Reliability based analysis of foundation settlement

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Abstract
This research was aimed at the development of a method that will assist in the process of calibration of load and resistance factors for service limit state with focus on the soils of the South-East zone of Nigeria based on standard penetration test (SPT) results. Reliability analysis, expressed in the form of reliability index (β) and probability of failure (Pf) were performed for foundation settlement using First Order Reliability Method (FORM) in MATLAB. The footings were designed for a 25 mm allowable settlement value as recommended in Eurocode 7 for serviceability limit state (SLS) design which is a conventional approach. Reliability indices were calculated based on the Burland and Burbidge foundation settlement prediction method. Results of the reliability analysis show that, as the variability of geotechnical properties at a site increases, larger values of settlement were obtained with a higher probability of occurrence. Sensitivity study indicated that the applied foundation pressure and coefficient of variation (COV) of SPT N-value significantly affected the magnitude of foundation settlements.

Keywords
Reliability-based design; First order reliability method; Foundation settlement; Reliability analysis; Standard penetration test
Introduction

According to the Canadian Foundation Engineering Manual [1], limit states design (LSD) involves the identification of all possible limit states or "failure" mechanisms, and the subsequent checking that the probability or likelihood of occurrence of each limit state identified will be within an acceptable or specified level of safety or reliability. The term "failure" is used here in the general sense of unsatisfactory performance. It does not necessarily mean rupture or collapse. The applicable, acceptable level of safety or reliability is usually defined by the target reliability index that is specified by governing codes. Each potential limit state identified is considered separately, and through the design process its occurrence is demonstrated to be sufficiently improbable (eliminated) or to be acceptable [1].

In geotechnical engineering, the bearing capacity and settlement of foundation were traditionally evaluated by a deterministic (empirical) approach [2-4]. The factor of safety used in the deterministic approach accounts for natural variability, statistical uncertainty, measurement errors, and limitations of analytical models and is an indirect way of limiting deformation [5]. Over the last two decades, there has been a slow but worldwide shift toward the increased use of risk-based design methodologies for geotechnical engineering [6-8]. Risk and reliability are complementary terms. Risk is unsatisfactory performance or probability of failure. On the other hand, reliability is satisfactory performance or probability of success [9]. Benefits of reliability method in concurrence with conventional design are: (i) All sources of uncertainties involved in the project are taken into account (ii) Support in decision making regarding risk-cost analysis (iii) Probability of failure can be known for each design method (iv) The structure can be designed according to serviceability conditions and (v) The overall risk involved in the project is clearly identified.

Practicing engineers know that uncertainty exists in any design. Typical sources of uncertainty are inherent variability, measurement errors, and transformation uncertainty [10]. Uncertainties in the geotechnical engineering are unavoidable. The geotechnical engineer deals mostly with natural materials and the variability of the materials is inevitable. Thus the factor of safety used in the deterministic approach does not consider the sources and amount of uncertainty associated with the system. Limit state (reliability) of the structure is difficult to estimate using these deterministic methods [5, 11, 12]. So it is inevitable to study the probability of failure of the structure. Moreover, in some cases though the probability of
failure is high, system shows high factor of safety in deterministic approach. This is because the factor of safety is chosen based on past experience and some possible outcomes like failure which leads to an uneconomical design [13]. Serviceability of the structure is difficult to estimate using deterministic methods [14-16]. Limit states are boundaries between safety and failure. For foundations, limit states can be grouped into sub-structural limit states for foundation movement (vertical settlement) which need to be estimated and compared with tolerable settlement criteria. Reliability of the system is the relationship between loads the system must carry and its ability to carry the load. Reliability of the system is expressed in the form of reliability index ($\beta$) which is related to the probability of failure of the system ($P_f$). In this study, reliability analysis was performed for foundation settlement using First Order Reliability Method (FORM).

The development of a new generation of reliability-based design code for foundations requires an effort to harmonize with structural codes. For this reason, geotechnical design codes around the world are beginning to move towards some form of reliability-based design (RBD). This requires definition of critical failure states in conjunction with load and resistance factors that are calibrated to achieve the target reliabilities associated with the various limit states. The research was aimed at the development of a methodology to assist in the process of calibration of load and resistance factors for service limit state with focus on the soils of the South-East zone of Nigeria. The states in the South-East zone of Nigeria include Abia, Anambra, Ebonyi, Enugu and Imo states.

