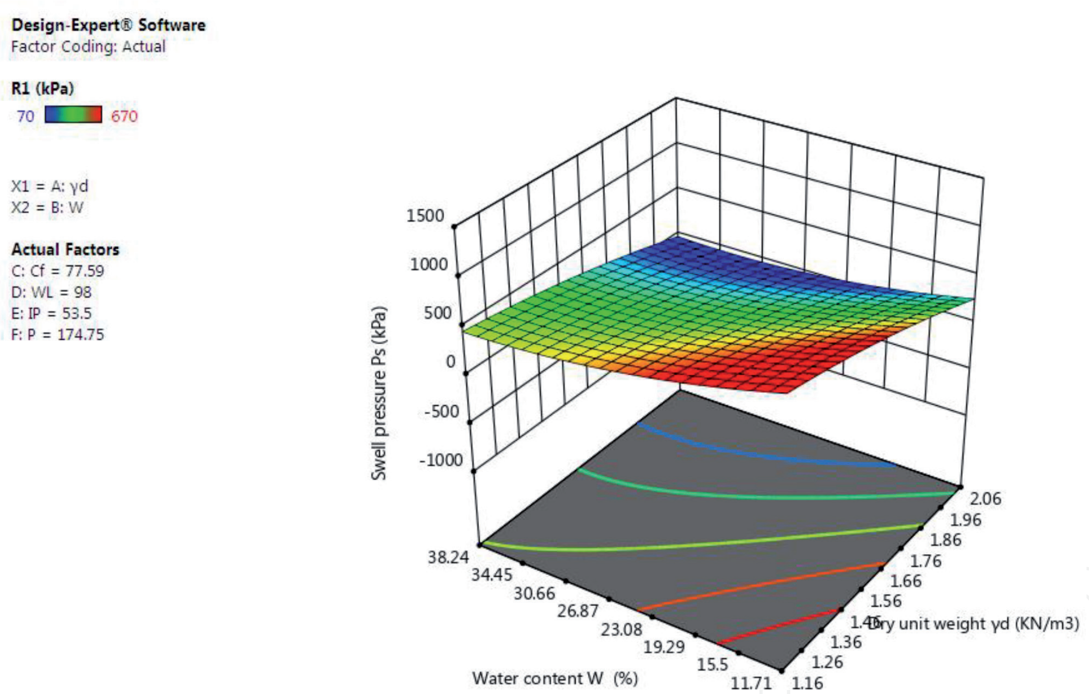

Figure 10.
Response surface 3D representing the swelling pressure dependence on the dry unit weight (kN/m³) and the water content (%).

optimize process parameters to achieve desirable responses. In this method, the answer can be written in the following form:

$$Y = \phi(\gamma d.w.Cf..Ip.Wl.Pc) \tag{3}$$

Where Y is the swelling pressure as the output process and ϕ is the response function, the approximation of Y is proposed using a quadratic mathematical model, which helps to study the interaction effects of process parameters with geotechnical characteristics. In the present work, the second order mathematical model based on RSM is given by the following elements:

$$Y = x_o + \sum_{i=1}^{k} y_i X_i + \sum_{ij}^{k} y_{ij} X_i X_j + \sum_{i=1\,ii}^{k} X_i^{\,2} + \varepsilon_{ij} \tag{4}$$

$$\left(\varepsilon_{ij} = y_{ij} - \overline{y}_{ij}\right) \tag{5}$$

Where x_0 is the free term of the regression equation, the coefficients $Y_1, Y_2, \ldots, Y_k$ and $Y_{11}, Y_{22}, \ldots, Y_{kk}$ are the linear and quadratic terms respectively, while $Y_{12}, Y_{13}, \ldots, Y_{(k-1)}$ are the interactive terms and ε_{ij} presents the fit error for the regression model.

