Neuro-Fuzzy Technique for the Estimation of Liquefaction Potential of Soil

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Abstract: Liquefaction is a phenomenon whereby a saturated or partially saturated soil substantially loses strength and stiffness due to combine action of ground acceleration and increase in pore water pressure. This phenomenon is common in sandy soil. Many various methods have been used to estimate the liquefaction potential of a region based on available data, like SPT-N value method, because it’s simplicity and requirement of less variables. This study is aimed to adopt SPT-N based technique for liquefaction assessment of soil for rivers coast regions of Allahabad (India) city. For the purpose of finding liquefaction potential Modified Seed's method was first used to develop liquefaction database of different sites. Further corrected SPT-N based values and liquefaction database through Modified Seed's method were used to develop Neuro-Fuzzy models. To develop Neuro-Fuzzy models bore log data were used. For the purpose of finding liquefaction potential Modified Seed's method was first used to develop liquefaction database of different sites. Further corrected SPT-N based values and liquefaction database through Modified Seed's method were used to develop Neuro-Fuzzy models. Five pertinent inputs were used to model liquefaction. These variables were depth, corrected SPT-N value, bulk density, natural moisture content and percentage of particles finer than 0.075mm.

Keywords: ANFIS, Earthquake, Liquefaction, Neuro - Fuzzy Model.

I. INTRODUCTION

When the ground is subjected to strong shaking, during an earthquake, certain types of soils liquefy, often leading to ground failures. Ground failure associated with liquefaction of soils is potentially very damaging. The cyclic shearing of saturated granular soils causes a progressive buildup of pore water pressure which eventually approaches a value equal to the initial confining pressures, thereby softening the soil causing large strain. Such a state has been termed as ‘initial liquefaction’ or ‘liquefaction’. For loose sands, the onset of liquefaction leads to very large formation and complete loss of shear strength behave as viscous fluid. For medium to dense sand, silty sands, and sandy silts, onset of liquefaction may not lead to complete loss of strength. However, some degree of softening and significant amount of cyclic strain does take place. Normally, the deformation results from the dynamic and static forces caused by earthquake. The ultimate deformation is controlled by:

- The degree of shear strength loss in the liquefied layer.
- The continuity and boundary conditions surrounding the failure.
- The magnitude and direction of the dynamic and static shear forces acting upon the mobilized soil.
- The time interval that these forces exceed the shear strength of the liquefied soil.

At first it was thought that the liquefaction can occur only in the clean and sandy soil, but as the work on this new phenomenon went on in 1960-1970 it was observed that soil liquefaction can occur in silty, gravelly soils and even in some cases of clay soils. It was observed that in most cases liquefaction starts when earthquake of large magnitude disturbs the soil. As a number of factors influence the liquefaction behavior for a particular area it is observed that light magnitude of earthquakes can also make huge disaster if soil is highly prone to liquefaction potential such as of higher peak ground acceleration and other human activities like blasting etc. The prediction of soil liquefaction is very complicated task because of the uncertainty of soil behavior, which also varies with the passage of time. To eliminate this drawback more data should be collected which gives an impression of engineering behavior from soil history and the future changes in the soil (Golesorkhi 1989). Generally liquefaction decreases at greater depths but in some cases liquefaction in greater depths is also observed. In this condition, the conventional seismic measure by reinforcement and improvement of upper soil strata is not much effective. Though it is very difficult to know the exact liquefaction behavior, but more effective engineering formulas and research works are going on to make understand this phenomenon to calculate its occurrence. Modified Seed’s method, Tokimatsu and Yoshimi method...
II. METHODS OF EVALUATING LIQUEFACTION POTENTIAL

The liquefaction potential is the ratio of the cyclic resistance ratio to the cyclic stress ratio. It also refers the probability of the soil to be actually liquefied and is related with not only the soil properties but also the seismic impact conditions. Site exploration techniques like SPT are one of the suitable methods for soil specimen collection. Now a days a new technique known as Neuro-fuzzy in the field of artificial intelligence is in progress. Neuro-fuzzy refers to the combination of artificial neural network and fuzzy logic. Neuro-fuzzy, which was first proposed by J.S.R. Jang in fuzzy modeling environment, is divided into two areas: linguistic fuzzy modeling which is focused on interpretability is mainly the Mamdani model; and precise fuzzy modeling that is focused on accuracy is mainly the Takagi-Sugeno-Kang (TSK) model. This study is the effort of assessing liquefaction potential at Allahabad city near the banks of rivers Ganga and Yamuna since alluvial soil is abundantly present in this area. Soil strata on the bank of rivers mainly consists sandy and clayey soil at various depths. The upper part of strata contains major portion of silty soil and sandy silt enhancing probability of liquefaction. It indicates that there is major potential of liquefaction occurrence in the upper soil zone at greater earthquake magnitude. Two different methods namely Modified Seed’s and ANFIS modeling approach are used to find out liquefaction potential of soil. There are many researchers have been carried out studies on finding liquefaction using methods soft computing like (Kayadelen, 2011, Ali Firat 2012 ) and others have suggested various analytical methods like (Bind 2004).

