International Journal of Civil Engineering and Technology (IJCIET)
Volume 9, Issue 7, July 2018, pp. 160–169, Article ID: IJCIET_09_07_016
Available online at http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=9&IType=7
ISSN Print: 0976-6308 and ISSN Online: 0976-6316

APPLICATION OF A MULTIVARIATE STATISTICAL ANALYSIS TOOL (PCA) FOR THE OPTIMISATION OF DAM FOUNDATION GROUTING

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ABSTRACT

Considering the success of the multivariate statistical study that addresses many processes and controls large amounts of non-structural and non-ordered data, the application of Principal Components Analysis (PCA) method has proven its efficiency processing grouting's data used for the watertightness of every dam's project. Grouting works designed to waterproof the foundation's soil require an original study making it possible to choose the technically and economically adequate solution for each case. This raises automatically the question of the quantity of the grout absorbed by the foundation that can not be calculated using empirical formulas and which remains related only to experience. This study was carried out on a number of exploration drillings will make it possible to highlight the existence of a potential correlation between the geological nature of the foundation and the absorption of the water in the Lugeon test in one hand and the cement grout in the other, so that we can optimize at the best the quantitative and qualitative consistency of grouting works based on obtained results.

Key words: Grouting Works, Waterthigtness, Water Absorption, Foundation Treatment, Dam, Multivariate Statistical Methods and PCA.

Cite this Article: Maha BEN TAHAR, Latifa OUADIF, Lahcen BAHI, Application of A Multivariate Statistical Analysis Tool (PCA) For The Optimisation of Dam Foundation Grouting, International Journal of Civil Engineering and Technology, 9(7), 2018, pp. 160–169.
http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=9&IType=7

1. INTRODUCTION

The construction of dams is a voluntarist policy and forward pioneering on which Morocco has been based for water resource mobilization. Present throughout the country, these structures designed to store water, require unconditionally a foundation that is water-tight [1], as perfect as possible, to ensure their durability and security. The four dams selected for this study: Dar

Khrofa, Tiouine, Ouljet Es-Soultane and Er-Rmel, are located in different structural areas having each one a particular geological history whose foundations differs from a geological and structural standpoint. These dams have been the subject of geological investigations made at study stage. Analysis data will focus on a number of polls/drilling located into the different areas of the foundation wherein permeability tests (Lugeon test) and grouting works are made in order to reduce seepage through the dam foundation and also improve the mechanical characteristics of the injected area in order to be able to handle the structures weight to construct by extending the impermeability and therefore lack of soil of the foundation [2].

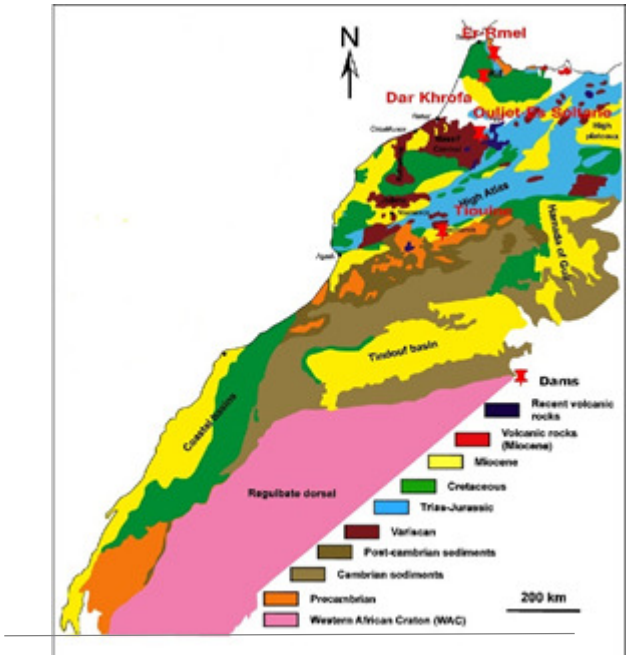


Figure 1 Localisation of studied dams on the map of geological domains of Morocco [3]

The purpose of this study is multi-dimensional statistical analysis across the principle component analysis (PCA) of polls and drilling, in order to identify potential existence of correlation [4] between the two fluid-absorption : water and the grout and nature of the soil, which subsequently will affect both quantitative and qualitative consistency of foundation treatment works: as it happens the grout injections and the conception of the grout curtain.

