**Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi**
Afyon Kocatepe University – Journal of Science and Engineering
https://dergipark.org.tr/tr/pub/akufemubid

**Araştırma Makalesi / Research Article**
**DOI: https://doi.org/10.35414/akufemubid.1287644**
AKÜ FEMÜBİD **24** (2024) 015603 (117-125)
AKU J. Sci. Eng. **24** (2024) 015603 (117-125)

# Application of Monte Carlo Simulation Technique for Slopes Stabilized with Piles

***Makale Bilgisi / Article Info**
Alındı/Received: 26.04.2023
Kabul/Accepted: 30.01.2024
Yayımlandı/Published: 27.02.2024

## Kazıklarla Güçlendirilmiş Şevlerde Monte Carlo Simülasyon Yöntemi Uygulaması

**Yeşim TUSKAN**[*], **Yusuf ERZİN**

*Manisa Celal Bayar University, Faculty of Engineering, Department of Civil Engineering, Manisa, Türkiye*



## Öz

This paper describes a numerical study and simulation model of a reinforced slope by anti-slide piles. A two-dimensional finite element method (2D-FEM) were utilized to assess factor of safety (FS) regarding the arching effect of a severely damaged outer eastbound slope at Manisa-Izmir State Road (Turkey). Additionally, a reliability-based design method, Monte Carlo Simulation (MCS), was then used to develop a model to accurately predict the stability of reinforced slopes and the probability of failure for the reinforced slope during an earthquake. The knowledge of probability and statistical theory were used in deterministic studies to solve the proposed problem and to produce numerical solutions without any physical testing. To evaluate the estimation capacity of the generated MCS and FEM models, reliability index and probability of failure were computed. Finally, the computed indices make it clear that both constructed MCS and FEM were able to predict FS values of landslide quite efficiently.

***Anahtar Kelimeler:*** *Slope Stability; Monte Carlo Simulation; Reliability Assessment; Finite Element Method.*

## Abstract

Bu çalışmada, kazıklarla güçlendirilmiş bir şevin simülasyon modeli geliştirilmiştir. Manisa-İzmir Devlet Yolu (Türkiye) doğu kesiminde yer alan hasar görmüş bir şevin güvenlik sayısının (FS) kemerlenme etkisi göz önüne alınarak değerlendirilmesi için iki boyutlu sonlu elemanlar yöntemi (2D-FEM) kullanılmıştır. Ek olarak, güvenilirliğe dayalı bir tasarım yöntemi olan Monte Carlo Simülasyonu (MCS), deprem sırasında güçlendirilmiş şevlerin stabilitesini ve güçlendirilmiş şevlerin kayma olasılığını doğru bir şekilde tahmin etmek için kullanılmıştır. Olasılık ve istatistiksel teori bilgisi, önerilen problemi çözmek ve herhangi bir fiziksel test olmaksızın sayısal çözümler üretmek için deterministik çalışmalarda kullanılmaktadır. Geliştirilen MCS ve FEM modellerinin tahmin kapasitesini değerlendirmek için güvenilirlik indeksi ve yenilme olasılığı hesaplanmıştır. Son olarak, hesaplanan indisler hem geliştirilmiş MCS'nin hem de FEM'in heyelanın FS değerlerini oldukça verimli bir şekilde tahmin edebildiğini açıkça ortaya koymaktadır.

***Keywords:*** *Şev Stabilitesi; Monte Carlo Simülasyonu; Güvenirlik Değerlendirmesi; Sonlu Elemanlar Yöntemi*

## 1. Introduction

The finite element method (FEM) is progressively utilized for preliminary design of geotechnical process (Li *et al.* 2013; Jiang *et al*. 2014; Mohammadi and Taiebat 2016, Dagli *et al.* 2018, Dagli *et al.* 2019). The FEM ordinarily utilized in practice is, while largely a deterministic method that does not proceed with the stochastic behavior of project variables (Cui and Sheng 2005). These substantial uncertainties with their imputation on performance and estimation of geotechnical design parameters with lack of essential in-situ information enforced the practice of geotechnical engineering. Due to these uncertainties, a deterministic study generating averaged values of the design variables is not performed successfully to model the system. Increasingly, geotechnical engineers utilized probabilistic estimation to quantify their degree of uncertainty. Probabilistic techniques are not new to incorporate this uncertainty by geotechnical engineers (Wang et al. 2012; Saghafian et al. 2013; Caballero and Rahman 2014; Chen et al. 2016; Ching and Wang 2016; Yazdani and Kowsari 2017, Erzin and Tuskan 2017, Erzin and Tuskan 2019), because of the remarkable quantity of additional computational effort. These methods have appeared as a significant practice for geotechnical tasks (Wang et al. 2012; Caballero and Rahman 2014; Chen et al. 2016; Ching and Wang 2016; Erzin and Tuskan 2016, Yazdani and Kowsari 2017, Yildizel *et al*. 2017). In these tasks, geotechnical studies are characterized by complex soil behavior to model the real system. Therefore, probabilistic approaches that utilized more realistic physical aspects