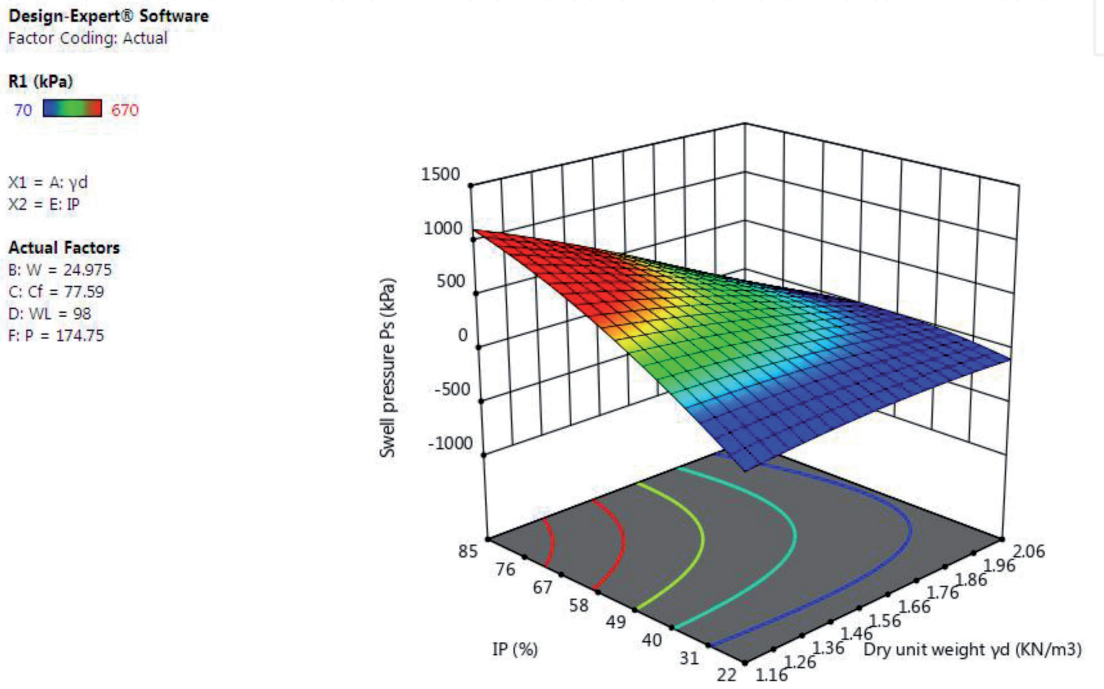

Figure 11.
3D response surface of Ps (kPa) dependence on the $\gamma_d\left(kN/m^3\right)$ **vs IP** *(%).*

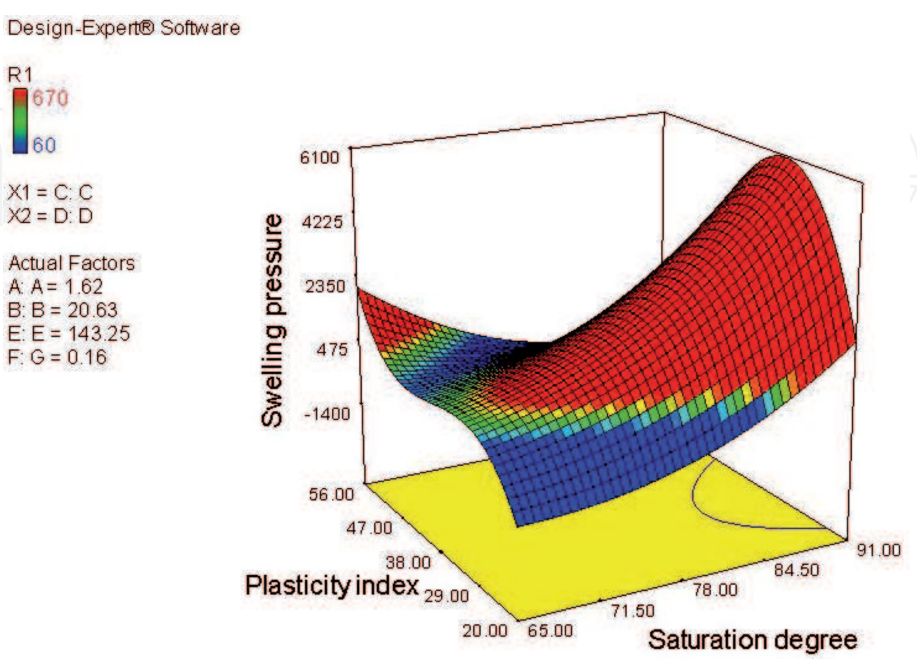

Figure 12.
Response surface 3D representing the swelling pressure dependence on the plasticity index and the saturation degree (%).