2. MAERIAL AND METHODS

The sites of the chosen dams are situated in the different structural fields of Morocco, each showing a special geological history.

Tiouine, an anti-Atlas occidental dam situated at 100 m to the entry of the river's gorges Iriri, a zone known by its structure relatively tectonized dominated by andesitic formations of volcanic nature, conglomeratic and sandstone of Precambrian III. The dam's zone is assigned by several fault systems, the principals of which are the directions of East-West and North-West South-East (sub-sidelong compared with the axis of the valley).

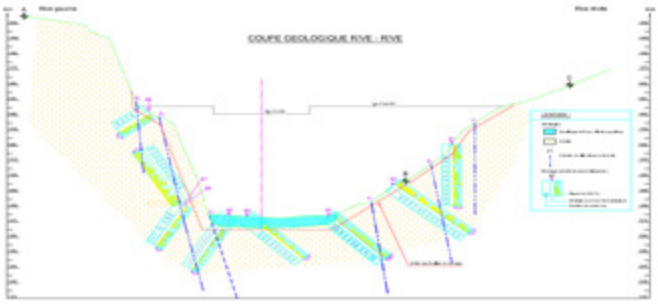


Figure 2 Geological section Est-West along the axis of Tiouine's dam [5]

Er-Rmel is situated in the Rif domain, the dam's substratum is formed of the same geological formations as that of the Tisirene's unity which is composed of Flysch where alternate siliceous sandstones with fine grain and argillites.

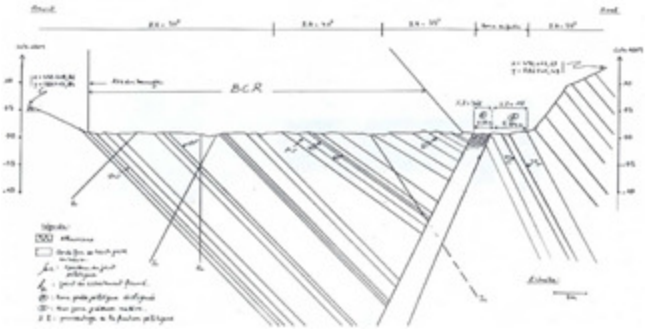


Figure 3 Geologic cut downstream-upstream of dam's Er-Rmel [5]

At Dar Khrofa, the geological context is that of Moroccan Rif. The site is founded on Oued El Makhazine. It is characterized by a very diverse foundation with alternation of argilitic dividings in sandstone and argillites of rare intercalations of stoneware benches.

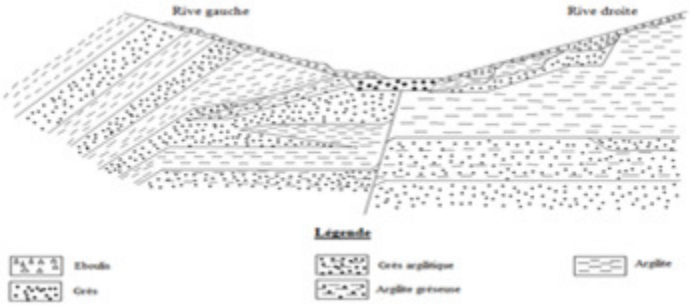


Figure 4 Sketch of the geologic cut according to the axis of dam's Dar Khrofa [5]

Situated in the Mesetien field, the Ouljet Es-Soltane's dam is found in a different context marked by the outcrop of schistoses formations of Viseen composed of black schists sometimes sericetic or micaceous which alternate with quartzed and stoneware shales who forms the foundation of the dam.