*Sorumlu Yazar/Corresponding Author: Yeşim TUSKAN*
*e-posta/e-mail: yesim.tuskan@cbu.edu.tr*

are now achievable. The Monte Carlo simulation (MCS), one of the most powerful probabilistic methods, is utilized in various engineering optimization problems (Zhou et al. 2003; Wang et al. 2012; Yazdani and Kowsari 2017). Accordingly, for solving various geotechnical problems, these applications designate that the MCS is useful to obtain an optimal solution. Zeng and Liang (2002) used Mohr Coulomb failure criteria in two-dimensional FE model, in which the soil is assumed to be an elastic–perfectly plastic material to model drilled shafts as a rigid material. The load reduction factor is used to form the arching effect of the reinforced slope. Three-dimensional FE simulation was modeled by Yamin (2007) to evaluate a closed solution for calculating the FS of a reinforced slope. The FE analysis was carried out in the study of Al Bodour (2010) by incorporating the strength reduction methodology into the FE simulations of anti-slide piles. Joorabchi (2014) redefine the major parameters that control a single row of drilled shaft stabilized slope.

This paper presents a numerical and an analytical case of landslide formation in Manisa-Izmir State Road, Manisa, Turkey. The site investigations were also conducted as a part of the case study of anti-slide piles. The main objectives of this study are to generate the FEM model of the pile/slope system from site investigations and to compare the probability of failure obtained from MCS for the prediction of factor of safety (FS) of reinforced slope.

**2. Case Study**

Landslides resulting in extensive damage continue to be a primary problem in geotechnical engineering. Roadways in landslide area are menaced by enormous geotechnical hazards. To ensure the safety of the roadways against slope failure, several structural or non-structural methods such as retaining walls, drainage techniques, biotechnical protection, anti-slide piles are utilized to reinforce of the landslides (Li et al. 2013). This study presents a case study on geotechnical and geologic characterization of a landslide that occurred in a sandstone-clay stone slope. A severely damaged pavement of the outer eastbound slope of Manisa-İzmir State Road in Manisa, Turkey is stabilized by anti-slide piles. The application efficiency of the slope stabilizing piles on measures of displacement and forces acting on pile has been proven by finite element method (Li et al. 2007). Therefore, designing a row of piles to stabilize an unstable slope involves both geotechnical and structural engineering issues that need to be taken into consideration. The arching effect, through the load transfer factor, is derived from a semi-empirical equation using a 2-dimensional finite element (2D-FE) parametric study. The load transfer factor is characterized as the ratio of the horizontal force at the pile-soil interface on the downslope side ($P_{\mathrm{down-slope}}$) to the soil-pile interface forces on the upslope side ($P_{\mathrm{up-slope}}$). The load transfer factor is stated mathematically as (Equations 1-3):

$$\eta = \frac{P_{\mathrm{down-slope}}}{P_{\mathrm{up-slope}}} \tag{1}$$

$$P_{\mathrm{up-slope}} = \int_0^{Lp}\int_0^{s} \sigma_x \, dsdz \tag{2}$$

$$P_{\mathrm{down-slope}} = \int_0^{Lp}\int_0^{s} \sigma_x^* \, dsdz \tag{3}$$

Where, $\sigma_x$ is the horizontal soil stresses on the up-slope side of the pile and $\sigma_x^*$ is the horizontal soil stresses on the down-slope side of the pile along top of the pile to the failure surface ($L_p$) with distance between two adjacent pile (s). A computer program in Matlab (MathWorks 2010) is then developed to incorporate the MCS mentioned for applications of in-situ experimental results validated by 2D-FE analysis. Furthermore, seismic displacement of the slope stabilized by one row of pile is computed using Stewart and Blake (Blake et al. 2003) method. The critical displacement is obviously selected to quantify the arching. The arching is extensively applied to the limit equilibrium process for the critical displacement that creates maximum load on pile ($P_{max}$) by means of load transfer factor (?) based on the 2D-FE modelling. The performance-based design according to geotechnical and structural issues are then presented to compute the factor of safety against sliding (FS) of the pile/slope system with a suitable displacement. The case study area is in Manisa–Izmir State Road near Izmir, Turkey. The failure extended from 27 m to the slope crest with an approximate total length of 80 m and a maximum width of 40 m and was in a thick layer of colluvial deposits which are irregularly present along the Zeytindagi valley (Figure 2).

Landslide mass thickness is 12 m according to 2D resistivity measurements. Starting on June 8, 2016, a steady substantial rainfall actualizes in western Manisa, primarily covering the whole area and causing severe landslide in the Manisa-Izmir State Road. On July 20, the damage of the retaining structure was initiated near the roadway at 2K+450 as depicted in Figure 3.

