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GEOSTATISTICAL INTERPOLATION FOR MODELING THE FACTOR OF SAFETY AGAINST LIQUEFACTION (CAPITAL CITY OF ALGERIA)

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ABSTRACT: In Algeria, active tectonics is located in the northern region of the country. Further south, the seismicity is expressed, all along the Tell, along the NE–SW direction fold bundles. The present work uses a number of empirical models from geotechnical earthquake engineering in combination with some geostatistics tools to assess the soil liquefaction potential over an extended area at the Airport of Algiers (Algeria), by the kriging approach. The GS+ geostatistics software along with variograms and the kriging method were all applied together for the purpose of modeling the variation of the factor of safety (FS) in the region under study. This approach allowed determining the missing data in that region. This geostatistical method helped to draw three maps at different soil depths, i.e. 1, 3 and 7m. The results obtained revealed that the models developed were potentially capable of accurately estimating the needed data. The factor of safety (FS) against liquefaction is uncorrelated beyond the distance for which the variogram model stabilizes within an interval ranging from 600 km to 1800 km, for the exponential model used in this study. The values of kriging standard deviation or kriging variance indicate that the standard deviation (SD) values are within the interval ranging from 0.505 to 0.779, 0.231 to 0.556 and 0.257 to 0.61 1respectively.

Keywords: Kriging; CPT; Site investigations; Factor of safety

1. INTRODUCTION

Soil liquefaction is a seismic ground failure process that takes place in loose, saturated granular sediments, mainly in sand and silty sand. This mechanism turned out to be the primary cause for the damage of soil structures, lifeline facilities, and building foundations in previous seisms. Indeed, today soil liquefaction should be viewed as a real concern as it clearly poses serious threats to the integrity of structures and facilities in the case of any possible future earthquakes in Algeria and around the world as well.

The occurrence of liquefaction in soils is often assessed using the originally simplified method proposed by Seed and Idriss (1971). This method is based on the Standard Penetration Test (SPT), Cone Penetration Test (CPT), Marchetti Dilatometer Test (DMT), Shear Wave Velocity Measurement Test, and other laboratory tests, such as the cyclic triaxial test [3].

Geostatistics, which was invented in 1962 by Georges Matheron, represents the set of probabilistic methods intended for the study of regionalized phenomena [7]. Geostatistical analysis, which takes into account two important issues, differs from the rest of the classical interpolation methods. The first issue lies in identifying the spatial structure of the variable studied using the variogram which is considered a basic tool of geostatistics; the second one concerns the use of this spatial structure with known measured values, for the optimal prediction at unmeasured points, using the Kriging technique [2].

Soil liquefaction potential at the Airport of Algiers may be evaluated through the use of a number of geotechnical data such as the type of soil, CPT value, depth of water table, mean grain size of soil particles and soil specific weight. These geotechnical data were gathered from subsoil investigation reports (geotechnical borehole logs), as indicated in Figure.1. It is worth specifying that the borehole data for the study area were collected at different depths, ranging from 10 m to 20 m below ground surface.

In order to determine the liquefaction potential in the areas where the borehole data are not available, a special statistical analysis was carried out by means of the Geostatistical Analysis program GS+. Geostatistics is closely linked to interpolation procedures but covers much more than simple interpolation issues in order to prepare a continuous map.

It is worth indicating that interpolation is about evaluating a variable at an indefinite position based on values collected in surrounding areas. A Kriging method of interpolation was employed in the present study for the purpose of interpolating the liquefaction potential. It is important to note that the geostatistical methods were initially used for mineral reserve calculations in the pioneering study of Krige (1951). Afterwards, the theory was reformulated in a very short form by the remarkable contributions of George Matheron. Subsequently, a novel scientific discipline, namely geostatistics, came into existence by uniting Krige's concepts and Matheron's theory of regionalized variables [2].