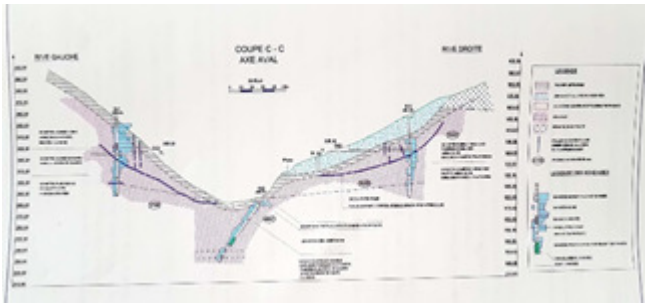


Figure 5 Geologic cut of downstream and upstream sides of the dam's Ouljet Es-Soltane [5]

A deep analysis is fulfilled on a number of drillings representing every dam in order to qualify water absorption during the Lugeon test (LU), as well as the consumption of the dried material (DM) in the foundation.

This approach has required on one hand, the Lugeon test realized on passes of 3m [6] which allows to have absorptions of water postponed from one drill to another, and even between the edges of one drill. And on the other hand the injection of the grout [7, 8, 9], in the same drills where the Lugeon test was fulfilled to be able to find or not the dependence between the two fluids studied in certain conditions well determined.

Table 1 Synthesis of the results of water absorption and injections carried out in drilling of treated dams

Dams	**Water Absorptio-n**		**Observations**	**Consumption in dried materials**		**Observations**
Paramete-rs / %	**<1LU**	**>50 LU**		**<25 Kg/ml**	**>100 Kg/ml**	
Dar Khrofa	7	33	The weak absorptions are linked to an alternation of argillites and of sandstone purely argilitic. Both strong and total absorptions are explained by the important openings of fissures and the porous character of likings.	25	55	Edges's permeable percentage to the grout (55%) is superior to edges permeable percentage on water (33%); this can be explained by the fracturation of cracks under the highest pressure of the grout injection (30bars).
Tiouine	60	5	The foundation's ground presents a permeability of fracture with weak Lugeon absorption.	61	8	The strong consumption is due to the fracturation phenomenon of some cracks of the andesitic rock.
Ouljet Es-Soltane	75	14	The substratum is almost waterproof corresponding to a massif of schists in alternation with deteriorated schists which raises up LU in some places of the substratum.	53	10	The strongest consumptions are registered in the edges of a depth beyond 10m located in the formations of deteriorated schists on cracks on his border with healthy schists
Er-Rmel	59	6	Weak absorptions testify of the waterthigtness of the stonewale rock except for few edges in the zone crushed by the fault (F1) where absorptions raise up.	67	24	Generally edges are characterised by the weak consumptions, except for some edges which has consumed a lot of grout and where a strong deterioration of the rock is identified or under the phenomenon of fracturation of the soil.

The absorptions in the substratum of the foundation happens to widely variate in each of treated dams, and the big heterogeneity determined from one drill to another has emphasized a relation between the nature of the ground and the quantities of grout injected, apart from some located areas where we found strong absorptions. To confirm this link, the Principal Component Analysis (PCA) will allow us to calculate correlation coefficients [10] existing between the different databases, and to examine the behavior of both variables: Water and cement's grout, in order to identify a coefficient of correlation which links them.

3. RESULTS AND DISCUSSION

3.1. Principal Component Analysis

The method of principal component analysis (PCA) is a descriptive method which belongs to geometrical methods particularly the sub-family of factorial analysis. Its aim is the analysis of data frames with no particular structure, and the summary of all the information contained in these boards, constituted often by a high number of lines and columns and some numerical characteristics, all grouped as a numerical population of variables and individuals.

If we consider a population of size $p \times n$ that we call *matrix of data*, where p variables describe n individuals, then each individual can be represented by a point in a p-dimensional space that forms a cloud, when $p \leq 2$, we can see the distance between the individuals, in the case of $p=3$, the distance is visualized with difficulty, but for $p>3$ the visualization is impossible.