II. ESTIMATION OF LIQUEFACTION POTENTIAL

In present work SPT values are taken for finding out the liquefaction potential. Then the liquefaction is calculated by two methods. First one is by using theoretical relationship and second is by ANFIS method. The brief discussions about these methods are given below:

A. Modified Seed’s method

Modified Seed’s had studied various places data and shown a very first generalized equation for suggestion liquefaction potential. This method has empirical approach finding out cyclic stress ratio. Cyclic stress ratio developed in the field due to earthquake shaking is readily computed from this method. This method is frequently used for liquefaction potential due to its simplicity, the various steps involved in this method are following:

1. Calculation of CSR:

Estimation of the cyclic stress ratio (CSR) induced at various depths within the soil by the earthquake. The average cyclic shear stress imparted by the earthquake in the top 12 m of a soil deposit can be estimated as:

$$CSR = \frac{\tau_{avg}}{\sigma'_v} = 0.65 \left( \frac{\sigma_{max}}{g} \right) \left( \frac{\sigma_v}{\sigma'_v} \right) r_d$$

Where $\sigma_v$ = total vertical stress

$\sigma'_v$ = total vertical effective stress ($\sigma_v$-u)

$\sigma_{max}$ = Peak horizontal acceleration at the ground surface

$g$ = acceleration due to gravity (9.81 m/s²)

$r_d$ = Average value of Stress reduction factor and is given by:

$r_d = 1.0 - 0.00765 z$ ; for $z \leq 9.15$ m

$r_d = 1.174 - 0.0267 z$ ; for $9.15 m < z \leq 23$ m

$r_d = 0.744 - 0.008 z$ ; for $23 m < z \leq 30$ m

$r_d = 0.50$; for $z > 30$ m

As depth (z) increases $r_d$ also increases.

2. Calculation of CRR:

Estimation of the cyclic resistance ratio (CRR) of the soil, i.e. the cyclic shear stress ratio which is required to cause initial liquefaction of the soil.

$$CRR_{7.5} = \frac{a+cx+ex^2+gx^3}{1+bx+dx^2+hx^4}$$

Above equation is valid for $(N_1)_{60} > 30$ where $x=(N_1)_{60} > 30$ and is fixed at

$$a = 0.048 \quad b = -0.1248$$

$$c = -4.721E^{-3} \quad d = 9.578E^{-3}$$

$$e = 6.136E^{-4} \quad f = -3.285E^{-4}$$

$$g = -1.673E^{-3} \quad h = 3.714E^{-6}$$

CRR$_{7.5}$ is the cyclic resistance ratio for magnitude of 7.5 earthquakes, magnitude smaller or larger than 7.5, introduces a correction factor namely magnitude scaling factor MSF defined by the following equation given by:

$$MSF = 10^{2.56/M^2.56}$$

The appropriate cyclic strength is then obtained by:

$$CRR = (CRR_{7.5}) \ MSF$$

3. Calculation of factor of safety:

If the cyclic stress ratio caused by an earthquake is greater than the cyclic resistance ratio of the in situ soil, then liquefaction could occur during the earthquake, and vice versa. The factor of safety (FOS) against liquefaction is defined as:

$$FS = CRR/CSR$$
Liquefaction is predicted to occur when FS ≤ 1.0, and liquefaction predicted not to occur when FS > 1. The higher the factor of safety, the more resistant against liquefaction, however, soil that has a factor of safety slightly higher than 1.0 may still liquefy during the earthquake.