**Materials and method**

The research made use of standard penetration test (SPT) data (using Donut hammer type) collected from 425 test holes (3825 data set) distributed over the study area (see the Appendix for the final average data). Foundation settlement estimations were made at depths of 0.6, 2.1, 3.6, 5.1, 6.6, 8.1, 9.6, 11.1 and 12.6 m and applied foundation pressures of 50, 100, 200, 300 and 500 kN/m$^2$.

The reliability analysis was performed using the First Order Reliability Method (FORM) in MATLAB R2014a (8.3.0.532) programme. FORM that uses the first terms of a Taylor series expansion to estimate the mean value and variance of performance function is so called because the variance is in form of second moment. The methodology of the First Order
Second Moment (FOSM) reliability method in detail is described in Baecher and Christian [17]. Optimization was performed by the aid of genetic algorithm which drives biological evolution. The genetic algorithm repeatedly modifies a population of individual typically random chromosomes. This study made use of 1000 runs (number of genetic algorithm).

The limit state function is defined as a function of capacity and demand; it is denoted as g and expressed as Eq. (1):

\[ g(R, Q) = R - Q \]  

Where: R - is the structural resistance or capacity of the structural component and Q is the load effect or demand of the structural component with the same units as the resistance.

The performance function \( g(X) \) is a function of capacity and demand variables \( (X_1, X_2, \ldots, X_n) \) which are basic random variables for both R and Q such that, Eq. (2):

\[
\begin{cases}
  g(X_1, X_2, \ldots, X_n) > 0 & \text{safe state} \\
  g(X_1, X_2, \ldots, X_n) = 0 & \text{limit state} \\
  g(X_1, X_2, \ldots, X_n) < 0 & \text{failure state}
\end{cases}
\]

Where: \( g(X) = 0 \) is known as a limit state surface and each X indicates the basic load or resistance variable.

The probability of failure \( (P_f) \) can be related to an indicator called the reliability index, \( \beta \). For the estimation of the probability of failure, the method employed involves approximate iterative calculation procedures. In this method, two important measures are used [18], Eq. (3):

\[(a)\] **Expectations**: \( \mu_i = E[X_i], i = 1, \ldots, n \)

\[(b)\] **Covariances**: \( C_{ij} = Cov[X_i, X_j], i, j = 1,2, \ldots, n \)

The “safety margin” is the random variable \( M = g(x) \) (also called the state function). Non-normal variables are transformed into independent standard normal variables, by locating the most likely failure point, \( \beta \)-index (called the reliability index), through an optimization procedure. This is also done by linearizing the limit state function in that point and by estimating the failure probability using the standard normal integral.

The reliability index \( \beta \), is then defined by Hasofer and Lind [19] as, Eq. (5):

\[
\beta = \frac{\mu_m}{\sigma_m}
\]
Where: $\mu_m$ - mean of M and $\sigma_m$ - standard deviation of M.

If R and S are uncorrelated and with $M = R - S$, then

$$\mu_m = \mu_R - \mu_S \quad \text{and} \quad \sigma_m^2 = \sigma_R^2 + \sigma_S^2$$

(6)

Therefore,

$$\beta = \frac{\mu_R - \mu_S}{(\sigma_R^2 + \sigma_S^2)^{1/2}}$$

(7)

A relationship can be drawn between the probability of failure ($P_f$) and the reliability index ($\beta$). It, however, holds true only when the safety margin (M), is linear in the basic variables, and these variables are normally distributed. This relationship is stated below, Eq. (8—10):

$$P_f = -\Phi(-\beta)$$

(8)

$$\beta = -\Phi^{-1}(P_f)$$

(9)

Where: $\Phi$ - is the standardized normal distribution function.

$$P_f = P\{R - S \leq 0\} = P(M \leq 0) = \varphi\left(\frac{0 - (\mu_R - \mu_S)}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right) = \Phi(-\beta)$$

(10)

