Validity of artificial neural modeling to estimate time-dependent deflection of reinforced concrete beams

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Abstract: The architecture and weights of an artificial neural network model that predicts time-dependent deflection have been developed and optimized. To satisfy the serviceability limit states, a concrete structure must be serviceable and perform its intended function throughout its working life. Excessive deflection should not impair the function of the structure or be aesthetically unacceptable. Cracks should not be unsightly or wide enough to lead to durability problems. Design for the serviceability limit states involves making reliable predictions of the instantaneous and time-dependent deflection of reinforced concrete beams. This is complicated by the nonlinear behavior of concrete caused mainly by cracking, tension stiffening, creep, and shrinkage. This paper provides a statistical approach for predicting the time-dependent deflection of reinforced concrete beams at service loads and outlines a validity of the proposed method in comparison with the American Concrete Institute (ACI) method.

1. Introduction
Owing to the huge importance of time-dependent deflection, satisfactory performance of concrete members should be considered. The calculation of time-dependent deflection for reinforced concrete beams is very convoluted due to several factors that have a significant effect on it, such as the compressive strength of concrete, tension reinforcement, compression reinforcement, the total time

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PUBLIC INTEREST STATEMENT
The application of artificial neural network (ANN) systems is growing rapidly in the financial and manufacturing sectors. Neural network systems offer several advantages over traditional methods for predicting the deflection of reinforced concrete beams. Therefore, during the last few years or so, the use of ANNs has increased in many construction engineering problems and has demonstrated some degree of success. ANNs are also being applied to solve problems of structural engineering, where the network is trained on a set of cause–effect data and trained to diagnose the observed effects in terms of unknown causes.
of the experiment, the loading history of the structure, and finally creep and shrinkage strain of the concrete. For many years, the main objective of extensive experimental research was the time-dependent deflection of reinforced concrete members. The test selected in this research was made by Gudonis et al. (2015). The study deals with singly reinforced concrete ties to examine experimentally the short- and long-term deflection for a duration of 315 days. Miàs, Torres, Turon, and Barris (2011) experimentally studied the long-term deflection of concrete beams reinforced with Glass Fiber Reinforced bar (GFRP) bars and compared with concrete beams reinforced with steel bars for a duration of 360 days. Gilbert and Nejadi (2004) studied flexural cracking due to the long-term deflection of flexural members under constant sustained service loads and shrinkage strain for a duration of 400 days. Paulson, Nilson, and Hover (1991) studied the long-term deflection of reinforced concrete beams with different compressive strengths for a duration of 360 days, whereas Espion (1988) covered all the experimental research on long-term deflection from 1907 to 1988.

However, there are a number of studies on the prediction of long-term deflection, such as Gholamhoseini (2016), who presented an experimental result for composite slabs subjected to sustained loads and shrinkage to study the long-term deflection and an analytical model to predict the long-term deflection considering the effect of creep and shrinkage.

Vakhshouri and Nejadi (2014) studied and compared the ratio between the calculated and predicted results of long-term to short-term deflection based on an experimental study. Gribniak, Bacinskas, Kacianauskas, Kaklauskas, and Torres (2013) statistically studied the accuracy of the prediction method suggested by the design codes and suggested a numerical technique influenced by different parameters for predicting long-term deflection.

Bacinskas, Kaklauskas, Gribniak, Sung, and Shih (2012) proposed a numerical technique to analyze the long-term deformation of reinforced concrete flexural members subjected to bending moments.

Mari, Bairón, and Duarte (2010) proposed a simplified formula to calculate the long-term curvatures and deflections of reinforced concrete flexural members, considering creep coefficient and shrinkage strain.

Gilbert and Nejadi (2008) suggested a technique for predicting the long-term deflection of reinforced concrete flexural members taking into account several factors; a comparison between the proposed technique and the experimental results was presented.

Rodriguez-Gutierrez and Aristizabal-Ochoa (2007) suggested an effective method to predict the long-term deflection of reinforced, pre-stressed, and composite concrete beams taking into account the effect of creep, shrinkage, and tension stiffening.

Espion and Halleux (1990) studied the variability of the ACI method for predicting the long-term deflection of reinforced concrete beams compared with the Comite Euro International du Beton (CEB) method.