This geostatistical interpolation technique takes into account both the distance and the degree of variation between given data points when the data to be estimated are in unknown areas. Note that kriging supposes that the distance or direction between sample points corresponds to a special correlation that can be employed in describing and elucidating the variation at the surface [5]. This is a technique that allows making optimal, unbiased estimates of regionalized variables at locations not previously sampled, using the essential properties of the semi-variogram as well as the initial set of data values.

Moreover, it aims to minimize the error variance and to fix the mean of the prediction errors to zero in order to prevent any overestimations or underestimations. The present study aims at mapping the factor of safety against liquefaction (FS) through the use of geostatistical methods. The results were mapped using the GS+ software program, and the variations of FS values were contoured at soil depths equal to 1, 3, and 7m.

Furthermore, the results found were validated by comparing the real or absolute values with the estimated ones in two boreholes. These data were then used for liquefaction analysis. The geostatistical analysis shows that the site studied presents a high risk of liquefaction, the latter requiring a significant improvement in the base soil (drainage or lowering of the water table), or a change of site, which is not possible (project already done) [4].

2. RESEARCH SIGNIFICANCE

In Algeria, active tectonics is located in the northern region of the country, mainly in the Tell. Further south, the seismicity is expressed, along the NE–SW direction fold bundles. The legislation of the majority of countries explicitly prohibits the construction of aerodromes in high-risk areas, except in places where the lack of space is obvious and where other risk variables are therefore taken into consideration. A geostatistical analysis was carried out to determine the risk of liquefaction on the site to show the consequences that can take place in case of risk.

3. INVESTIGATION AREA

As a first step, it was decided to conduct an expertise of the basement and foundations in the course of the construction of a new terminal and a freight station at Algiers International Airport.

The site under study, namely the Airport of Algiers, is located about 20 km south-east of the city of Algiers, in the great coastal Mitidja plain which lies between the mountains of the Tellian Atlas and the Mediterranean sea. The location of the penetrometer tests is given in Fig.1. Note that for each penetrometric curve, the values of the peak resistance qc and lateral friction force fs were recorded every 0.15 m to a depth of up to 20 m, depending on the rejection of the test as a result of the penetrometer entering in contact with rocky soil.

The above-mentioned figure shows the boring locations as well as the boundaries of the area under consideration. Figure2 in 3D shows the data set of the peak resistance q_c on the site under consideration.

4. LIQUEFACTION POTENTIALOF SOIL USING DATA OBTAINED FROM THE CONE PENETRATION TEST

The approach initially suggested by Robertson and Wride (1998), and afterwards updated by Robertson (2009) for the assessment of the liquefaction potential of sandy soils employing data provided by the Cone Penetration Test (CPT), is adopted in the present study. It is interesting to mention that the form given below is selected for the Cyclic Stress Ratio [11]:

$$CSR = \frac{\tau_{av}}{\sigma_v^{'}} = 0.65\frac{a_{\max}}{g}\frac{\sigma_v}{\sigma_v^{'}}\frac{r_d}{MSF}\frac{1}{K_\sigma} \qquad (1)$$

Where a_{max} is the peak horizontal acceleration generated by the earthquake at the ground level, g is the gravitational acceleration, σ_v and σ'_v are the total and effective vertical overburden stresses, respectively, and rd the depth-dependent shear-stress reduction coefficient. Also, MSF is the magnitude scaling factor, and K_σ the overburden correction factor for the cyclic stress ratio (CSR).Furthermore, the form given below is adopted for the shear-stress reduction factor r_d [13]:

$$r_d = \frac{1-0.4113\times Z^{0.5}+0.04052\times Z+0.001753\times Z^{1.5}}{1-0.4177\times Z^{0.5}+0.05729\times Z-0.006205\times Z^{1.5}+0.001210\times Z^{2}} \qquad (2)$$