The performance function used for this study is Eq. (11):

$$G(X) = S_e - \left[ (0.14 \times \alpha \times B_R) \left( \frac{1.71}{N_{60(a)}^{1.4}} \right) \left( \frac{1.25 \left( \frac{B}{B_R} \right)}{0.25 + \left( \frac{L}{B} \right)} \right)^2 \left( \frac{B}{B_R} \right)^{0.7} \left( \frac{q}{P_a} \right) \right]$$

(11)

Where: $G(X)$ - performance function; $S_e$ - allowable settlement (25 mm); $N_{60(a)} \approx 15 + 0.5$ ($N_{60} - 15$), $N_{60(a)}$ - adjusted $N_{60}$ value; $B_R$ - reference width (0.3 m); $B$ - width of the actual foundation (m); $\alpha$ - depth of stress influence correction factor; $L$ - length of foundation (m); $q$ - applied foundation pressure (kN/m²); $P_a$ - atmospheric pressure (100 kN/m²).

After the performance function $G(x)$ and the underlying random variables have been defined, the probability of failure ($P_f$) and the reliability index ($\beta$) were evaluated for each design case using the methodology described herein.
In this study, the footings were designed for a 25 mm allowable settlement value as recommended in Eurocode 7 [20] for serviceability limit state (SLS) design of footings which is the average value that can be encountered in practice. The exceedance of this limiting value (25 mm) is likely to cause the occurrence of an ultimate limit state (ULS). In the Burland and Burbidge [21] method used in this study, $\alpha$, $P_a$, $B$ and $L$ are assumed to be deterministic values. The random variables considered are the SPT $N_{60}$ value and the applied foundation pressure.

Figure 1 shows the flow chart for the reliability analysis procedure used in this study.

Figure 1. Flow chart for the reliability analysis
Results and Discussion

Reliability Analysis

Reliability, as a measure of structural performance, was expressed in terms of reliability indices which were calculated for total settlement of shallow foundations for the South-East zone of Nigeria based on the Burland and Burbidge [21] settlement prediction method.

In this study, reliability indices were calculated with the objective of developing a risk analysis procedure specifically for prediction of settlement of foundations lying on soils. Reliability indices were calculated based on the assumption that settlement is lognormally distributed.

Tolerable (allowable) settlement of 25 mm, as recommended by Eurocode 7, was considered and was treated as deterministic value. Variations of safety index with foundation depth are shown in Figures 2 - 6.
Figure 3. Variation of safety index with foundation depth for 100 kN/m² applied pressure

Figure 4. Variation of safety index with foundation depth for 200 kN/m² applied pressure
From the results of this study, it was observed that, as the variability of geotechnical properties at a site increases (i.e., as the site becomes more heterogeneous), larger values of settlement were obtained with a higher probability of occurrence. In Figures 2 to 6, as the coefficient of variation (COV) of the SPT N-value increases, there is an increase in the inherent variability of the site and/or the measurement error, the reliability index (β) of settlements decreased (and invariably, the associated probability of failure (P_f) increased), indicating that both the range and the maximum value of the expected settlement become larger. These results also confirmed the conclusion of Salahudeen et al. [13] that the success of a foundation design that estimates settlements from field test results depends on the
uncertainty of the site geotechnical parameters. Using these predicted settlement values, without considering the qualities and uncertainties in the available test type, test results and design information, can be misleading.

The probability of failure ($P_f$) decreases with increasing foundation embedment depth, increases with increasing $\text{COV}_N$ value and increases with increase in applied foundation pressure. These trends are to be expected. Firstly, a more restrictive $\beta$-value leads to a reduction in the design value of the foundation applied stress. Secondly, an increase in the uncertainty of SPT $N$-value yields a less reliable compressibility value. Thirdly, as the footing embedment depth increases, the correlation between the compressibility characteristics of the soil beneath the footing decreases [13]. These trends are in conformity with findings reported by Akbas and Kulhawy [22]. It should be noted that high value of safety (reliability) index (with reference to the target reliability index) implies that the structure is too safe and the consequence of this is a conservative design with high cost (uneconomical) while a lower value implies unsafe structure.

For applied foundation pressure, not less than 200 kN/m$^2$, the reliability indices at depths in the range of 0.6 m and 3.6 m are either negative or very low indicating either certainty of failure or unreliable safety. Based on this observation, footings with applied pressure of greater than 200 kN/m$^2$ should either be piles or rafts in this region. The variability of the geotechnical parameters significantly affects the magnitude of settlements as shown in Figures 2 to 6. Therefore, the uncertainty in these parameters should be considered for a more robust foundation design procedure. This goal can be achieved systematically and consistently using principles of reliability based design (RBD) [23-25].