PCA allows us to have new variables (Principal Components) that reduce the dimension of the space while keeping a maximum of the complete variance of the cloud [11].

3.2. Extraction of Principal Components

After having carried out data's analysis of different drills forming the principal regions, the determination of statistical characteristics of position and of dispersion therefore proves to be in a great use for a more clear visualization of the behavior of variables as well as their dispersion regarding the average. The studied variables are: the water absorption (LU) and the consumption in dried substance MSC (Kg/ml).

The different statistical characteristics of position and dispersion representatives are:

- The average
- The median
- The maximum and minimum
- The standard deviation according to the depth

Table 2 PCA's data and choice of principal components for studied dams

Studied dams	**Number of individuals (in edges)**	**Principal components retained**
	232 Greenish to greyish or purplish argillites with interstratification of sandstone-like bar of centimetric thickness	3
Dar Khrofa	398 Massive sandstones with argillites interstratification	3
Tiouine	103 Andesites	2
Ouljet Es-Soltane	29 Schists altered on cracks and old alluvium	2
Er-Rmel	132 Tisirene unity composed of Flyschs (Beddings of fine sandstones and argillites)	2

The « STATISTICA » software allows to apply the PCA analysis which is achieved in our case on a population = edges × variables, the diagonalization by the software of the data of departure's matrix gives a histogram of eigenvalues, from which we can select, by using Kaiser's criterion [14], the values explaining the essential of total inertia and indicating then the part of whole information contained on every factor (axes), or principal component [12]. Afterwards, the projection of variables and individuals on factorial plans will allow to well visualize the correlations between the different parameters studied and the axes retained.

3.3. Interpretation of PCA's results

To interpret the factorials axes obtained by the PCA, we can either use the matrix of components which link the initial variables with the new axes or use the space projection, in this case, this means projecting the space of « n principal components » dimensions in spaces of two dimensions [13]. These projections can help to acquire a comprehension between the categories and the new axes by visual reading; still, the matrix of components is a very concise means to develop such a comprehension.

First, the software provides the matrix of correlations, which gives the linear coefficients of correlation of taken variables two by two. We notice that the obtained matrices of correlation for the four dams show values that are generally low, some being positives, others negatives.

Table 3 dam's matrices of correlation

Variables	LU	Kg/ml
LU	1	-0,07
Kg/ml	-0,07	1

Dar Khrofa's dam

Variables	LU	Kg/ml
LU	1	0,45
Kg/ml	0,45	1

Tiouine's dam

Variables	LU	Kg/ml
LU	1	0,49
Kg/ml	0,49	1

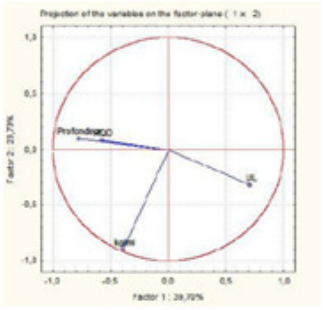
Ouljet Es-Soltane's dam

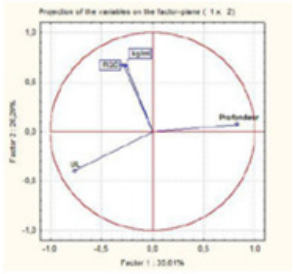
Variables	LU	Kg/ml
LU	1	0,10
Kg/ml	0,10	1