As for the magnitude scaling factor (MSF), the lower-bound equation that was proposed by [13] is used:

$$MSF = (\frac{M_W}{7.5})^{-2.56} \qquad (3)$$

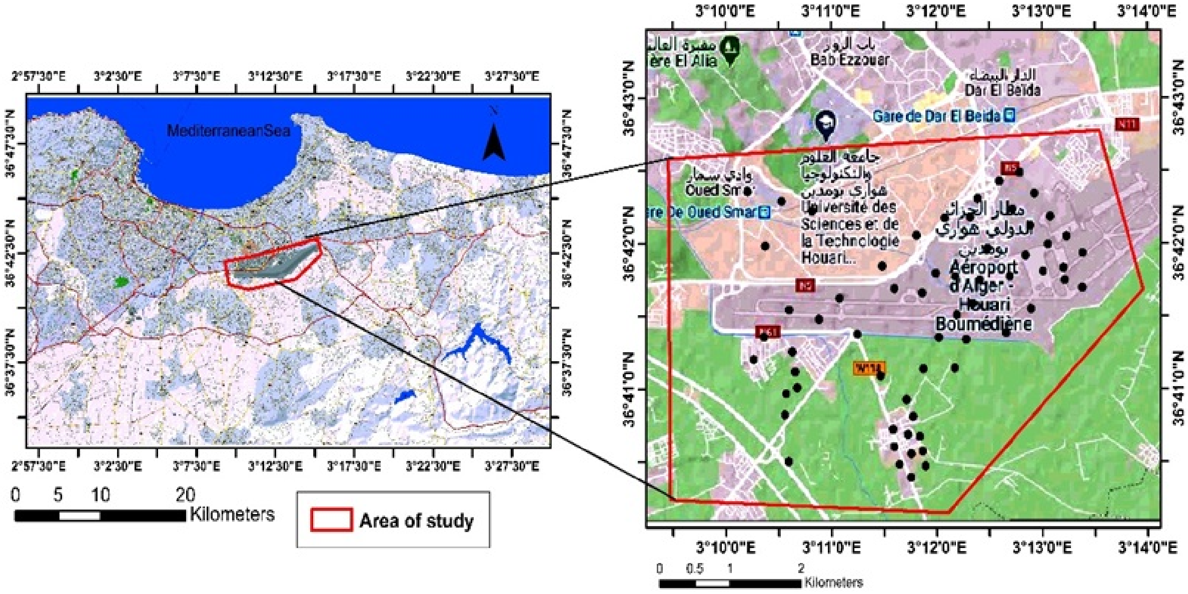

Fig.1Investigation area borehole locations

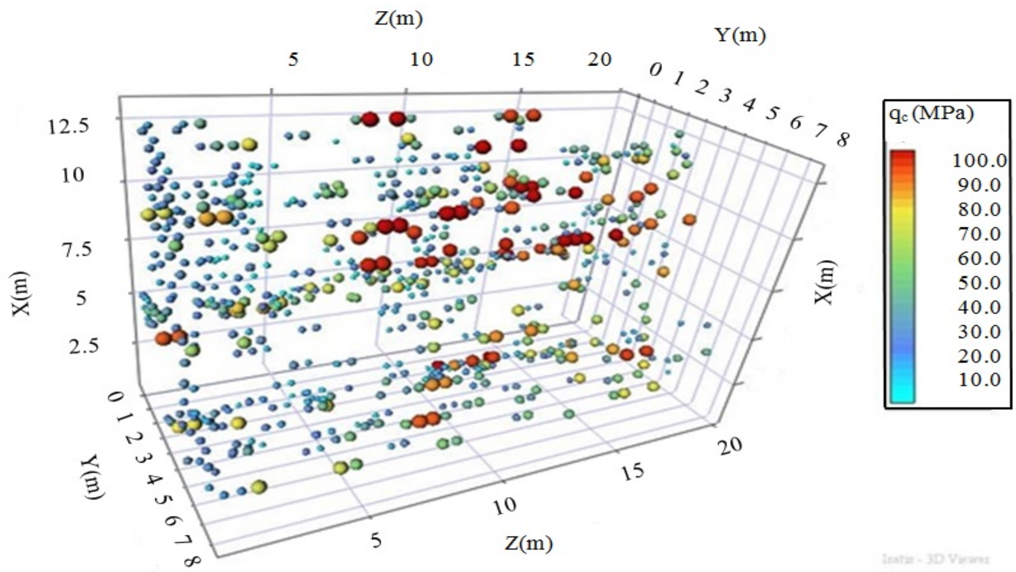

Fig.2 Dispersion of peak resistance at the area

Similarly, the cyclic resistance ratio (CRR) is evaluated according to the method developed by [9] and updated by [10], as expressed below:

$$CRR = \begin{cases} 0.833\left(\frac{(q_{c1N})_{cs}}{100}\right) + 0.05 & \text{for} \quad (q_{c1N})_{cs} < 50 \\ 93\left(\frac{(q_{c1N})_{cs}}{100}\right)^3 + 0.08 & \text{for} \quad 50 \le (q_{c1N})_{cs} < 160 \end{cases} \tag{4}$$

Where the clean-sand equivalent normalized cone tip resistance $(q_{c1N})_{cs}$ is defined as:

$$(q_{c1N})_{cs} = K_c \times q_{c1N} \tag{5}$$

Here K_c is the conversion factor that is expressed as:

$$\begin{cases} K_c = 1 \ \text{for} \ I_c \le 1.64 \\ K_c = -0.4031 I_c^4 + 5.5881 I_c + 33.75 I_c - 17.88 \ \text{for} \ I_c > 1.64 \end{cases} \tag{6}$$

On the other hand, the soil behavior type (SBT) index I_c was defined by [10]:

$$I_c = \left[(3.47 - \log Q)^2 + (1.22 + \log F)^2\right]^{0.5} \tag{7}$$

Note also that the normalized tip resistance Q and the normalized friction ratio F are stated as:

$$Q = \left[\frac{(q_c - \sigma_{v0})}{P_a}\right]\left(\frac{P_a}{\sigma'_{v0}}\right)^n \quad (8)$$

$$F = \left[\frac{f_s}{(q_c - \sigma_{v0})}\right] \times 100\% \quad (9)$$

Taking into account the two quantities CSR and CRR, the factor of safety against liquefaction may therefore be expressed as [6] [8]:

$$FS = \frac{CRR_{7.5}}{CSR} \quad (10)$$

5. THE GEOSTATISTICAL KRIGING INTERPOLATION METHOD

Geostatistics is a branch of statistics applied to problems in geology and hydrology. It is increasingly employed in mapping regionalized variables. Kriging is a geostatistical approach that offers the advantage of preserving the spatial continuity of the parameters for a possible mapping [12]. It is worth indicating that in the geostatisticalkriging algorithm, the weighting rule and, consequently, the resulting map can straightforwardly be determined based on the spatial behavior of the characteristics of the element to be examined. The preliminary step to using kriging is the variographic analysis which is carried out for the purpose of assessing the function of the spatial continuity of a regionalized variable [4].

The variogram $\gamma(h)$ an be described as the magnitude of dependence between attributes at two different locations:

$$2\gamma(h) = \mathrm{Var}[Z(u+h) - Z(u)] \quad (11)$$

Note that $2\gamma(h)$ is the value of the variogram corresponding to a separation distance h, Z(u) is the value of the random variable at position u, Z(u+h)is the value of the previous random variable at a distance h from Z(u), and Var[] is the variance operator. The models fitted to the semi-variance data of equation 11 for soil parameters are given in Table 2. Three model parameters, namely Nugget, Range, and Sill, were obtained after fitting the semi-variogram model; these parameters were employed in describing the nature of spatial variability.

The parameter Range represents an estimate of the maximum distances over which the measured parameter Z is spatially correlated. Note that as h increases, the semi-variogramvalue rises to a specific degree, but remains unchanged for values greater than the parameter known as the Sill.The semi-variogram value is 0 at zero separation distance; this is called the nugget effect which represents the unexplained or random variance that is mainly attributed to errors occurring during sampling and measurements.