**Sensitivity Study**

A sensitivity study indicated that the applied foundation pressure and COV of SPT $N$-value are the most influential in evaluating the magnitude of foundation settlements. Variations of reliability index with foundation applied pressure are shown in Figure 7.
Similarly, typical values of reliability index ($\beta$) and corresponding probability of failure ($P_f$) are given as a function of the allowable settlement for serviceability limit state (SLS) design of footings. It was observed that, as the inherent variability of the site geotechnical parameters increases, there is an increasing probability of exceeding this allowable settlement value. This implies that site characteristics need a serious consideration in a reliability based design of foundations. It is important to note that the results presented in this study are specific to the Burland and Burbidge [21] settlement prediction method. The variation of safety index with applied foundation pressure for 2.1 m embedment only is shown in Figure 7. For applied foundation pressure, greater than 200 kN/m$^2$ based on COV of SPT N-value of 26 and 30 %, it is recommended that deep foundation should be used.

**Target Reliability Levels**

The acceptable safety levels can be expressed in terms of target reliability index ($\beta_T$), which should be established for various design requirements. The selection of the target reliability level is a multi-specialty task involving a structural safety analysis, and an economic analysis, which are the most two important factors. Generally, reliability indices below the target reliability value, $\beta_T$, are not acceptable. Target reliability indices calculated for settlement of foundations can vary with the suggested values of tolerable total and differential settlements and COV of SPT N-value. In other words, for each assumption of an allowable settlement value, different values of target reliability indices can be obtained. Likewise, for each assumption of COV of SPT N-value, different values of target reliability

Figure 7: Variation of safety index with applied foundation pressure
indices can be obtained. AASHTO-LRFD code [26] does not assume a specific value for allowed total settlement because it is only calibrated for strength limit states and is still not calibrated for serviceability limit states [27]. However, an allowable settlement value of 25 mm was recommended by Eurocode 7 for serviceability limit state.

The reliability levels implicit in footings designed by allowable stress concepts are variable. These reliability levels were calculated using the deterministic and statistical parameters based on First Order Reliability Method (FORM) in MATLAB program. The highest reliability levels of 10.05 was recorded for applied foundation pressure of 50 kN/m$^2$ with foundation embedment depth of 12.6 m with a corresponding probability of failure ($P_f$) of 1.998E-23 while the lowest observed was -15.73 at applied foundation pressure of 500 kN/m$^2$ with foundation embedment depth of 0.6 m with a corresponding probability of failure ($P_f$) of 1 based on COV of SPT N-value of 26% as recommended for Burland and Burbidge method. The variation of safety index with settlement is shown in Figure 8.

![Figure 8. Variation of safety index with settlement](image)

The target reliability indices ($\beta_T$) with their corresponding target probability of failure ($P_fT$) values (in parenthesis) based on allowable total settlement of 25 mm for serviceability limit state(SLS) design of 11.59 (2.00E-21%), 5.39 (0.00000332%), 3.84 (0.0059%), 3.15 (0.0789%), 2.04 (2.07%), 1.38 (8.38%) and 0.96 (16.9%) respectively for 10%, 20%, 26%, 30%, 40%, 50% and 60% COV of SPT N-value were recorded.
The implication of using a lower value of COV of SPT N-value (with respect to the suggested 26% COV value associated with the Burland and Burbidge [21] method) for design is that, the safety of the structure will be overestimated which is very risky and dangerous. On the other hand, using a higher value of COV of SPT N-value for design will lead to higher foundation size and an economic comparison might result in the recommendation of a mat or deep foundation system instead (which is uneconomical). Circumstances that could warrant this condition include poor quality site investigation and a highly variable geology.