Er-Rmel's dam

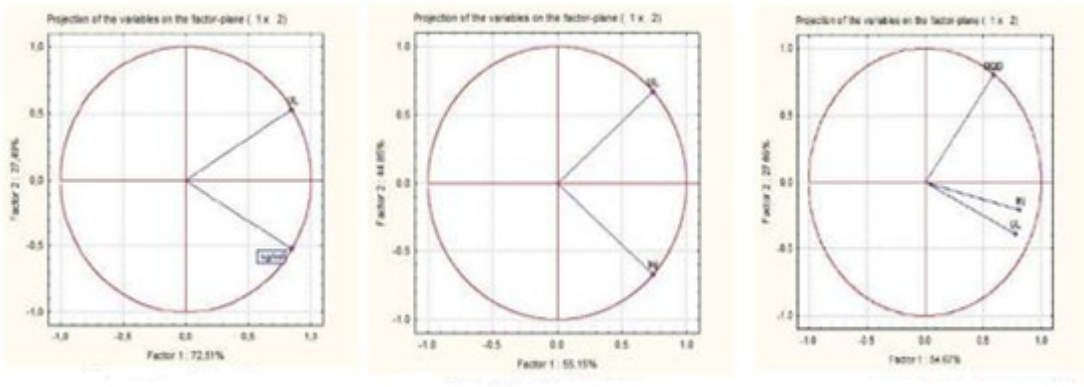
3.3.1. Projection of variables

According to every case, the definition of factorials plans is linked to the number of principal components retained (2 or 3 axes) (Table 2). The most interesting points are generally those which are very near to one of the axes, and very far from the origin. These points are well correlated with this axis and explain it the best: they are the most speaking points; there true distance of the origin is well performed on the factorial plan.





Dar Khrofa's dam



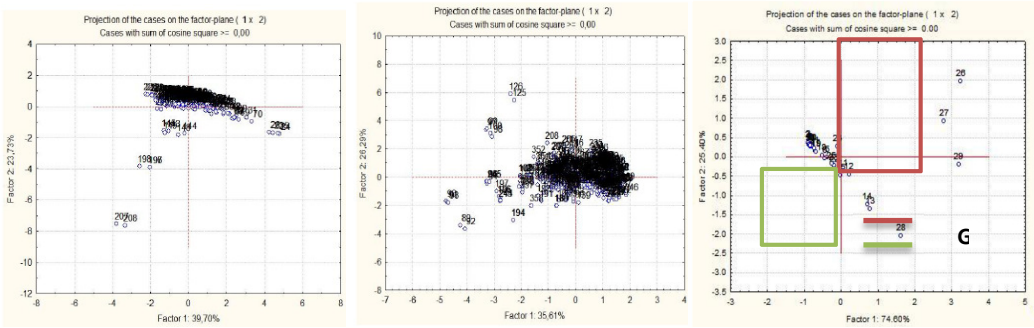
Tiouine's dam **Er-Rmel's dam** **Ouljet Es-Soltane's dam**

Figure 6 Projection of variables on the factorial plans of 2 dimensions

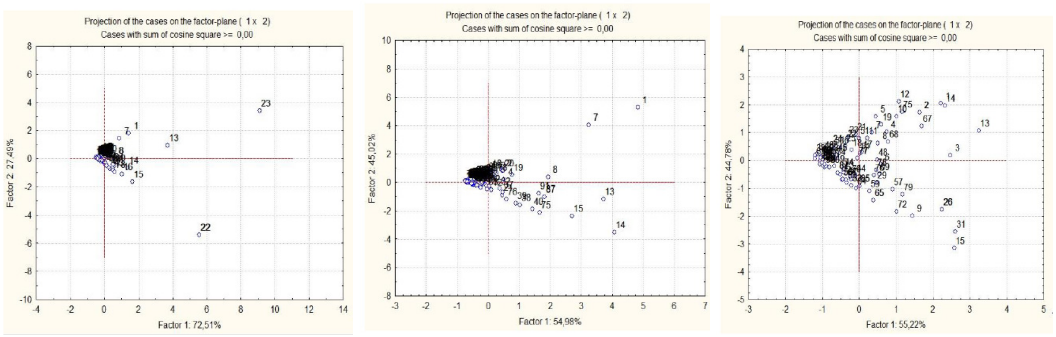
On the factorial plans (1*2) of all treated cases, we note that the variables are situated on the circle of correlation and then very well represented on the mapping, but their behavior differs from one dam to another : the water absorption and the consumption in dried substance are positively correlated and follows practically the same variation in Ouljet Es-Soltane's dam and seem to be linked to the nature of the foundation which shows a lithology marked by the presence of altered schists on cracks which are more absorbent than the healthy schists, given that the presence of cracks facilitate the flow of fluids (water and grout) between them. The same for Tiouine's dam, where we found a low value of correlation's coefficient in the order of 0.45, which remains non representative despite its andesitic homogenous formation, and Er-Rmel's dam where the maximum coefficient obtained remains widely low to correlate the two variables. Whereas for Dar Khrofa's dam, the two PCA applied on the argillites and the sandstone have revealed that the variables are not correlated between themselves, in other words, they are independent, what is confirmed by the negative correlation coefficient of -0.07.