The method of predicting time-dependent deflection is illustrated in ACI code 318–11, which is suitable for normal concrete strength, but this method has variability of about ±30% around the mean value. A statistical investigation is presented in this paper to assess the variability of the ACI method considering the results of time-dependent deflection experiments, compared with the architecture and weights of artificial neural network (ANN) models that predict time-dependent deflection. The following effects are included in the proposed models: compression reinforcement and the total time of the experiment.

The main purpose of this paper is to investigate statistically the variability of time-dependent deflection prediction made by the ACI code and a numerical technique proposed in this paper.
using ANN based on a large set of data (200) of previously tested beams excluded from time-dependent experiments, available in the literature.

2. Serviceability

Normal-strength concrete generally means concrete with uniaxial compressive strength in the range of 20–45 MPa. For the serviceability requirements of structural safety, the structure should be fit for human use and solid against external and internal fallouts. For the requirement of durability of the structures, cracks and vibrations should be kept as reasonable as possible. For the requirements of safety, the structure should be sufficiently tough for all types of prospective loads that could act on it. The prediction of structural strength could be assumed accurately if the structure is built and designed according to construction codes, taking into account the most accurate external and internal loads and moments that may act on the structure (Nilson, Darwin, and Dolan 2010). The appearance or durability of the structure should not be affected by either the deflection or the cracking in the concrete. The serviceability of concrete structures becomes much more substantial design seeking than previously. Nowadays, efficient design procedures enable designers to satisfy the requirements for the ultimate limit state, (Kong and Evans 2014). The limit-state requirements could be controlled by limiting the span/depth ratio and crack widths according to ACI318–11 table 9.5 (a) and 9.5 (b). Moreover, serviceability failure of corroded reinforced concrete (RC) beams caused by excessive cracking should also be considered. However, cracking of the concrete cover and reduction in the bond strength (which may result in slip between the corroding reinforcement and the concrete) also decrease the stiffness of the RC beams. As a result, displacements of the RC beams increase and may exceed the limit value specified in the code, i.e., it has been noted that corrosion may also cause serviceability failure due to excessive displacements (Val and Chernin 2009). Shrinkage and creep due to sustained loads cause additional long-term deflections, which may exceed short-term deflections on the structure. These deflections may be two to three times as large as the immediate elastic deflection that occurs when the sustained load is applied. Such deflections are influenced by temperature, humidity, curing conditions, age at the time of loading, quantity of compression reinforcement, and magnitude of the sustained load. According to ACI Code 9.5.2.5, additional long-term deflection resulting from creep and shrinkage for flexural members is determined by multiplying the immediate deflection caused by the sustained load considered by the factor given by Equation (1):

\[
\lambda = \xi (1 + 50\rho')
\]

(1)

where

\[
\rho' = \left( \frac{A_s'}{b'd} \right)
\]

(2)

\(\rho'\) is the ratio of compression reinforcement at mid-span for simple and continuous beams and at support for cantilevers; \(A_s'\) is the area of the compression reinforcement; \(b\) is the width of compression face of number; \(d\) is the distance from the extreme compression fiber to the centroid of tension reinforcement; and \(\xi\) is a time-dependent factor equal to 2.0, 1.4, 1.2, and 1.0, respectively, for 5 years or more, 12, 6, and 3 months.

In addition, in the establishment of a safety specification, consideration must be given to the consequences of failure. In some cases, a failure would merely be an inconvenience. In other cases, loss of life and significant loss of property may be involved. A further consideration should be the nature of failure, should it occur. A gradual failure with considerable waning permitting remedial measures is preferable to a sudden, unexpected collapse. It is evident that the selection of an appropriate margin of safety is not a simple matter. However, progress has been made toward rational safety provisions in designing codes (Nilson et al. 2010).

The elastic analysis requirement of ACI318–11 states that the effective moment of inertia \(I_e\) should not be greater than \(I_o\) for the calculation of immediate deflection:
where

\[ Mcr = \frac{frIg}{yt} \]  

Here, \( Mcr \) is the cracking moment, \( Ma \) is the maximum moment member at the stage when deflection is calculated, \( Icr \) is the moment of inertia of the cracked section; \( fr \) is the modulus of rupture (the tensile stress at which cracking occurs by flexure); \( Ig \) is the moment of inertia of concrete gross section neglecting reinforcement; and \( yt \) is the distance from the centroid axes of the cross section to the extreme fiber in tension.