However, considering the manner in which SPT is mostly being carried out in the sites which is not free from poor conduct of the test with a lot of negligence on several standard procedures that implied in the test, the use of COV value of 30% of SPT N-value based on the Burland and Burbidge [21] method for SLS design, is highly recommended for RBD of footings total settlement on soils in the South-East zone and in Nigeria generally. This COV value of 30% of SPT N-value corresponds to target reliability index ($\beta_T$) of 3.15 and target probability of failure ($P_{fT}$) of 0.0789%. This $P_{fT}$ value seems satisfactory. Ahmed [27] reported a COV of SPT N-value of up to 48% for automatic hammer SPT test and in a research study on RBD for foundations, Phoon et al. [10] estimated that the coefficient of variation (COV) of measurement error for SPT N-value was between 15 and 45%, for a range of cohesion less soils.

In some studies, reported in the literature, the selected target probability of failure ($P_{fT}$) for SLS design of footings varies considerably. To evaluate deformation factors for settlement design for footings on sand, Fenton et al. [28] used a maximum target probability of failure ($P_{fT}$) of 5%, which corresponds to a reliability index of 1.645. Popescu et al. [29] also selected 5% as the $P_{fT}$ for both differential settlement and bearing capacity. Value of $P_{fT}$ as high as 30% was reported by Zekkos et al. [30]. For all of the studies reported, the probability of failure is high. In a study on the reliability analysis of settlement for shallow foundations in bridges by Ahmed [27], target reliability index ($\beta_T$) of 3.5 which corresponds to probability of exceeding the limit (Targeted probability of failure, $P_{fT}$) of 0.02% for total settlement was recommended related with allowable suggested total settlement value of 37.5 mm. For allowable settlement of 40 mm, Subramaniam [9] reported a reliability index of 2.83 corresponding to probability of failure of 0.23%.

For tower structures, taking into account foundation movement analyses, structure foundation interaction, and precedents, Phoon et al. [10] recommended a target reliability
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index of 2.6, which corresponds to a $P_{fT}$ of about 0.47% for the SLS of foundations. However, considering the subjectivity inherent in SLS design, this target probability of failure ($P_{fT}$) can only be considered as an estimate [10]. This $P_{fT}$ values could be decreased for less restrictive design conditions or where uncertainty is reduced considerably by some means, such as local experience with the soil conditions. Conversely, it could be increased for more restrictive design conditions with high level of uncertainty [22]. The selected value of $P_{fT}$ should be consistent with the implied reliability levels in existing designs. However, the target reliability levels implicit in existing designs probably could be higher than the calculated mean value; this is because engineers usually use other indirect means of introducing safety, by applying conservative design parameters, or by interpreting their results conservatively. The resulting increase in the reliability is difficult to quantify, because it is based on individual judgment and experience.

Conclusion

The development of new generation of design codes that include reliability has been accepted as a rational measure of structural performance including geotechnical structures like foundations.

The variability of the geotechnical parameters is highly influenced and has a significant effect on the settlements and safety of any structure.

The sensitivity study indicated that the applied foundation pressure and COV of SPT N-value significantly affected the magnitude of foundation settlements.

The target reliability indices ($\beta_T$) with their corresponding target probability of failure ($P_{fT}$) values (in parenthesis) based on allowable total settlement of 25 mm for serviceability limit state (SLS) design of 11.59 (2.00E-21%), 5.39 (0.00000332%), 3.84 (0.0059%), 3.15 (0.0789%), 2.04 (2.07%), 1.38 (8.38%) and 0.96 (16.9%) respectively for 10%, 20%, 26%, 30%, 40%, 50% and 60% COV of SPT N-value were recorded. This COV value of 30% of SPT N-value corresponds to target reliability index ($\beta_T$) of 3.15 and target probability of failure ($P_{fT}$) of 0.0789% which is satisfactory.

Recommendations

Based on the results of the study carried out, the following are hereby recommended:
1. The methodology outlined and reliability analysed can be used as a basis for the establishment of RBD approach of footings in Nigeria and development of a LRFD specifications.

2. The use of COV value of 30% of SPT N-value based on the Burland and Burbidge method for SLS design is recommended for RBD of footings total settlement on soils in the South East zone of Nigeria.