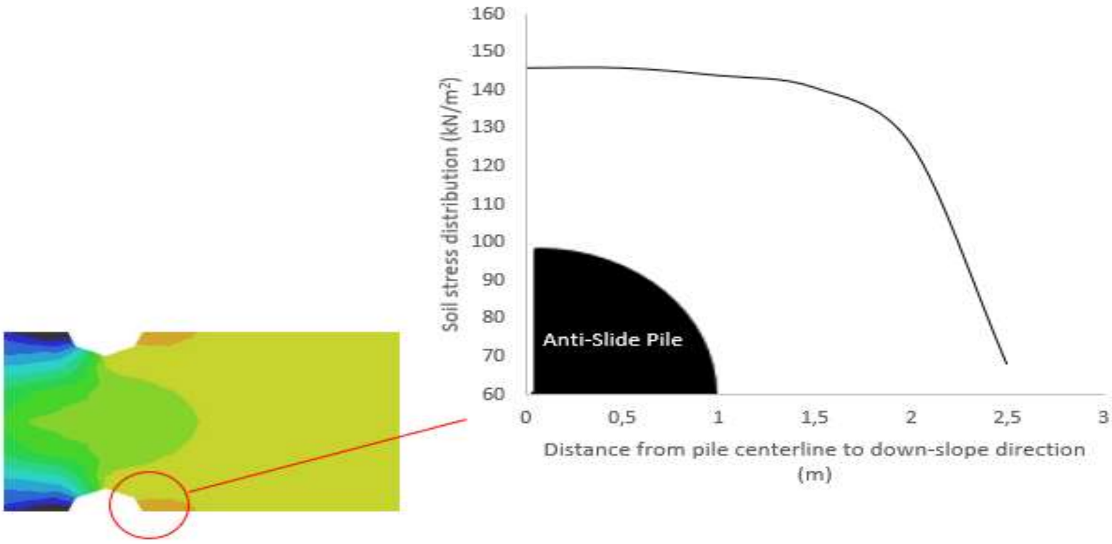


**Figure 1.** The variation of the horizontal soil stresses due to the soil arching effect

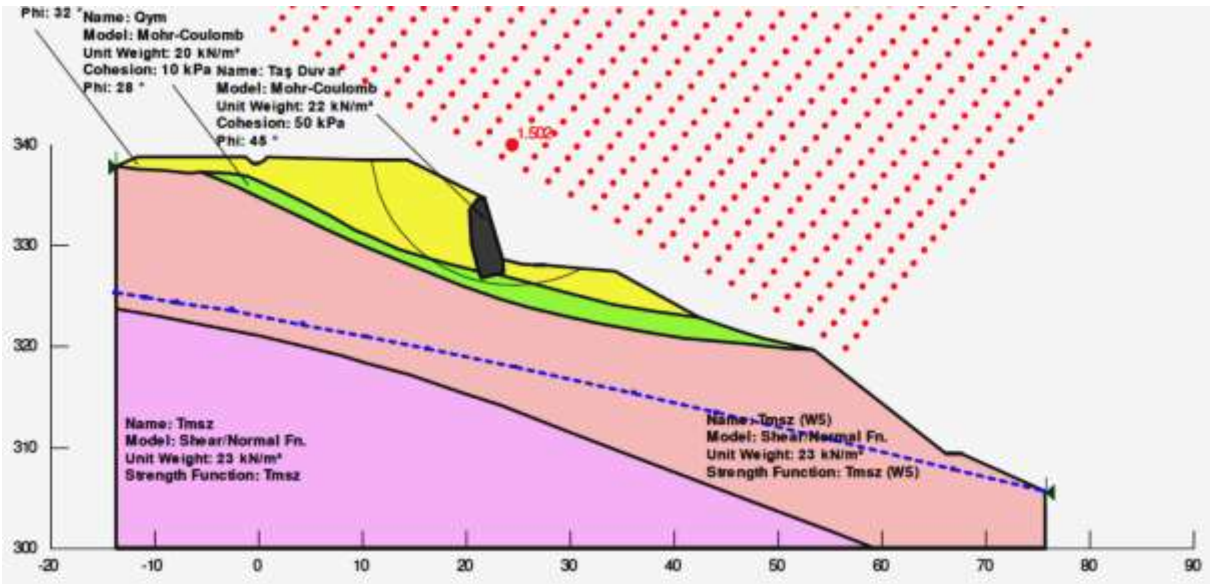


**Figure 2.** Landslide geometry

Additionally, two strain gages at each intermediate level were installed in the directions of up-slope and down-slope side. Also, two of the entire inclinometers were placed inside each anti-slide pile to measure the shaft tilt due to slope movement apart from the soil mass. In addition to these inclinometers, six in-place inclinometers were instrumented inside the soil mass to measure deflections at up-slope, down-slope and between the anti-slide piles. Four piezometers placed across the slope to monitor the ground water level. All instruments except the inclinometers were multiplexed with four 16-channel multiplexers. Additionally, current action velocity along this critical slip surface is 1mm/day according to Table 1. One of the important factors activating mass movements was intense surface water and groundwater movement in permeable layer. mm along the slip surface over a period of approximately two-week indicating a near horizontal slip surface located at depth 10.70m to 11.80m. The main formations around the project area and its surroundings are Zeytindagi Formation (Tmsz) and Quarry (Qym) units (Figure 4). The stratigraphic of these formations, the lithological and structural properties are described below. The unit is named as Zeytindagi formation which starts with red colored conglomerate - sandstone at the base and continues with sandstone, claystone, shale, clayey limestone, limestone and, coal - peat intermediate levels. The other rock formations are sandstone, claystone, marl, shale, clayey limestone, volcanic fragments, schists, limestones, quartzites and, coal - peat intermediate levels. In sandstones, the grains were large sand, small pebbles and coarse silt size, quartz, quartzite, chert, granite, feldspar. Slope stability analyses were performed on cross section B-B' oriented through the highest part of the landslide sliding mass. The results of slope monitoring show a maximum deflection up to 25 and metamorphic rock fragment. Among the highly fragile marls and clayey limestones, the coal levels in the form of bands form the usual appearance of the Zeytindagi Formation. Very smooth layouts are available. Layer thickness varies between 1-40 cm. The age of this unit was determined as early Miocene.