In this study, the semi-variogram models were applied for the purpose of estimating the spatial distribution of safety factors against liquefaction through ordinary kriging. It is important to recall that a kriged estimate is defined as a linear estimator of the variable Z at location u in space, where the value of Z is unknown; this is achieved by means of kriging interpolation techniques. The kriged estimate depends on various features of the spatial correlation structure, i.e. variogram, but does not change from one situation to another. This estimate may be evaluated on the basis of the expression below:

$$Z* = \sum_{i+1}^{n} \lambda_i Z(u_i) \quad (12)$$

Here $Z(u_i)$ is a value of Z at position u_i it is provided either from field data at that position or from antecedently simulated nodes. $Z(u_i)$ is a weight that is assigned to field data at position u_i it is dependent on the characteristics of the spatial correlation structure.

6. RESULTS AND DISCUSSION

In this study, the kriging method was applied using the GS+ software. Various variograms were developed with data collected at depth of 1, 3, and 7m. The ordinary kriging method was employed to prepare the factor of safety (FS) maps after fitting the appropriate theoretical mathematical models to experimental variograms. A histogram, as well as the basic statistical analysis of the FS values, is given in Figure.3 and Table1. This gives an idea about the characteristics of soils at the depth of 1, 3 and 7 m in the region. It is agreed that the histogram represents the left-skewed FS.

The variograms are drawn in Figure.4 at the depth of 1, 3 and 7 m. These variograms were used to conduct the geostatistical analyses while taking great care to fit the developed models to the experimental variograms to a moderate level. Table 2 clearly displays the properties of these best fit models. Note that the mean value is equal to 1.1713, 0.5656 and 0.628 with a standard deviation of 0.6075, 0.312 and 0.3439 for 1, 3 and 7m respectively. It is worth indicating that a high kurtosis number indicates the existence of a sharp peak, which is also observed in the frequency distribution.

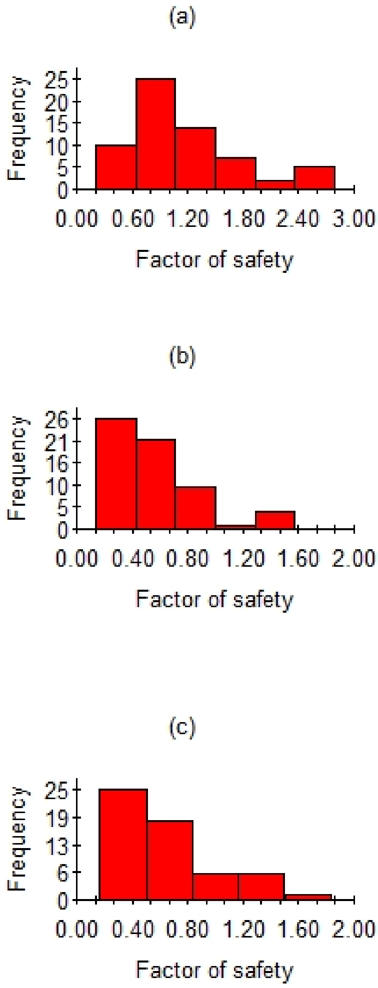

Fig.3 Histogram of the factor of safety (FS) against liquefaction for (a) 1m, (b) 3m and (c) 7m