3.3.2. Projection of individuals

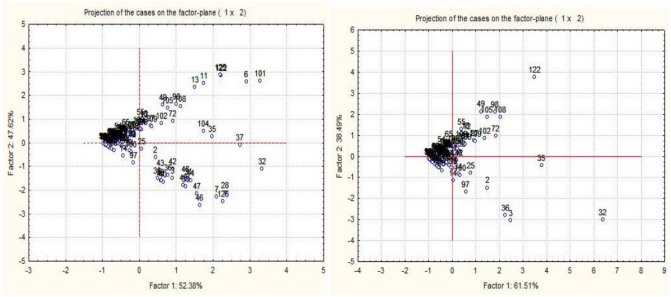
The projection of individuals on the factorial plans, allows also to obtain a cloud of points explaining the relationship of individuals with the factors:



Dar Khrofa's dam **Ouljet Es-Soltane's dam**



Tiouine's dam



Er-Rmel's dam

Figure 7 Projection of individuals on factorial plans of 2 dimensions

The projection of individuals on the factorial plan (1*2), shows in all presented cases, the presence of a cloud of points gathering the majority of edges; the individuals are close to each other which proves that they have a similar behavior, which means they have close answers to the variables of the analysis, with the exception of atypical individuals who emerges from clouds of points. We can then draw a distinction between three different cases:

Dar Khrofa's dam where the atypical values correspond to edges having high consumption in dried substances (>100 Kg/ml), high water absorptions (>150 LU) or both at the same time, either for the Massive sandstones with argillites interstratification or Greenish to greyish or purplish argillites with interstratification of sandstone-like bar of centimetric thickness.

- At Ouljet Es-Soltane's dam, the outliers are divided in two groups G1 and G2 : we can explain the behavior of the two groups towards the pressure of injection by :
  - **For group 1:** the sensibility of some zones of altered schists on cracks to the big pressure of grout injection, which reaches 30 bars, causes its fracturation and afterwards an important penetration of the grout.
  - **For group 2:** the existence of cracks having important openings facilitates the flow of the two fluids.
- For Tiouine's and Er-Rmel's dams: we have noticed that there a specific number of points that come out of the cloud. This had lead us to proceed as follow :
  - First, identify the atypical values which are generally edges with very high values of a variable and very low of the other.
  - Eliminate these outliers and redo the calculation and the presentation of the scatter plot as many times as it takes to make sure of the behavior of the rest of the individuals.

We notice that at each time we eliminate a group of outliers, we will have other groups that come out of the cloud and a coefficient of correlation which remains low or which decreases compared with the previous one in most cases.

In addition to the results above, we add that for an andesitic cracked formation, we cannot correlate the water absorption with the consumption of dried substances, because each of the two variables is influenced by the variation of the openings of the cracks, and that for the sandstone foundation of Er-Rmel's dam, the presence of values extremely low or high can be justified mainly by the closure of stratification joints in one hand, and that we have maybe encountered a brecciated fault zone in the other hand.