Acknowledgement

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Appendix

A: Table 1. Average values of the 425 SPT bore holes from the four states

<table>
<thead>
<tr>
<th>Depth</th>
<th>AVERAGE VALUES FOR THE STATES UNDER SOUTH EAST (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ABIA N-value N60</td>
</tr>
<tr>
<td>0.6</td>
<td>14 12.50 11</td>
</tr>
<tr>
<td>2.1</td>
<td>21 18.74 17</td>
</tr>
<tr>
<td>5.1</td>
<td>42 37.49 36</td>
</tr>
<tr>
<td>6.6</td>
<td>50 44.63 42</td>
</tr>
<tr>
<td>8.1</td>
<td>56 49.98 50</td>
</tr>
<tr>
<td>9.6</td>
<td>69 61.58 61</td>
</tr>
<tr>
<td>11.1</td>
<td>94 83.90 69</td>
</tr>
<tr>
<td>12.6</td>
<td>100 89.25 86</td>
</tr>
</tbody>
</table>

B: RELIABILITY ANALYSIS PROGRAM MAIN PROGRAM

clear; clc; close all

% The following is the routing for the fixed data
[br, alpha, l, b, pa]...
    = salahudeen_input_mode1;

% The following is the routine for coefficient of variation for the Random Variables
se = input(' input the allowable settlement in mm');
disp(' ')
% cov1 = input(' input coefficient of variation of spt blow counts');
disp(' ')
cov2...
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= salahudeen_covariance_mode1;
disp(’’); c_prob = 0.1; m_prob = 0.1;
% Now we input the data that are required via keyboard
n = input(’input the spt blow count’);
disp(’ ’)
gen = input(’input number of GA generation’);
disp(’ ’)
q = input(’input applied foundation pressure’);
disp(’ ’)
%%%%%
beta_mode_1 = safety_index(n,q,b,l,se,br,alpha,pa,...
   cov1,cov2,...
gen,c_prob,m_prob);
pf1 = salahudeen_probability_of_failure(beta_mode_1);
%%%%%
disp(’this is the safety index for failure’)
disp(’ ’)
disp(beta_mode_1)
disp(’ ’)
disp(’this is the probability of failure for failure’)
disp(’ ’)
disp(pf1)