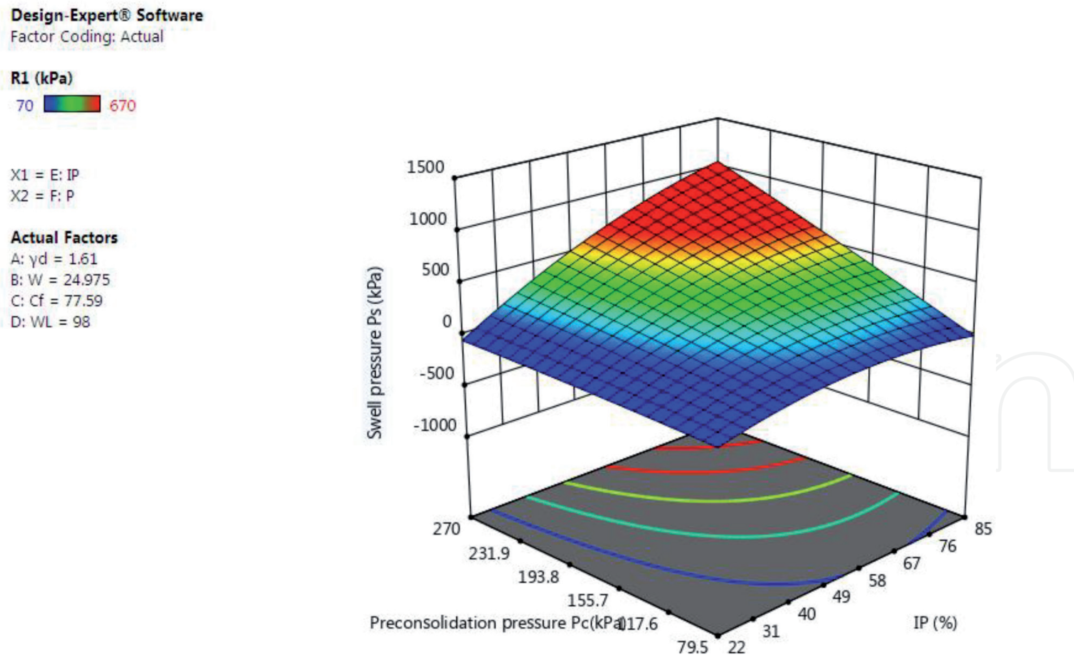

Figure 13.
Response surface 3D representing the swelling pressure dependence on the Preconsolidation pressure and the plasticity index (%).

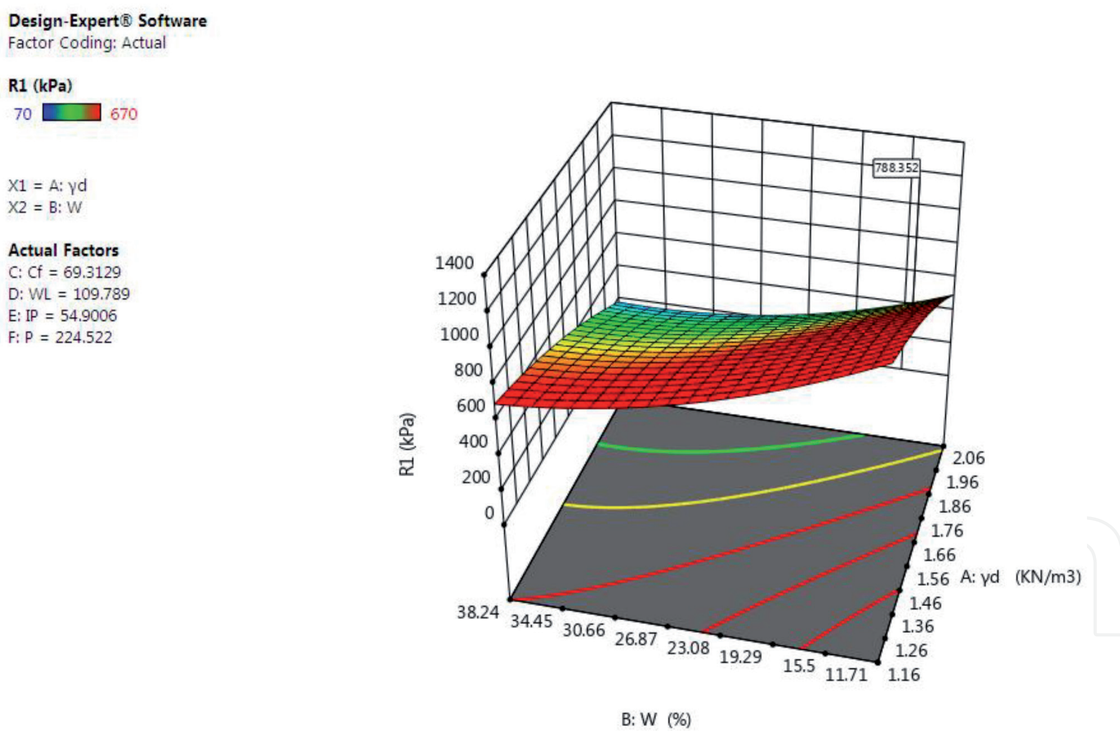

Figure 14.
3D surface of Ps vs. $\gamma_d\left(\mathbf{kN/m^3}\right)$ *and* **w %.**