### 3. ANN approach

ANNs are highly adaptive data-driven trainable systems capable of capturing hidden and complex behaviors through learning from training examples. Several ANN architectures were examined in this study to develop a feed-forward back-propagation multilayer perception network that can accurately predict the time-dependent deflection of reinforced concrete beams. The network architecture adopted in this investigation consists of an input layer, an output layer, and a hidden layer. The input layer contains two variables, representing the total time of the experiment and the compression reinforcement. The output layer consists of one unit, representing the time-dependent deflection factor, \( \lambda \), and the hidden layer includes one processing unit, which are shown in Figure 1. The most adequate division for the adopted data has been utilized in this research based on the results shown from Tables 1 to 6, Figure 1. Structure of the ANNs, weights, and threshold-level details for the optimal model division (81 14 5).

$$Ie = \left( \frac{Mcr}{Ma} \right)^3 Ig + \left( \frac{Mcr}{Ma} \right)^3 Icr \leq Ig$$

### Table 1. Effect of data division on the performance of ANNs

| Data Division | Training Error | Testing Error | Coefficient of Correlation (%) |
|---------------|----------------|---------------|--------------------------------|
| Training%     | Testing% | Querying% |       |       |                 |
| 80            | 10      | 10      | 11.7  | 10.65 | 63.5           |
| 80            | 5       | 15      | 11.1  | 7.8   | 79.5           |
| 81            | 14      | 5       | 11.3  | 11.56 | 91.4           |
| 70            | 10      | 20      | 11.8  | 7.28  | 57.6           |
| 70            | 12      | 18      | 11.7  | 10.6  | 68.4           |
| 75            | 20      | 5       | 10.4  | 14.3  | 72.6           |
| 65            | 20      | 15      | 11    | 11    | 79.7           |
| 65            | 15      | 20      | 10.7  | 11    | 58.9           |
| 60            | 25      | 15      | 12.2  | 10.59 | 64.2           |
| 60            | 10      | 30      | 11.5  | 11    | 58              |
| 60            | 30      | 10      | 11.5  | 11.8  | 60.3           |
| 65            | 25      | 10      | 10.6  | 13    | 70              |
where the division of data, type of division, momentum effect, learning effect, and the effect of transfer function all have been tested. Thus, the adopted model was divided as 81% training, 14% learning, and 5% querying, with a testing error of 11.3, a training error of 11.5, and correlation coefficient of 91.4%, while the learning rate was 0.2, the momentum rate was 0.8, and the transfer function was sigmoid for both the hidden and output layers. A comparison was made of the best three divisions. The comparison was based on the coefficient of correlation value, as shown in Figure 2, Figure 3 and Figure 4, and the standard division and mean value, as shown in Table 7 for the limited sample, where the best selected division according to this comparison was (81 14 5).

4. Experimental database
In this study, long-term deflection results for 240 concrete beams were collected from the published literature, as shown in Appendix A. Only rectangular, simply supported beams that

| Table 2. Effects of method of division on ANN performance |
|---------------------------------------------------------|
| **Data Division (%)** | **Choices of Division** | **Training Error (%)** | **Testing Error (%)** | **Coefficient of Correlation (r) %** |
| Training | Testing | Querying | Striped | 11 | 10.39 | 36.2 |
| 81 | 14 | 5 | Blocked | 10.2 | 11.4 | 72.1 |
| 81 | 14 | 5 | Random | 11.3 | 11.56 | 91.4 |