SAFETY INDEX
%%%%%
function beta_mode_1 = safety_index(n,q,b,l,se,br,alpha,pa,...
   cov1,cov2,...
gen,c_prob,m_prob)
%
cv(1) = cov1; cv(2) = cov2;
%
[DISTYPE1,DISTYPE2] = distribution_mode1;
%
rfmu(1) = n; rmfx1 = n*cv(1);
rfmu(2) = q; rmfx2 = q*cv(2);
%
if(DISTYPE1 == 1)
%
% DOING NORMAL
%
mean(1) = rfmu(1);
sd(1) = rmfx1;
elseif(DISTYPE1 == 2)
%
% DOING LOGNORMAL TRANSFORMATION
%
[mean(1) sd(1)] = lognormal(rfmu(1),rmfx1);
elseif(DISTYPE1 == 3)
%
% DOING GUMBEL TRANSFORMATION
%
[mean(1) sd(1)] = gumbel(rfmu(1),rmfx1);
elseif(DISTYPE1 == 4)
%
% DOING WEIBULL TRANSFORMATION
%
[mean(1) sd(1)] = weibull(rfmu(1),rmfx1);
elseif(DISTYPE1 == 5)
% DOING FRECHET TRANSFORMATION
% [mean(1) sd(1)] = frechet(rfmu(1),rmfx1);
end
if(DISTYPE2 == 1)
% DOING NORMAL
% mean(2) = rfmu(2);
sd(2) = rmfx2;
elseif(DISTYPE2 == 2)
% DOING LOGNORMAL TRANSFORMATION
% [mean(2) sd(2)] = lognormal(rfmu(2),rmfx2);
elseif(DISTYPE2 == 3)
% DOING GUMBEL TRANSFORMATION
% [mean(2) sd(2)] = gumbel(rfmu(2),rmfx2);
elseif(DISTYPE2 == 4)
% DOING WEIBULL TRANSFORMATION
% [mean(2) sd(2)] = weibull(rfmu(2),rmfx2);
elseif(DISTYPE2 == 5)
% DOING FRECHET TRANSFORMATION
% [mean(2) sd(2)] = frechet(rfmu(2),rmfx2);
end
% sev1 = sd(1); sev2 = sd(2);
% % %
% dev1 = mean(1); dev2 = mean(2);
% % %
nume = se - (br*0.14*alpha*(1.71/(dev1^1.4))*... (((1.25*(l/b))/((0.25 + (l/b))^2)) *((b/br)^0.7)*(dev2/pa))*1000;
% %
number_of_genes = 2;
cross_over_probability = c_prob; mutation_probability = m_prob;
tournament_selection_parameter = 0.75;
population_size = 20;
fitness = zeros(population_size,1);
population = initialize_population(number_of_genes,population_size);
% % %
% GENES DECODING
for j = 1:1:gen
for i = 1:1:population_size
  disp('      ')
  disp('chromosomes population')
  disp(population)
  %
  ca1 = population(i,1); ca2 = population(i,2);
  %
  if (ca1 == 1)
    part1 = 0+((0.14*alpha*br)*(2.394/(dev1^2.4))*... (((1.25*(l/b))/((0.25 + (l/b))^2)) *((b/br)^0.7)*(dev2/pa))*1000;
else
    part1 = 0;
end
%
if(ca2 == 1)
    part2 = 0 - ((0.14*alpha*br)*(1.71/(dev1^1.4))*((1.25*(l/b))/((0.25+(l/b))^2)*((b/br)^0.7)*(1/pa)))*1000;
else
    part2 = 0;
end
%
deno = sqrt(((part1^2)*(sev1^2)) + ((part2^2)*(sev2^2)));
%
if(deno<= 0)
    beta(i) = 1000;
else
    beta(i) = nume/deno;
end
end
%
beta_gen(j) = min(beta);
%
maximum_fitness = 0.0; % Assume non-negative fitness value
for i = 1:1:population_size
    if(beta(i)<=0)
        fitness(i) = 1;
    elseif(beta(i)>=1000)
        beta(i) = 1000;
        fitness(i) = 1/beta(i);
    else
        fitness(i) = (1/(beta(i)));
    end
    if(fitness(i) > maximum_fitness)
        maximum_fitness = fitness(i);
        best_individual_index = i;
        beta_best = beta(i);
    end
end
%%%%%%%%%%%%%%%%%%%%%%  TOURNAMENT SELECTION ROUTINE
% Initially, the random set of chromosomes were generated, decoded and
% evaluated using First Order Reliability Method (FORM). Next a temporary
% population is generated through tournament selection
% The notation 1:2:population_size in the for loop indicates that only
% every i value will be considered, i.e i = 1,3,5,7,...
% Finally, the temporary population replaces the original population.
% %
% temp_population = population;
for i = 1:2:population_size;
    i1 = tournament_select(fitness,tournament_selection_parameter,number_of_genes);
    i2 = tournament_select(fitness,tournament_selection_parameter,number_of_genes);
    chromosome1 = population(i1,:);
    chromosome2 = population(i2,:);
end
%%%%%%%%%%%%%%%%%%%%%%%%% CROSSOVER OPERATION
% So far, the selected individuals are copied unchanged to the next
% generation (i.e. to the new population). Of course in order to improve
% the results, one should modify the selected individuals, using crossover
% and mutation.
r = rand;
if(r<cross_over_probability)
new_chromosome_pair = cross(chromosome1,chromosome2);
temp_population(i,:) = new_chromosome_pair(1,:);
temp_population(i+1,:) = new_chromosome_pair(2,:);
else
    temp_population(i,:) = chromosome1;
    temp_population(i+1,:) = chromosome2;
end
%%% %%%%%%%%%%%%%%%%% %%%%%%%%%%%%%%%%%%%%%% MUTATION OPERATION
for i = 1:population_size
    original_chromosome = temp_population(i,:);
    mutated_chromosome = mutate(original_chromosome,mutation_probability);
    temp_population(i,:) = mutated_chromosome;
end
% % ELITISM % %
% In order to achieve a monotonous increase in the fitness values, we
% should use elitism.
    temp_population(i,:) = population(best_individual_index,:);
    population = temp_population;
% end
% Loop over generations
%
beta_mode_1 = min(beta_gen);
%
disp('   This is the set of the safety indices for all the chromosomes');
disp('    ');
disp(beta)

References


27. Ahmed, A. Y., Reliability analysis of settlement for shallow foundations in bridges, A published dissertation of the Faculty of Graduate College, University of Nebraska, Lincoln Nebraska. UMI dissertation publishing, USA, 2013.