On the other hand, the coefficient of determination R^2 is defined by the ratio of the dispersion of the results, given by the relationship:

$$R^2 = \frac{\sum\left(y_i - \bar{y}\right)^2}{\sum\left(\bar{y}_i - \bar{y}\right)^2} \tag{6}$$

Where y_i: is the calculated response to the i^{th} experience;
$\bar{y}_i$: is the average value of the measured responses.

Analysis of variance (ANOVA) is used to test the validity of the model, as well as to examine the significance and suitability of the model. The model is adequate within a 95% confidence interval. When the values of P are less than 0.05 (or 95% confidence), the models obtained are considered statistically significant. In other words, the closer the R^2 approaches to the value 1, the model is compatible with the real (experimental) values.

3D representation on **Figure 14** clearly optimize the parameters effects on Ps value, based on RSM multifactor data, numerical optimization is possible. Including factors and propagation of error for all variables is available in the settings of Design-Expert software, and limits factor ranges to factorial levels (−1 to +1) in coded values, the area of this experimental design provides the best predictions.

6. Conclusion

Design Of Experiments DOE techniques, using specifically two-levels factorial design method (High and low levels) can efficiently identify the significant factors. Most importantly in this technique is to randomly test at least twice (repeat and replications), in order to reduce the influence of the none assigned variables and the randomness of responses. The present experimentation which was based on six parameters (dry unit weight $\gamma_d\left(kN/m^3\right)$, water content $w\left(\%\right)$, Clay fraction Cf (%), plasticity index $I_p\left(\%\right)$, Limite of liquidity (%), the preconsolidation pressure $P_c\left(kPa\right)$ and the swelling pressure) on the measured response swelling pressure Ps (kPa) as the output parameter. All parameters varied between 2 levels and revealed that dry unit weight, plasticity index, limit of liquidity, preconsolidation pressure have the main effects on the swelling clayey soil pressure in Tebessa province. The effect of the last factor considered as well as all interaction, to be less or non-significant. The DOE method is most frequently used in simple designs regards to regular fractions, but it does not work as well in more complex settings, such as some nonregular fractions.

Fortunately, the present available general methods work satisfactorily in various situations. It uses a representative polynomial or regression model, by means of one or more methods under the DOE planning analysis and will depend of the user's goal, i.e. if users want a simple analysis, the statistical analysis using the ANOVA approaches can be the ideal method.

In the present research optimization process stage is achieved with response surface method RSM and it revealed that the output parameter (swelling pressure Ps) is strongly affected by plasticity index and liquid limits when desirability is maximized, otherwise the desirability is minimized. In the twice cases the range of all contributed parameters is fixed. Other parameters such as saturation degree show complexed response surface with unclear contribution. Hence the final model of the output response (Ps) do not take in consideration parameters with complex response surface.

Furthermore, the planning of DOE experiments is extremely important in researches because it can reduce cost and time that needs to execute the experimental tests.

Author details

Yacine Berrah[1*], Serhane Brahmi[2], Nouar Charef[3] and Abderrahman Boumezbeur[4]

1 Environment Laboratory, Mining Institute, Larbi Tebessi University, Tebessa, Algeria

2 Water and Environment Laboratory, Mining Institute, Larbi Tebessi University, Tebessa, Algeria

3 Cherif Messadia University, Souk, Ahras

4 Department of Geology, Larbi Tebessi University, Tebessa, Algeria

*Address all correspondence to: yacine.berrah@univ-tebessa.dz

References

[1] Box GEP, Hunter JS, Hunter WG (2005) Statistics for experimenters. Design, innovation, and discovery, 2nd edn. Wiley-Interscience, Hoboken

[2] Montgomery DC (2012) Design and analysis of experiments. Wiley, New York

[3] Maxwell SM, Delaney HD (2003) Designing experiments and analyzing data: a model comparison perspective, 2nd edn. Tylor & Francis, New York

[4] Astakhov VP (2006) Tribology of metal cutting. Elsevier, London

[5] Astakhov VP, Osman MOM, Al-Ata M (1997) Statistical design of experiments in metal cutting—Part 1: methodology. J Test Eval 25(3):322-327