4. CONCLUSION

The analysis in principal components realized on the drills located at the level of the waterthigtness veil of the four studied dams has shown that the behavior of water is different from the grout injection regarding the absorption under pressure at the level of microcracks crossing the rock of every foundation.

Theoretically, the two fluids must be correlated since they cross the same geological formations, which is not always the case seen that we have revealed low coefficients of correlations in all cases studied, but the geology of each site and its mechanical parameters have confirmed that the effects of lithology on the absorptions, throughout the homogenous foundations where the values are more important than heterogeneous ones. With these facts, we can confirm that the PCA proved it's efficiently for the interpretation of a great number of data, in order to have a total vision on the relationship between water and cement's grout consumptions in studied drills, but having a lot of outliers in every scatter plot drive us to look for other influencing factors that can help refining the interpretation of the results, such as, the pressure of injection, the frequency of cracks and the quality index, the study the homogenous foundations from a geological point of view since they have given important correlation's coefficients compared with the other foundations and eliminate the results of absorption obtained in the altered parts of the foundation which generate atypical values disturbing the coefficient of correlation.

REFERENCES

[1] Lauga, R. Tendances Actuelles en Matière de Coupures Etanches par Injections ou par Parois Moulées, Comité Marocain des Grands Barrages CMGB, 1992, pp. 26-29.

[2] Elbaz, A. and Elqalli, R. Voile d'étanchéité et étude des paramètres d'injection du barrage El Ghrass, PFE (1996-1997), pp 16-25.

[3] Michard, A. Eléments de Géologie Marocaine, Edition du service géologique du Maroc, Rabat, 1976.

[4] Sabarly, F. Les injections et les drainages de fondation de barrages en roches peu perméables, Géotechnique, 1968, pp. 242-243.

[5] Documentation du Service Géologie d'Exécution des barrages, Direction des Aménagements Hydraulique, Secrétariat d'état auprès du Ministère de l'Equipement, du Transport, de la Logistique et de l'Eau, Rabat.

[6] Cassan, M. Les essais d'eau dans la reconnaissance des sols, Eyrolles, 1980, pp. 223. https://trid.trb.org/view/1045759

[7] Perret, S. Contribution à l'étude des critères d'injectabilité des coulis de ciment dans les sols fins, National Library of Canada, 1997, pp. 114.

[8] Lombardi, G. Fissured rock masses permeability and Groutability, Rev. Franç. Géotech. N° 51, avril 1990, pp. 5-29.

[9] Lombardi, G. Aspects spécifiques de l'injection du massif rocheux, Symposium sur l'injection, Rabat, 8 Février 2007.

[10] Sinan, M. Méthodologie d'identification, d'évaluation et de protection des ressources en eau des aquifères régionaux par couplage des SIG, de la géophysique et de la géostatistique : Thèse de Doctorat, Université Mohamed V, Faculté des Sciences, Rabat.

[11] Kassou, A. and Aissa, M. Modélisation numérique de la minéralisation polymétallifère du gisement de Tighza (Maroc central) par l'outil SIG et la géostatistique. Afrique Science: Revue Internationale des Sciences et Technologie, 7(1), 2011.

[12] Bennis, K. and Bahi, L. PCA and cluster analysis for criteria mapping in landfill sitting, International Journal of Engineering and Technology (IJET).Vol 6 No 5 Oct-Nov 2014, 2224-2260.

[13] Baba, K. Ouadif, L. Application des méthodes d'analyses statistiques multivariées à la délimitation des anomalies de Sidi Chennane (Multivariate Statistical Analysis tool for the interpretation of geoelectrical data: application to Sterile Bodies in the Sidi Chennane phosphatic deposit (Morocco)), J. Mater. Environ. Sci. 5 (4) (2014). 1005-1012.

[14] Mnassri, B. Analyse de données multivariées et surveillance des processus industriels par analyse en composantes principals. Université d'Aix-Marseille Ecole Doctorale en Mathématiques et Informatique de Marseille – ED 184, 39.