B. ANFIS method

Adaptive Neuro-Fuzzy Inference System (ANFIS) is one of the most successful schemes which combine the benefits of ANN and FIS into a single capsule. According to the Neuro Fuzzy approach, a neural network is proposed to implement the fuzzy system. A typical architecture of an ANFIS, in which a circle indicates a fixed node, whereas a square indicates an adaptive node, is shown in Fig. 2. In this structure, there are input and output nodes, and in the hidden layers, there are nodes functioning as membership functions (MFs) and rules. For simplicity, we assume that the examined FIS has two inputs and one output. In this study the Sugeno type Fuzzy Inference System (FIS) was used, and each rule was defined as a linear combination of input variables (fig 1). The corresponding final output of the FIS was simply the weighted average of each rule’s output. A Sugeno FIS consisting of two input variables x and y, for example, one output variable f will lead to two fuzzy rules:

Rule 1: If x is A₁, y is B₁ then f₁ = p₁x + q₁y + r₁
Rule 2: If x is A₂, y is B₂ then f₂ = p₂x + q₂y + r₂

Where x and y are the two crisp inputs, and A₁ and B₁ are the linguistic labels associated with the node function. P₁, q₁ and r₁ are the consequent parameters of the rule. A₁ and B₁ are the linguistic labels, which are represented by fuzzy sets shown in below:

![Fig.1. Sugeno method of fuzzy inference system.](image)

The system has a total of five layers. The functioning of each layer is described as shown in fig. 2.

![Fig.2. First order Sugeno ANFIS architecture.](image)

**Input node (Layer 1):** Nodes in this layer contains membership functions. Parameters in this layer are referred to as premise parameters. Every node i in this layer is a square and adaptive node with a node function:

\[ O_i^1 = \mu A_i(x) \quad \text{for } i = 1, 2 \]  \hspace{1cm} (4)

Where \( x \) is the input to node i, and \( A_i \) is the linguistic label (small, large, etc.) associated with this node function. In other words, \( O_i^1 \) is the membership function of \( A_i \) and it specifies the degree to which the given \( x \) satisfies the quantifier \( A_i \).

**Rule nodes (Layer 2):** Every node in this layer is fixed node labeled II, whose output is product of all incoming signals.

\[ O_i^2 = w_i = \mu A_i(x) \mu B_i(y) \quad \text{for } i = 1, 2 \]  \hspace{1cm} (5)

**Average nodes (Layer 3):** Every node in this layer is fixed node labeled N. The \( i^{th} \) node calculates the ratio between the \( i^{th} \) rule’s firing strength to the sum of all rule’s firing strengths. Every node of these layers calculates the weight, which is normalized. For convenience, outputs of this layer are called normalized firing strengths.

\[ O_i^3 = \bar{w}_i = \frac{w_i}{w_1 + w_2} \quad \text{for } i = 1, 2 \]  \hspace{1cm} (6)

**Consequent nodes (Layer 4):** Every node i, in this layer is an adaptive node with a node function.

\[ O_i^4 = \bar{w}_i f_1 = \bar{w}_i \left(p_i x + q_i y + r_i\right) \]  \hspace{1cm} (7)

Where \( \bar{w}_i \) is a normalized firing strength from layer 3 and is the parameters set of this node. Parameters in this layer are referred to as consequent parameters.
III. METHODOLOGY

To estimate liquefaction potential of sandy soil SPT tests data on different stations were collected as it is the most suitable site exploration test for sandy soil. Data collected from SPT tests were utilized to find out liquefaction potential through Modified Seed’s methods, further these data were used to develop ANFIS models. Output parameter that is occurrence of liquefaction in the ANFIS model is designed to answer in yes/no format based on Modified Seed’s. The soil properties found through SPT and other laboratory test used as input vectors in ANFIS method is shown below:

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>RANGE OF INPUT PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT PARAMETER</td>
<td>RANGE</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>1.5-12</td>
</tr>
<tr>
<td>SPT-N value</td>
<td>2-50</td>
</tr>
<tr>
<td>Particle finer than 0.075 mm (%)</td>
<td>2.33-97.9</td>
</tr>
<tr>
<td>Natural water content (%)</td>
<td>0.55-43.9</td>
</tr>
<tr>
<td>Bulk density (gm/cc)</td>
<td>1.18-3.99</td>
</tr>
</tbody>
</table>

The brief methodology adopted is discussed under following sub-headings:

A. Experimental method

The data of standard penetration test were collected in order to develop soil database. Disturbed and undisturbed soil specimen was collected from these bore-holes up to depth of 12 meters as well as SPT N-values were also determined at a regular depth interval of 1.5 m. Disturbed soil samples were used to determine liquid limit, plastic limit, angle of internal friction, particle size finer than 2 mm, 0.075 mm and 0.002mm. Undisturbed samples were used to find out natural water content and bulk density.