### 3. Material and Method

The Monte Carlo simulation method has been utilized by several geotechnical researchers as a powerful numerical technique useful for solving a variety of complex problems (Murthy 2000; Xiao et al. 2016). The knowledge of probability and statistical theory were used in deterministic routines to solve the proposed problem and to produce numerical solutions without any physical testing (Nowak and Collins 2000)

**Table 1.** Inclinometer Measurements of Boreholes

| Borehole Number | Application Depth (m) | Measurement Period (day) | Sliding Depth (m) | Sliding Quantity (mm) | Movement Velocity (mm/day) |
|---|---|---|---|---|---|
| B-01 | 30.00 | 14 | - | - | - |
| B-02 | 39.00 | 20 | 11.80 | 14.00 | 1.00 |
| B-03 | 30.00 | 22 | - | - | - |
| B-04a | 39.00 | 22 | 10.70 | 13.55 | 1.00 |
| B-04b | 39.00 | 22 | 10.70 | 13.55 | 1.00 |
| B-05 | 30.00 | 14 | - | - | - |
| B-06 | 30.00 | 14 | - | - | - |

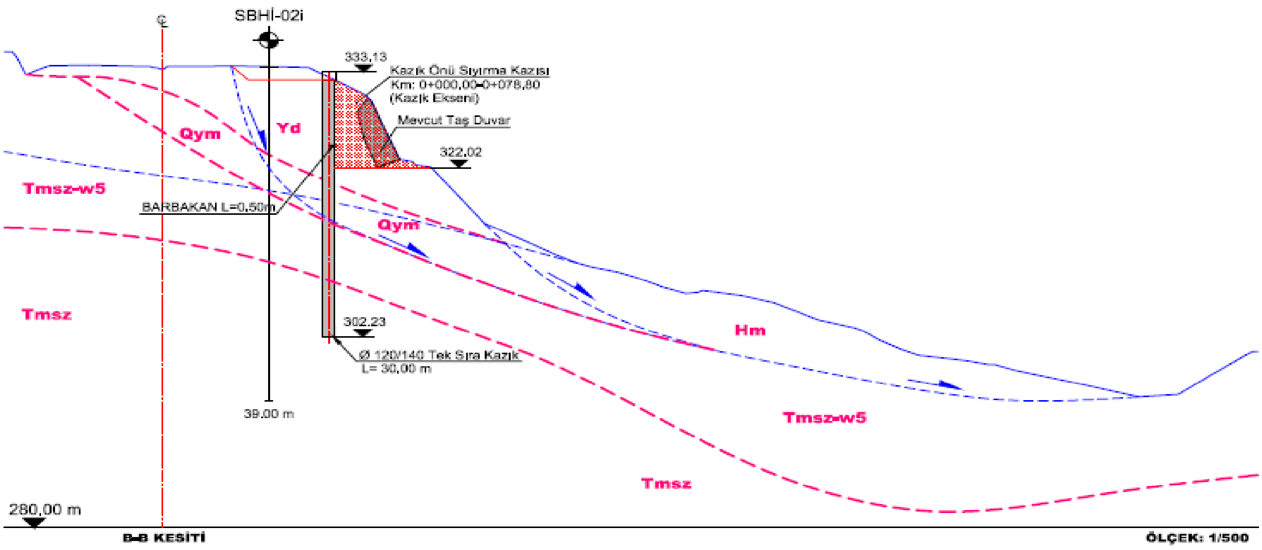


**Figure 4.** Cross-sectional view of landslide instrumentation

In addition, various error solutions of this technique have been identified, including measurement error, spatial variability error, statistical prediction error and conversion error. The measurement error is assumed to be the same and independent of the normal distribution. Observed error is not generally considered in the geotechnical reliability-based design (RBD) spatial variability error accounts for a trend in on-site or laboratory testing. They analyze residual errors, including the prediction of autocorrelation distance (Vanmarcke 1977).

Therewithal, conversion errors are related to the conversion of measured geotechnical parameters to parameters used in soil survey in addition, modelling error has been used to relate the field of prediction to real-world phenomena and ideal calculation models (Kulhawy and Mayne 1990; U.S. EPA. 1997; Uzielli et al. 2006; Phoon 2008; Li et al. 2014; Li et al. 2016; Wang et al. 2016). The proposed pile / slope system consists of two main parts, including soil properties and pile parameters.

In this article, the pile related components are determined but uncertain parameters when compared to the soil properties due to the controllable structure in the pile system. A log-normal distribution is applied to the properties of the three soils during non-slip pile stabilizing slope. Recently, the Monte Carlo simulation, which is the most successful method of modelling anti-slide pile reinforced slope, has been developed using a randomly generated sample-based method with acceptance-rejection algorithm.