| Table 3. Effects Number of nodes on ANN performance (optimal model) |
|---------------------------------------------------------------------|
| **Model No.** | **Parameters Effect** | **No. of Nodes** | **Training Error (%)** | **Testing Error (%)** | **Coefficient of Correlation (r) %** |
| 1 | Choices of division (Random) | 1 | 11.3 | 11.56 | 91.4 |
| 2 | Learning Rate = (0.2) | 2 | 10.9 | 11.6 | 64.2 |
| 3 | Momentum Term = (0.8) | 3 | 10.9 | 11.6 | 64.4 |
| 4 | Transfer function in the hidden layer (Sigmoid) | 4 | 10.8 | 11.1 | 63.7 |
| 5 | Transfer function in the output layer (Sigmoid) | 5 | 11.4 | 12.2 | 56.6 |
| 6 | | 6 | 11.1 | 11.6 | 61.7 |
| 7 | | 7 | 10.7 | 11.4 | 65.4 |

| Table 4. Effects of momentum term on ANN performance (optimal model) |
|---------------------------------------------------------------------|
| **Parameters Effect** | **Momentum Term** | **Training Error (%)** | **Testing Error (%)** | **Coefficient of Correlation (r) %** |
| Model No. (1) choices of division (Random) | 0.1 | 11.3 | 11.7 | 75.2 |
| Learning Rate (0.2) | 0.2 | 11.26 | 10.4 | 76.9 |
| No. of Nodes (1) | 0.3 | 11.3 | 10.5 | 54.4 |
| Transfer function in the hidden layer (Sigmoid) | 0.4 | 13.9 | 13.5 | 73.7 |
| Transfer function in the output layer (Sigmoid) | 0.5 | 13 | 9.7 | 57.9 |
| 0.55 | 11.7 | 9.2 | 50 |
| 0.6 | 11.3 | 9.4 | 81.6 |
| 0.7 | 11 | 9.4 | 65 |
| 0.8 | 11.3 | 11.56 | 91.4 |
| 0.9 | 11.6 | 11.4 | 91.2 |
| 0.95 | 11.4 | 12 | 86.4 |
had complete information about dimensions, reinforcement details, compressive strength, and total duration of the experiment were considered. Out of the 240 specimens, 200 were utilized.

### 5. ANN model equation

The best selected for division can be depended on the standard division value, mean value, and the correlation coefficient for the best selected division, this had shown in Figures 2–4 and Table 7. For the reasons above, the small number of connection weights obtained by NEUFRAME for the optimal ANNs model for the selected division (81 14 5), which structure detailed in Figure 1 enables the network to be translated into relatively simple formula. The prediction of long-term deflection can be expressed as follows:

$$\text{prediction of long-term deflection} = \text{formula}$$

| Parameters Effect | Learning Rate | Training Error% | Testing Error% | Coefficient of Correlation (r)% |
|-------------------|---------------|-----------------|----------------|-------------------------------|
| Model No. (1) choices of division (Random) Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.1 | 10.3 | 12.5 | 85 |
| Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.2 | 11.3 | 11.56 | 91.4 |
| Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.3 | 10.9 | 10.7 | 85.3 |
| Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.4 | 11.4 | 10.7 | 78.6 |
| Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.5 | 11.3 | 12 | 79.5 |
| Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.6 | 11.5 | 7.6 | 87.7 |
| Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.7 | 11.5 | 9.7 | 54 |
| Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.8 | 11.7 | 9 | 74.5 |
| Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.9 | 12 | 11.4 | 71.3 |
| Momentum Term (0.8) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid) | 0.95 | 11 | 13.7 | 86 |

| Parameters Effect | Transfer Function | Hidden Layer | Output Layer | Training Error% | Testing Error% | Coefficient Correlation (r)% |
|-------------------|-------------------|--------------|--------------|-----------------|-----------------|-----------------------------|
| Model No. (1) choices of division (Random) No. of Nodes (1) Momentum Term (0.8) Learning Rate (0.2) | sigmoid | Sigmoid | 11.3 | 11.56 | 91.4 |
| Model No. (1) choices of division (Random) No. of Nodes (1) Momentum Term (0.8) Learning Rate (0.2) | sigmoid | tanh | 13.8 | 10.2 | 72.14 |
| Model No. (1) choices of division (Random) No. of Nodes (1) Momentum Term (0.8) Learning Rate (0.2) | tanh | sigmoid | 10.4 | 12.4 | 74.6 |
| Model No. (1) choices of division (Random) No. of Nodes (1) Momentum Term (0.8) Learning Rate (0.2) | tanh | tanh | 15.6 | 10.7 | 63 |