B. Data modification & Correction for overburden pressure

Corrected SPT-N values were required to apply modified Seed’s method to calculate liquefaction potential hence standard method for SPT-N value correction was adopted as given by IS: 2131-1981. N- value obtained from SPT test is corrected first which is either calculated by the equation:

\[ N_i = C_N \times N \]  \hfill (9)

Where, \( C_N \) is correction factor and It can calculate from the formulae:

\[ C_N = 0.771 \log_{10} (2000/p) \]  \hfill (9)

Where, \( p \) is effective overburden pressure in kN/m².

C. Dilatancy correction:

The values obtained in overburden pressure \( (N_i) \) shall be corrected for dilatancy if the stratum consist of fine sand and silt blow water table for values of \( N_i \) greater than 15

\[ N'' = 15 + 0.5(N_i - 15) \]  \hfill (9)

Calculation of CSR value through Modified Seed’s method is calculated for specific depth of water table, peak horizontal acceleration and earthquake magnitude. Therefore CSR values were interpreted for different combination of depth, peak horizontal acceleration and earthquake magnitude as shown below in Table:

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>ASSUMED WATER TABLE AND EARTHQUAKE MAGNITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. No.</td>
<td>Parameters</td>
</tr>
<tr>
<td>1</td>
<td>Depth of water table (m)</td>
</tr>
<tr>
<td>2</td>
<td>Earthquake Magnitude (Recter scale)</td>
</tr>
<tr>
<td>3</td>
<td>Peak Horizontal Ground Acceleration</td>
</tr>
</tbody>
</table>

- ANFIS method Network Architecture

A total combination of 5 input variables comprising depth \( (z) \), SPT-N value \( (N) \), natural / field moisture content \( (w) \), bulk density and particle size finer than 0.075 mm were used for ANFIS model development. Datasets were normalized using the following equation:

\[ \text{Normalized value} = \frac{\alpha_{\text{actual}} - \alpha_{\text{min}}}{\alpha_{\text{max}} - \alpha_{\text{min}}} \]  \hfill (10)

Where, \( \alpha \) is the input and output parameter’s value.

ANFIS tool built in MATLAB (R2011 a) software used for all operations in which networks were trained for 50 numbers of epochs and three membership functions was allotted for each five input. Grid partitioning method and triangular membership function for input variables were used to generate fuzzy inference system, whereas linear membership function was used for target variable. Hybrid optimization technique was used for training FIS. Initially liquefaction potential model were developed using two fundamental input variables i.e. depth \( (z) \) and SPT-N value...
(N) subsequently further inputs were selected randomly from remaining set of inputs to study the effect of individual parameter on liquefaction. To identify different network architecture with its fundamental attributes a coding method was used for different networks. As such AxMxWx denotes Ax as peak horizontal acceleration at 0.15g, Mx as earthquake magnitude value at 6 and Wx as depth of water table at 0 m. AyMyWy denotes Ay as peak horizontal acceleration at 0.35g, My as earthquake magnitude value at 7 and Wy as depth of water table at 4m. AxMzWz denotes Ax as peak horizontal acceleration at 0.15g, Mz as earthquake magnitude value at 8 and Wx as depth of water table at 8m. And below is a sample of input data:

<table>
<thead>
<tr>
<th>TABLE III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GANGA BANK BORE-LOG</strong></td>
</tr>
<tr>
<td><strong>Depth</strong> (m)</td>
</tr>
<tr>
<td>B1-1</td>
</tr>
<tr>
<td>B2-1</td>
</tr>
<tr>
<td>B3-1</td>
</tr>
<tr>
<td>B4-1</td>
</tr>
</tbody>
</table>

**IV. RESULTS AND DISCUSSION**

As said above in assumed water table and earthquake magnitude that two peak ground acceleration, three water table depth and three earthquake magnitude values were considered for assessing liquefaction potential through Modified Seed’s and ANFIS method. This resulted in total of eighteen combinations of peak ground acceleration, water table and earthquake magnitude values. The figure of all five inputs and outputs with their respective positions are shown in membership function plot in Fig.3 below for model AxMxWx for Yamuna bank zone. The similar pattern was also observed for remaining models. It has already described that ANFIS network were trained for 50 iterations. Fig.4 below shows the obtained curve for training. It may be seen that with the increasing iterations the error is also minimized. The training error is reached in the range of $8 \times 10^{-7}$ which represents the training capability of ANFIS technique.