### 3.1. Development of Monte Carlo Simulation Model

In the estimation of the FS, Equation 4 has been developed and is an empirical equation with the arching effect using the empirical load transfer factor Formula as previously mentioned. This section describes how to apply the equation developed to simulate FS. In the model, all inputs; c, $\varphi$, $\psi$, $\beta$, D, s/D and $\Omega$ are considered as continuous distributions. The inputs of parametric study used in MCS, and their corresponding distribution function are shown in Table.

**Table 2.** Input Data for Monte Carlo Simulation

| Input Parameters | Minimum | Maximum | Function |
|---|---|---|---|
| c (kN/m$^2$) | 12 | 48 | Uniform |
| $\varphi$ (°) | 10 | 40 | Uniform |
| $\beta$ (°) | 25 | 45 | Uniform |
| $\psi$ | 0.15 | 0.9 | Uniform |
| D (m) | 0.6 | 2 | Uniform |
| s/D | 1 | 3 | Uniform |

In this research, a computer code was used as Monte Carlo simulator. The MCS analysis includes two sampling schemes, a Latin Hypercube sample, and a simple random sampling. The Latin Hypercube sampling was selected according to literature (U.S. EPA. 1997) 4000 simulations to generate the same accuracy level (Li et al. 2014) were utilized for all possible randomly selected combinations.

The MCS model is deeply affected by the relation between input variables. Therefore, to obtain an improved MCS model for FS simulation, the relation of the input variables was investigated and considered. (Presented in Table 3). As shown in Table 3, there is a relationship between friction angle, cohesion, slope gradient and pile parameters (s and s/D). For this reason, existing formulas were used to calculate one of these as a function of other factors. Correlations shown in Table 3 were considered to simulate the pile stabilization cases.

**Table 3.** Correlation coefficient for MCS model inputs

| | c | $\varphi$ | $\beta$ | $\psi$ | D | s/D |
|---|---|---|---|---|---|---|
| c | 1 | | | | | |
| $\varphi$ | 0.031 | 1 | | | | |
| $\beta$ | 0.006 | 0.05 | 1 | | | |
| $\psi$ | 0.004 | -0.03 | -0.02 | 1 | | |
| D | 0.012 | 0.04 | 0.004 | -0.045 | 1 | |
| s/D | 0.010 | 0.03 | 0.002 | -.0.036 | 0.85 | 1 |

The program comprises rank-order correlations with a significant level using correlation matrix among model inputs. The following steps were performed to statistically estimate FS. Figure 5 shows the statistical summary of FS obtained with the MCS model. The minimum and maximum FS are 0.32 and 2.55 respectively. Also, the average value of FS was simulated as 1.4.

The probability of failure for the pile/slope system is calculated by utilizing the MCS method, as described as Equations 1 and 2. The probability of failure and the incorporated coefficient of variance (c.o.v.) are given in Equations 4 and 5, respectively.

$$P_f = \frac{1}{N}\sum_{i=1}^{N} I_i\left[\frac{F_R - F_D + \Delta F_A}{F_D - \Delta F_A} < 0\right] \tag{4}$$

$$\delta(P_f) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[I_i\left[\frac{F_R - F_D + \Delta F_A}{F_D - \Delta F_A} < 0\right] - P_f\right]^2} / P_f \tag{5}$$

5

where $P_f$ is the calculated probability of failure for the pile/slope system, δ is the coefficient of variance (c.o.v.) of $P_f$, N is the sample numbers. To obtain the estimated probability of failure, the randomly generated soil parameters can be inputted into the proposed Matlab program for Monte Carlo simulations. Also, the bias of load transfer factor η will be considered using Equation 6.

$$\eta = \delta\eta(c, \varphi, \beta, D, s, \psi) \tag{6}$$

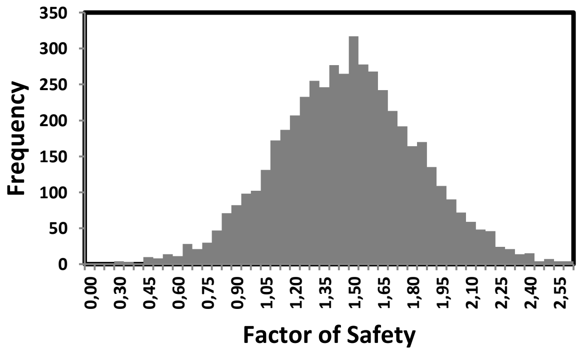


**Figure 5.** Distribution of the Factor of safety (FS) obtained by MCS model

In addition, Figure 3 shows the results of the measured FS and the predicted FS generated by semi empirical equation and 2D-FE model, and the simulated FS obtained by MCS model. Figure 6 shows that the FS was simulated with about 85% confidence. This indicates that the probability of a stable slope is 85%. A sensitivity analysis was also carried out in Table 4. Figure 7 shows the flow chart of Monte Carlo simulation. The Table 4 shows the sensitivity of FS results. The FS, in a descendent order, is sensitive to ϕ, β, ψ, c, D and s/D.