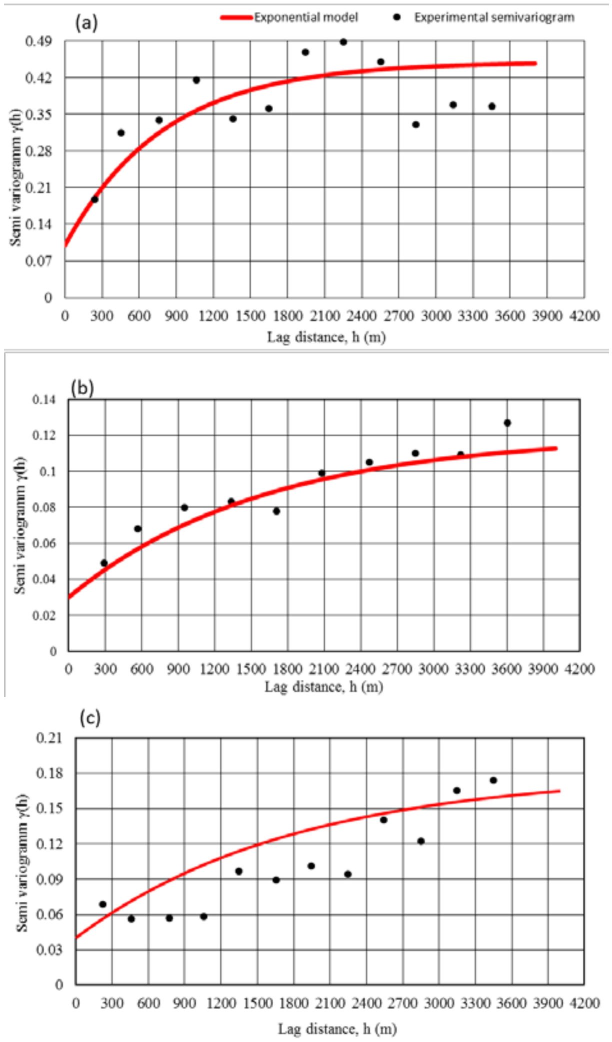

Fig.4 Experimentatl and theoretical semivariograms for FS (a) 1m, (b) 3m and (c) 7m

Table 1Statistical analysis of the factor of safety at depth equal to 1, 3 and 7m

Parameter	Number of values	Mean	Standard deviation	Minimum value	Maximum value	Skewness	Kurtosis
FS 1m	62	1.1713	0.6075	0.400	2.67	1.01	0.24
FS 3m	60	0.5656	0.312	0.22	1.57	1.37	1.75
FS 7m	56	0.628	0.3439	0.27	1.55	1.02	3.02

Table 2 Parameters of variogram models

Parameter	Model	Nugget	Sill (C0+C)	Range	$C/C+C_0$	r^2
FS 1m	Exponential	0.15	0.45	600	0.667	0.60
FS 3m	Exponential	0.03	0.12	1600	0.750	0.86
FS 7m	Exponential	0.04	0.18	1800	0.778	0.72

The factor of safety (FS) against liquefaction is uncorrelated beyond the distance for which the variogram model stabilizes within an interval ranging from 600 km to 1800 km, for the exponential model used in this study (Fig 4).

The variogram is the centerpiece of spatial kriging analysis as it allows detecting anomalous points due to their position with respect to the others. It is important to mention that the isolated points must be eliminated in order to have a good spatial correlation. After developing the experimental variogram, it must be calibrated by means of a model that suits it best. Note that finding the theoretical model that suits well that variogram is not always easy.