![Fig.3. Membership function for model AxMxWx for Yamuna bank zone.](image)

![Fig.4. Training error for model AxMxWx for Yamuna bank zone.](image)

![Fig.5. Surface view of model AxMxWx for Yamuna bank zone.](image)
It was found that predictability increases with increasing number of input therefore only 5 numbers of inputs were finally adopted in all ANFIS models. It may be seen from above results that most of the predicted results from ANFIS models were in accordance with SESD’s method. It shows the higher prediction capability of ANFIS technique. Using the liquefaction values through modified seed’s method and ANFIS (by validating the networks) method, graphs were prepared for comparative analysis for these eighteen set of combinations of peak ground acceleration, water table and earthquake magnitude values. As discussed above that only some of the results are shown here therefore these eighteen figures are the graphical presentation of some Tables only. And below one table and some view of fig 6-9:

**TABLE IV**  
LIQUEFACTION FOR GANGA BANK FROM MODEL AXM wxWx

<table>
<thead>
<tr>
<th>Depth</th>
<th>N. value</th>
<th>N°</th>
<th>CSR</th>
<th>CRR</th>
<th>Liq. by Modified Seed’s method</th>
<th>Liq. by ANFIS method</th>
<th>Liq. by Modified Seed’s method</th>
<th>Liq. by ANFIS method</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>17</td>
<td>17.73353</td>
<td>0.092662</td>
<td>0.338647</td>
<td>3.554888</td>
<td>3.843056</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>4.5</td>
<td>8</td>
<td>8.433434</td>
<td>0.094144</td>
<td>0.340494</td>
<td>1.744825</td>
<td>2.137022</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>6.747858</td>
<td>0.093025</td>
<td>0.124024</td>
<td>1.335458</td>
<td>1.960111</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>1.5</td>
<td>13</td>
<td>16.96917</td>
<td>0.096339</td>
<td>0.324165</td>
<td>3.303814</td>
<td>3.410978</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>20.07854</td>
<td>0.095262</td>
<td>0.384309</td>
<td>4.034238</td>
<td>4.101385</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>4.5</td>
<td>50</td>
<td>35.5566</td>
<td>0.094164</td>
<td>1.076591</td>
<td>5.3</td>
<td>5.344542</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>1.5</td>
<td>7</td>
<td>9.854094</td>
<td>0.096381</td>
<td>0.189442</td>
<td>1.565949</td>
<td>2.737088</td>
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<td>NO</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>15.79171</td>
<td>0.095262</td>
<td>0.303088</td>
<td>3.170575</td>
<td>3.255081</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>1.5</td>
<td>14</td>
<td>18.23366</td>
<td>0.096381</td>
<td>0.346145</td>
<td>3.612067</td>
<td>3.477791</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>16.61109</td>
<td>0.095262</td>
<td>0.317422</td>
<td>3.220282</td>
<td>3.220894</td>
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<td>NO</td>
</tr>
<tr>
<td>4.5</td>
<td>26</td>
<td>22.11757</td>
<td>0.094164</td>
<td>0.427626</td>
<td>4.542004</td>
<td>3.397616</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>
The lowest value of coefficient of determination was 0.8166 for model AxMxWx (peak horizontal ground acceleration of 0.15, earthquake magnitude 6 and water table zero that is at ground level) for Ganga bank zone. Coefficient of determination in other models was also found more than 0.8 this indicates the accuracy of the ANFIS models.

V. CONCLUSIONS

Best value of average absolute error and regression for Yamuna Bank zone were 0.179 and 0.9787 for model AxMxWx and AyMxWx respectively. Lowest performance measures i. e. highest average absolute error and lowest regression for Yamuna Bank zone were 4.570 and 0.8735 respectively for models AxMzWx and AyMyWy respectively. It indicates that ANFIS models of Yamuna bank zone gave very less error and higher regression. For Ganga bank zone, best average absolute error and regression were found for model AxMxWx and AyMzWz that is 0.914and 0.9687 respectively. Average absolute error 4.673 for model AyMyWy and regression 0.8080 for model AyMxWz were the least performance measure for this zone. It may be seen from the validated results that only two wrong prediction were made by ANFIS models in Yamuna bank zone. It was for model AxMxWx and AxMzWz. Other predictions were in accordance with Modified SEED’s method. Similarly only three wrong predictions were made by Ganga bank zone ANFIS models. Based on above discussion on less average absolute error, high regression value and accuracy in prediction in occurrence/non-occurrence it may be said that ANFIS models may satisfactorily be used in place of theoretical method, which will reduce the tedious calculations requirements of theoretical methods with considerable accuracy.

VI. REFERENCES