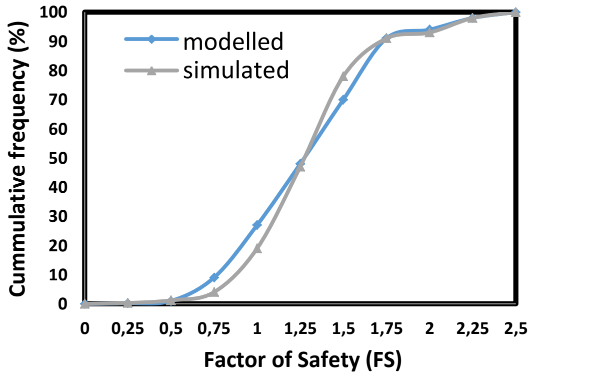


**Figure 6**. Modelled and simulated factor of safety results versus cumulative frequency (%)

**Table 4.** Sensitivity range of input variables due to correlation analysis

| Variables | Correlation coefficient |
|---|---|
| c | +0.06 (4) |
| φ | +0.64 (1) |
| β | -0.21 (6) |
| ψ | -0.45 (2) |
| D | +0.41 (3) |
| s/D | +0.35 (5) |

As it can be seen, from the figure that the φ, among others, is most effective between correlation coefficient to generate FS.

### 4. Results and Discussion

A comparison for the probability of failure with or without pile installation, calculated by the parameters, namely, maximum force on pile $P_{max}$ = 785 kN and for location = 26.5 m is shown in Figure 8. This figure only shows 5.000 sample calculations. Clearly, after pile installation, the probability of failure of the slope has dramatically reduced from 6.40% to 3.08%, with corresponding reliability indices of 2.1 and 4.14, respectively. The piles at the location equal to 26.5 m are founded to be exposed to the largest net forces having higher internal moments and shears along the pile. Thus, six different combinations are selected from these considerations depicted in Figure 9.

The mean FS value simulated with MCS is 1.23, while the actual FS is 1.20. ψ, β and s/D are in an indirect relationship with the FS, which means that any increase in these parameters causes a decrease in the FS. The slope is reinforced with a single row of anti-slide pile with a wide variety of pile geometry and soil properties (Table 2). The overall FEM results including FS and $P_{max}$ are summarized in Table 5. Furthermore, the sensitivity analysis results demonstrated that the D and s/D among other variables, were the most effective two variables on the FS value.