[6] Astakhov VP, Al-Ata M, Osman MOM (1997) Statistical design of experiments in metal cutting. Part 2: application. J Test Eval (JTEVA) 25(3):328-336

[7] Astakhov VP (2012) Design of experiment methods in manufacturing: Basics and practical applications. In: Davim JP (ed) Statistical and computational techniques in manufacturing. Springer, London, pp 1-54

[8] J.-J. Zhang, B.-W. Gong, B. Hu, X.-W. Zhou, and J. Wang, "Study of evolution law of fissures of expansive clay under wetting and drying cycles," Rock and Soil Mechanics, vol. 32, no. 9, pp. 2729-2734, 2011.

[9] ASTM. _2006b_. "Standard test method for expansion index of soils." Annual book of ASTM standards: D4829-03, Vol. 4.08, ASTM, West Conshohocken, Pa., 900-903.

[10] Chen, F.H.: Foundations on Expansive Soils. Elsevier (2012).

[11] K. Terzaghi, "Stability of slopes of natural clay," in Proceedings of the 1st International Conference on Soil Mechanics and Foundation Engineering, vol. 12, no. 3, pp. 161-165, Harvard University, Cambridge, Mass, USA, 1936.

[12] Komornik, A., Wiseman, G., and Ben-Yaacob, Y., "Studies of In-Situ moisture and Swelling Potential Profiles," Proceedings, 2nd International Research and Engineering Conference on Expansive Soils, Texas A&M Univ. Press, College Station, TX, pp. 348-361. (1969).

[13] Fredlund, D. G., Hasan, J. U., and Filson, H. L., "The Prediction of Total Heave," Proceedings of 4th International Conference on Expansive Soils," ASCE and International Society for Soil Mechanics and Foundation Engineering, Denver, pp. 1-17. (1980).

[14] Berrah, Y., Boumezbeur, A., Kherici, N.: Application of dimensional analysis and regression tools to estimate swell pressure of expansive soil in Tebessa (Algeria). Bull. Eng. Geol. Environ. (2016).

[15] Rao, S. M., "Identification and Classification of Expansive Soils," Exapnsive Soils—Recent Advances in Characterization and Treatment, Taylor & Francis, pp. 15-24. (2006).

[16] Jennings, J. E. B. and Knight, K., "The Prediction of Total Heave from the Double Oedometer Test," Transact. S. African Inst. Civil Eng., Vol. 7, pp. 285-291. (1957).

[17] Yilmaz I. Indirect estimation of the swelling percent and a new classification of soils depending on liquid limit and cation exchange capacity. Engineering Geology 85, 295-301. (2006).

[18] Magnan, D., 1993. Caractérisation in situ des sols gonflants : l'essai Expansol.

Thèse de doctorat, Université J. Fourier, Grenoble (France), p 190.

[19] Vijayvergiya V.N., Ghazzaly, G., 1973. Prediction of swelling potential for natural clays. Proceedings, 3rd International Conference on Expansive Soil, Haifa, vol. I, pp. 227-236.

[20] Banerjee, A., Puppala, A.J., Patil, U.D., Hoyos, L.R., Bhaskar, P.: A simplified approach to determine the response of unsaturated soils using multistage triaxial test. IFCEE **2018**, 332-342 (2018)

[21] Pedarla, A.: SWCC and Clay Mineralogy Based Models for Realistic Simulation of Swell Behavior of Expansive Soils (2013)

[22] Pedarla, A., Chittoori, S., Puppala, A.J.: Influence of mineralogy and plasticity index on the stabilization effectiveness of expansive clays. Transp. Res. Rec. **2212**, 91-99 (2011).

[23] KAYABALI, Kamil et DEMIR, Saniye. Measurement of swelling pressure: direct method versus indirect methods. Canadian Geotechnical Journal, 2011, vol. 48, no 3, p. 354-364.

[24] CHEN, Fu Hua. Foundations on expansive soils. Elsevier, 2012.

[25] Myers, R., Khuri, A., & Carter, W. (1989). Response Surface Methodology: 1966-1988. *Technometrics, 31*(2), 137-157. doi:10.2307/1268813

[26] SAID, Khairul Anwar Mohamad et AMIN, Mohamed Afizal Mohamed. Overview on the response surface methodology (RSM) in extraction processes. *Journal of Applied Science & Process Engineering*, 2015, vol. 2, no 1.