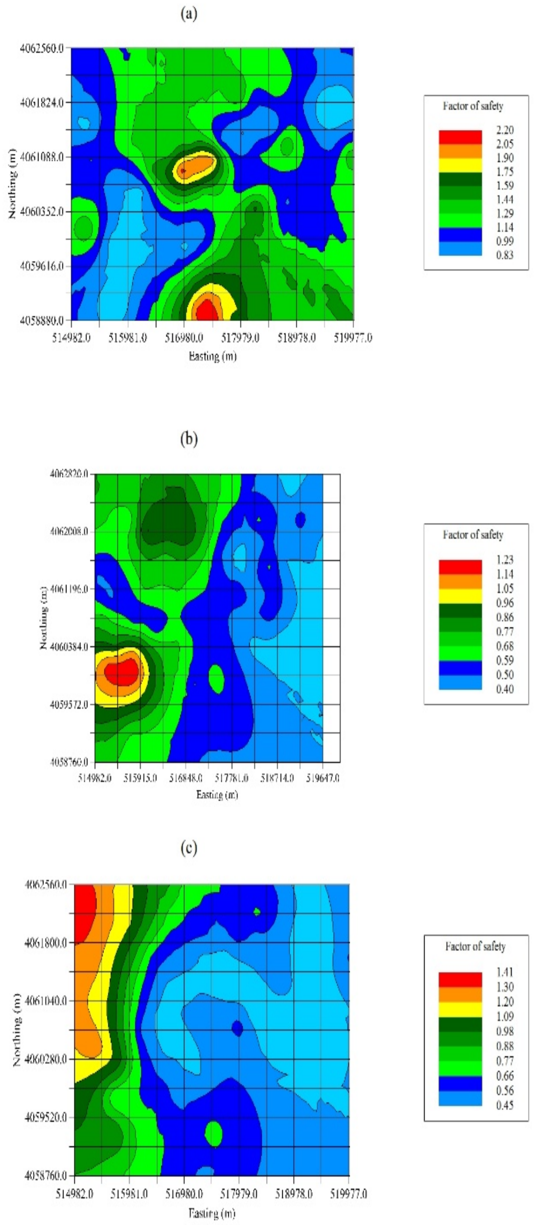

Fig.5 Factor of safety (FS (a) 1, (b) 3 and (c) 7m) hazard map predicted by ordinary kriging for earthquake magnitude of 6.8 and peak ground acceleration of 0.3 g

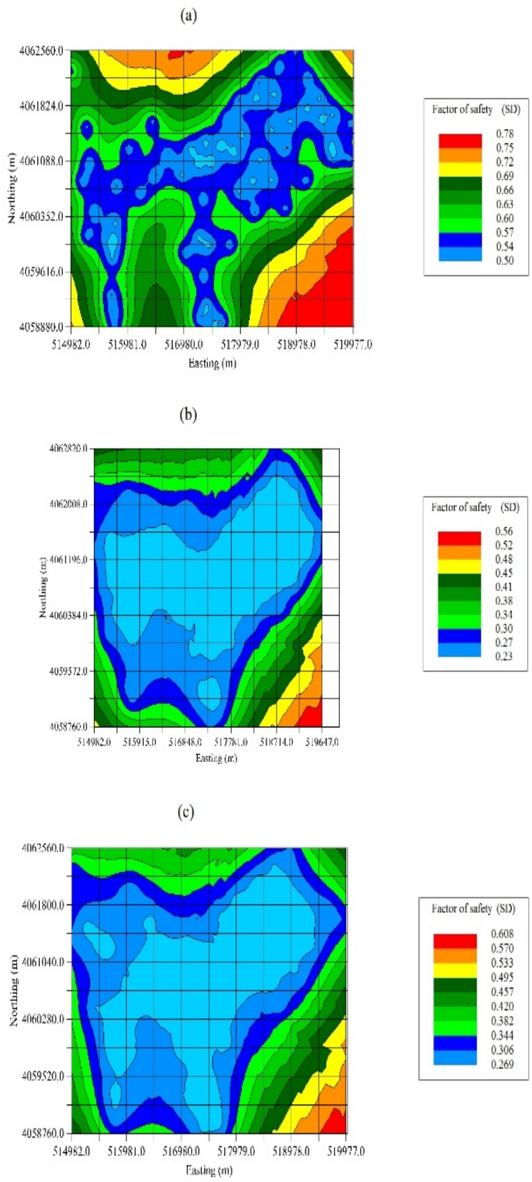

Fig.6 Map of standard deviation of (FS (a) 1, (b) 3 and (c) 7m) for earthquake magnitude of 6.8 and peak ground acceleration of 0.3 g

On the other hand, the geostatistical probabilistic framework allows quantifying the uncertainty related to the interpolated value using the average estimate of the error and the standard deviation of the estimated error. Basically, the estimate is better than the average estimate of the error and the reduced parameters using contour interpolation. Theoretically, this method offers better estimation capacities in comparison with the other methods, because the former one is unbiased and is based on error minimization.

The ordinary kriging exponential model is applicable to the data at depth of 1, 3 and 7m.Figure

5 depict the factor of safety hazard map predicted by ordinary kriging for earthquake magnitude of 6.8 and peak ground acceleration of 0.3g. Figure 6 indicates that the standard deviation (SD) values are within the interval ranging from 0,505 to 0, 0.779, 0231 to 0.556 and 0.257 to 0.611.