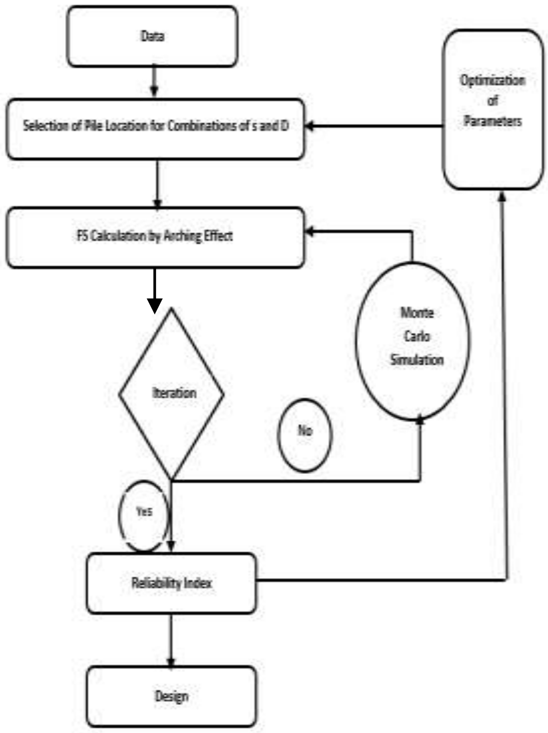


**Figure 7.** Flow Chart of Monte Carlo Simulation

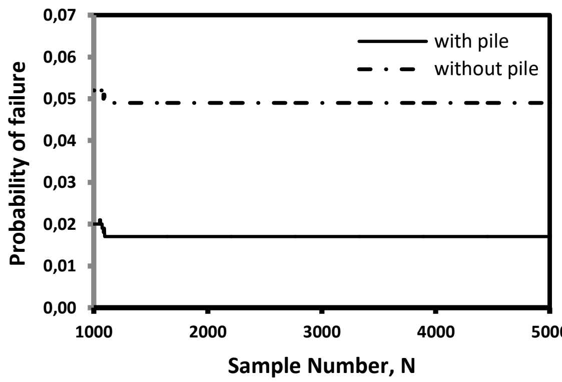


**Figure 8.** Comparison of Probability of failure considering with or without pile installation

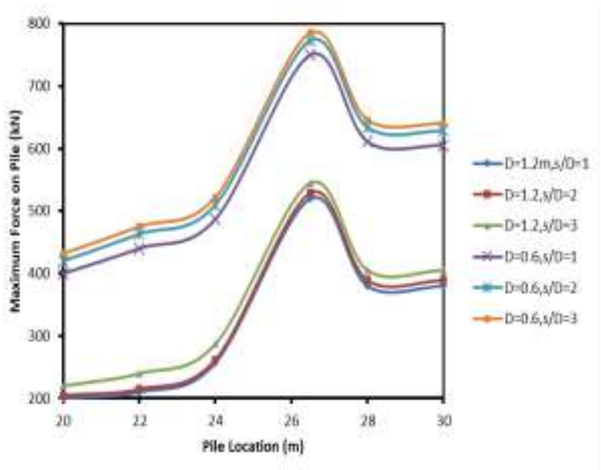


**Figure 9.** Maximum force –pile location relation of the system for different (s, D) combinations

**Table 5.** FEM results of slope reinforced with one row of anti-slide pile.

| | c (kN/m$^2$) | φ (°) | β (°) | ψ | D (m) | s/D | $P_{max}$(kN) | FS |
|---|---|---|---|---|---|---|---|---|
| 1 | 24 | 25 | 35 | 0.45 | 0.6 | 1 | 715 | 1.23 |
| 2 | 24 | 25 | 35 | 0.45 | 0.6 | 2 | 723 | 1.22 |
| 3 | 24 | 25 | 35 | 0.45 | 0.6 | 3 | 768 | 1.20 |
| 4 | 48 | 25 | 30 | 0.35 | 0.6 | 1 | 755 | 1.25 |
| 5 | 48 | 25 | 30 | 0.35 | 0.6 | 2 | 768 | 1.24 |
| 6 | 48 | 25 | 30 | 0.35 | 0.6 | 3 | 780 | 1.23 |
| 7 | 24 | 15 | 35 | 0.55 | 1.0 | 1 | 618 | 1.34 |
| 8 | 24 | 15 | 35 | 0.55 | 1.0 | 2 | 645 | 1.32 |
| 9 | 24 | 15 | 35 | 0.55 | 1.0 | 3 | 654 | 1.29 |
| ⋮ | | | | | | | | |
| 64 | 12 | 25 | 35 | 0.35 | 1.2 | 1 | 498 | 1.45 |
| 65 | 12 | 25 | 35 | 0.35 | 1.2 | 2 | 516 | 1.43 |
| 66 | 12 | 25 | 35 | 0.35 | 1.2 | 3 | 525 | 1.41 |

## 5. Conclusion

In this study, the performance of the MCS and FEM models to predict the factor of safety (FS) has been investigated. For this purpose, a MCS was developed by using the large field experimental data. The FS values predicted from the MCS model was compared with the experimental values taken from the large-scale experimental study and FEM model developed. The results indicated that the predicted values from the MCS model matched the modelled values much better than those obtained from the FEM model.

Also, the nature of the problem suggests that the proposed model can be directly apply to developed conditions and should only be used for the specified parameters and ranges. Therefore, considering the MCS model's accuracy, the model can be utilized at the preliminary planning stage of the FS value without a need to perform any manual work. To evaluate the estimation capacity of the generated MCS and FEM models, reliability index and probability of failure were computed.

The computed indices make it clear that both constructed MCS and FEM were able to predict FS values of landslide quite efficiently and outperformed the FEM models. Thus, the developed MCS models can be used satisfactorily to predict the factor of safety (FS) of the slope/pile system.

**Declaration of Ethical Standards**

The authors declare that they comply with all ethical standards.

**Credit Authorship Contribution Statement**

Author 1: Resources, Investigation, Methodology, Formal analysis, Writing – original draft, Visualization

Author 2: Resources, Visualization

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data Availability**

All data generated or analyzed during this study are included in this published article.

## 6. References

Al Bouder, W., 2010. Development of Design and Analysis Method for Slope Stabilization Using Drilled Shafts. Ph.D. Dissertation, University of Akron, Ohio, 215.

Blake, T.F., Hollingsworth, R.A. and Stewart, J.P., 2003. A Screen Analysis Procedure for Seismic Slope Stability, *Earthquake Spectra*, **19**(3),697–712.

Caballero, W.L. and Rahman, A., 2014. Application of Monte Carlo simulation technique for flood estimation for two catchments in New South Wales, Australia, *Natural Hazards,* **74(3)**, 1475–1488.

Chen, Q., Wang, C. and Juang, C.H., 2016. Probabilistic and spatial assessment of liquefaction-induced settlements through multi-scale random field models*, Engineering Geology*, **211**, 135-149.

Ching, J. and Wang, J.S., 2016. Application of the transitional Markov chain Monte Carlo algorithm to probabilistic site characterization, *Engineering Geology*, **203**, 151-167.

Cui, L. and Sheng, D., 2005. Genetic algorithms in probabilistic finite element analysis of geotechnical problems, *Computers and Geotechnics*, **32(8)**, 555-563.

Dagli, B.Y., Tuskan, Y. and Gökkuş, Ü., 2018. Evaluation of offshore wind turbine tower dynamics with numerical analysis, *Advances in Civil Engineering*, 1-11.

Dagli, B.Y., Uncu, D. and Tuskan, Y., 2019. Deniz Boru Hattı Dinamik Davranışının Sonlu Elemanlar Yöntemi ile Analizi, *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, **23**(2), 404-410.

Erzin, Y. and Tuskan, Y., 2016. Prediction of Standard Penetration Test (SPT) Value in Izmir, Turkey using General Regression Neural Network. *International Conference on Agricultural, Civil and Environmental Engineering (ACEE-16) April*, 18-19.

Erzin, Y. and Tuskan, Y., 2017. Prediction of standard penetration test (SPT) value in Izmir, Turkey using radial basis neural network, *Celal Bayar University Journal of Science*, 13(2), 433-439.

Erzin, Y. and Tuskan, Y., 2019. The use of neural networks for predicting the factor of safety of soil against liquefaction, *Scientia Iranica*, **26**(5), 2615-2623.