Figure 2. Histograms of computed time-dependent deflection according to ACI and ANN to actual measured time-dependent deflection for division (81 14 5).
and

$$X_1 = 0.06 + 177.857\rho - 20\% - 0.002287$$

(6)

Table 7. Mean and standard deviation value for a limited sample for each conducted division of ANNs

|                  | $\lambda_{ACI}/\lambda_{EXP}$ | $\lambda_{ANN}/\lambda_{EXP}$ (80 5 15) | $\lambda_{ANN}/\lambda_{EXP}$ (65 20 15) | $\lambda_{ANN}/\lambda_{EXP}$ (81 14 5) |
|------------------|-------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| **Mean Value**   | 1.369754                      | 1.059444                              | 1.242124                              | 1.165407                              |
| **Standard Deviation Value** | 0.74                          | 0.478007                              | 0.624773                              | 0.279377                              |

$$\lambda_{(81 14 5)} = \frac{1.6067}{1 + e^{-(0.569 - 3.3602 \tanh X_1)}} + 0.527$$

(5)

Table 8. Results of the comparative study

| $\rho'$ | Time (Days) | $\lambda$ ACI | $\lambda$ ANN |
|--------|-------------|---------------|---------------|
| 0      | 1825        | 2             | 2.133858      |
| 0      | 579         | 1.571667      | 1.150227      |
| 0      | 1825        | 2             | 1.7943        |
| 0      | 1825        | 2             | 1.794387      |
| 0      | 360         | 1.4           | 0.9936        |
| 0      | 88          | 0.988333      | 0.798227      |
| 0.000629 | 817        | 1.630129      | 1.287661      |
| 0.007499 | 360        | 1.018217      | 0.69          |
| 0.007499 | 360        | 1.018217      | 0.69026       |
| **Correlation of coefficient (R%)** | **82.6%** | **91.4%** | **91.4%** | **91.4%** |
To assess the validity of the ANN model for long-term deflection, the predicted values of time-dependent deflection are plotted against the measured (observed) values of time-dependent deflection for the validation data set for the optimal model, as shown in Figure 2 and summarized in Table 8. Figure 2 clearly shows the generalization capability of the ANN techniques using the validation data set. The coefficient of determination ($R^2$) is 83.53%; therefore, it can be concluded that the ANN model show very good agreement with the experimental results than that of ACI.

6. Results and discussion
The developed and trained ANN model was evaluated using the experimental database described earlier. The network-predicted time-dependent deflection factor compared to that calculated using ACI 318–11 was then compared to the experimentally measured values.

The performance of each method was assessed based on the average, standard deviation (STDV) for the ratio of calculated to measured time-dependent deflection factor ($\frac{\lambda_{\text{ANN}}}{\lambda_{\text{exp}}}$), and the correlation factor ($R$), as well as the mean absolute percentage error (MAPE), the average accuracy percentage (AA), and finally the $R^2$, as listed in Tables 7–9. Results show that ANNs have a better capacity to evaluate the time-dependent deflection factor of the reinforced concrete beams compared to other existing methods. It was also noted that code equations exhibited significant scatter, resulting in the high STDV.

To produce these solutions, numerous trials were performed. During these trials, error categorization was set up for the conceptual estimate. Schexnayder and Mayo (2003) proposed that the error of estimation was approximately around ±25%. In this study, the error categorization is based on MAPE. According to this, MAPE of the ANN model is very good. Therefore, high predication accuracy requires more time to train the network and search for a sophisticated ANN model.

7. Conclusion
This study investigated the use of ANNs to predict the time-dependent deflection of reinforced concrete beams and compared such predictions with those of several existing time-dependent deflection experimental data. A successfully trained ANN model can be used as an effective tool for predicting the time-dependent deflection of reinforced concrete beams and for evaluating the effect of compression reinforcement and the total time of experiment on the deflection behavior of such beams in a more accurate way compared to the existing standards ACI 318-11. The parametric study revealed the inability of code equations to provide a consistent safety margin for reinforced concrete beams based on a comparison for the range of parameters tested, which needs to be addressed through the adjustment of the parameters’ exponents.