Figure 7 clearly illustrates the estimated and real values. The quantity r^2 refers to the proportion of variation that is represented by the best-fit line and represents the square of the correlation coefficient. The y-intercept of the best-fit line is also provided. The model under consideration turned out to be acceptable and was therefore validated. Standardized errors are close to 0. This result confirms the high accuracy of the estimator, and the variance of errors is close to 1.

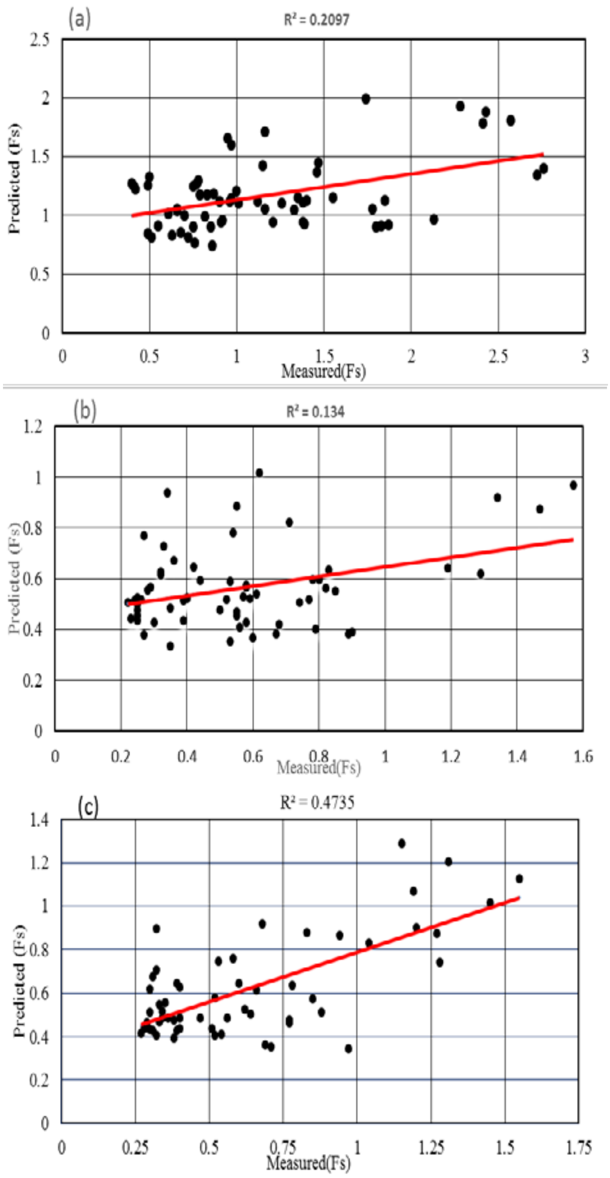

Fig.7 Cross validation of the semivariogram model for the factor of safety (FS (a) 1m, (b) 3m and (c) 7m)

7. CONCLUSIONS

This study aimed to highlight the advantages of using the kriging technique in determining the variation of the factor of safety against liquefaction (FS) at the Airport of Algiers. The variograms were prepared at three depth values for the data at hand. The kriging method was used to estimate the values of the factor of safety against liquefaction (FS) within the area under study.

Afterwards, the contour map was prepared for better visualizing the variation of the factor of safety against liquefaction (FS). The model was validated and the correlation coefficient found confirms the acceptance of the model. In Algeria, active tectonics is located in the northern region of the country, mainly in the Tell. The latter are most often the cause of the violent earthquakes that Algeria experiences.

Further south, the seismicity is expressed, all along the Tell, along the NE–SW direction fold bundles. The geostatistical analysis shows that the site presented a great risk of liquefaction, the latter requiring a significant improvement of the base soil (drainage or lowering of the water table), or a change of site, which is not possible (project already done).

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