Jiang, S.H., Li, D.Q., Zhang, L.M. and Zhou, C.B., 2014. Slope reliability analysis considering spatially variable shear strength parameters using a non-intrusive stochastic finite element method, *Engineering Geology*, 168, 120-128.

Kulhawy, F.H. and Mayne, P.W., 1990. Manual on estimating soil properties for foundation design, Electric Power Research Institute (EPRI) Palo Alto, CA (USA); Cornell Univ., Ithaca, NY (USA). Geotechnical Engineering Group, 25-36.

Liang, R. and Zeng, S., 2002. Numerical study of soil arching mechanism in drilled shafts for slope stabilization, *Soils and Foundations*, **42(2)**, 83-92.

Liang, R.Y., Joorabchi, A.E. and Li, L., 2014. Analysis and design method for slope stabilization using a row of drilled shafts, *Journal of Geotechnical and Geo-environmental Engineering*, **140(5)**, 1–12.

Li, T.L., Long, J.H. and Li, X.S., 2007. Types of loess landslides and methods for their movement forecast, *Engineering Geology*, **15(4)**, 500–506.

Li, S., Zhao, H.B. and Ru, Z., 2013. Slope reliability analysis by updated support vector machine and Monte Carlo simulation, *Natural Hazards*, **65(1)**, 707–722

Li, T.L., Wang, C.Y. and Li, P., 2013. Loess deposit and loess landslides on the Chinese loess plateau, *Progress of geo-disaster mitigation technology in Asia*, 235-261

Li, Z., Huang, H. and Xue, Y., 2014. Cut-slope versus shallow tunnel: Risk-based decision-making framework for alternative selection, *Engineering Geology*, **176**, 11–23.

Li, J.H., Zhou, Y., Zhang, L.L., Tian, Y., Cassidy, M.J. and Zhang, L.M., 2016. Random finite element method for spud can foundations in spatially variable soils, *Engineering Geology*, **205**, 146-155.

MathWorks, Neural Network Toolbox 7.0., 2010. MathWorks Announces Release 2010a of the MATLAB and Simulink Product Families, MathWorks Inc.

Mohammadi, S. and Taiebat, H., 2016. Finite element simulation of an excavation-triggered landslide using large deformation theory, *Engineering Geology*, **205**, 62-72.

Murthy, K., 2000. Monte Carlo: Basics, Monte Carlo: Basics. arXiv preprint cond-mat/0104215, Chapter, 9.

Nowak, A. and Collins, K., 2000. Reliability of Structures First edition, McGraw Hill Higher Education, USA.

Phoon, K.K., 2017. Role of reliability calculations in geotechnical design. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, **11**(1), 4-21.

Saghafian, B., Golian, S., Elmi, M. and Akhtari, R., 2013. Monte Carlo analysis of the effect of spatial distribution of storms on prioritization of flood source areas, *Natural Hazards*, **66(2)**, 1059–1071.

U.S. EPA., 1997. Ecological risk assessment guidance for Superfund: process for designing and conducting ecological risk assessments, Interim Final. Washington, DC: Office of Solid Waste and Emergency Response. EPA.

Uzielli, M., Lacasse, S., Nadim, F. and Lunne, T., 2006. Uncertainty-based Characterization of Troll Marine Clay, Characterization and Engineering Properties of Natural Soils, Eds. T. S. Tan, K. K. Phoon, D. W. Hight & S. Leroueil, Taylor & Francis, Leiden, **4**, 2753-2782.

Vanmarcke, E.H., 1977. Probabilistic modeling of soil profiles, *Journal of the Geotechnical Engineering Division*, **103(11)**, 1227–1246.

Wang, J.P., Lin, C.W., Taheri, H. and Chan, W.S., 2012. Impact of fault parameter uncertainties on earthquake recurrence probability examined by Monte Carlo simulation an example in Central Taiwan, *Engineering Geology*, **126**, 67-74.

Wang, X.G., Jia, Z.X., Chen, Z.Y. and Xu, Y., 2016. Determination of discontinuity persistent ratio by Monte-Carlo simulation and dynamic programming, *Engineering Geology*, **203**, 83-98.

Xiao, J., Luo, Z., Martin II, J.R., Gong, W. and Wang, L., 2016. Probabilistic geotechnical analysis of energy piles in granular soils, *Engineering Geology*, **209**, 119–127.

Yamin, M.M., 2007. Landslide stabilization using a single row of rock-socketed drilled shafts and analysis of laterally loaded shafts using shaft deflection data." Ph.D. Dissertation, University of Akron, Ohio, 335.

Yazdani, A. and Kowsari, M., 2017. A probabilistic procedure for scenario-based seismic hazard maps of Greater Tehran, *Engineering Geology*, **218**, 162-172.

Yildizel, S.A., Tuskan, Y. and Kaplan, G., 2017. Prediction of skid resistance value of glass fiber-reinforced tiling materials, *Advances in Civil Engineering*, *2017*.

Zhou, G., Esaki, T., Mitani, Y., Xie, M. and Mori, J., 2003. Spatial probabilistic modeling of slope failure using an integrated GIS Monte Carlo simulation approach, *Engineering Geology*, **68**, 373-386