This approach takes into consideration the influence of compression reinforcement and the total time of experiment as considered by the ACI 318-11 method. The statistical approach based on ANNs was studied, and a conservative estimation was proposed for the calculation of long-term deflection. A better approximation and lower scatter than the long-term deflections were calculated with the ACI code and simplified methods were obtained according to the standard division values. It is concluded that, in order to accurately predict the time-dependent deflections at any time of the service life of normal-strength concrete beams, loaded at any age, the effect of numerous factors, such as the compressive strength of the concrete, tension reinforcement, loading history of the structure, compression reinforcement, environmental condition, total time of the experiment, creep coefficient, and shrinkage strain, should be

| Table 9. Accuracy of the ANN model |
|-----------------------------------|
| MAPE                              | 7.452571% |
| AA%                               | 92.54743% |
| $R^2$                             | 83.59%    |
considered in the calculation parameter. The agreement between the predicted results of time-dependent deflection and the proposed model by ACI (318–2011) is good with a coefficient of correlation (R) of 91.4%.

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Appendix A. The Considered Test Adopted in the ANN Structure Models

| No. | Study Name          | No. of Samples | As’ | b    | d    | h    | ρ’   | Time days | fc’ Mpa |
|-----|---------------------|----------------|-----|------|------|------|------|-----------|---------|
| 1   | Faber (1927)        | 1              | 0   | 50.8 | 114.3| 127  | 0    | 619       | 20.1    |
| 2   |                     | 2              | 0   | 50.8 | 114.3| 127  | 0    | 1825      | 20.1    |
| 3   |                     | 3              | 0   | 50.8 | 114.3| 127  | 0    | 1825      | 20.1    |
| 4   |                     | 4              | 0   | 50.8 | 114.3| 127  | 0    | 1825      | 20.1    |
| 5   |                     | 5              | 35.6| 50.8 | 114.3| 127  | 0    | 473       | 19.3    |
| 6   |                     | 6              | 35.6| 50.8 | 114.3| 127  | 0    | 1721      | 19.3    |
| 7   | Glanville & Thomas (1939) | X49          | 0   | 101.6| 177.8| 209.6| 0    | 220       | 24      |
| 8   |                     | 88D            | 0   | 101.6| 177.8| 209.6| 0    | 225       | 28.1    |
| 9   |                     | 77L            | 0   | 101.6| 177.8| 209.6| 0    | 285       | 15.4    |
| 10  | Gilkey & Ernet (1935) | 8             | 0   | 76.2 | 136.5| 152.4| 0    | 579       | 30.4    |
| 11  |                     | 66             | 0   | 76.2 | 136.5| 152.4| 0    | 326       | 27.3    |
| 12  |                     | 67             | 0   | 76.2 | 136.5| 152.4| 0    | 326       | 28.8    |
| 13  |                     | 2              | 0   | 76.2 | 136.5| 152.4| 0    | 592       | 38.3    |
| 14  |                     | 1              | 0   | 76.2 | 136.5| 152.4| 0    | 592       | 38.7    |
| 15  |                     | 63             | 0   | 76.2 | 136.5| 152.4| 0    | 340       | 26.8    |
| 16  |                     | 68             | 0   | 76.2 | 136.5| 152.4| 0    | 326       | 28.3    |
| 17  |                     | 65             | 0   | 76.2 | 136.5| 152.4| 0    | 326       | 27      |
| 18  |                     | 10             | 0   | 76.2 | 136.5| 152.4| 0    | 579       | 28.9    |
| 19  |                     | 9              | 0   | 76.2 | 136.5| 152.4| 0    | 579       | 28.4    |
| 20  |                     | 6              | 0   | 76.2 | 136.5| 152.4| 0    | 586       | 33.8    |
| 21  |                     | 5              | 0   | 76.2 | 136.5| 152.4| 0    | 586       | 33.8    |
| 22  | Washa (1947)        | A/D            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 33.7    |
| 23  |                     | A/S            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 30.3    |
| 24  |                     | B/D            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 28.6    |
| 25  |                     | B/S            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 31.8    |
| 26  |                     | C/D            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 28.8    |
| 27  |                     | C/S            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 28.7    |
| 28  |                     | D/D            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 20.3    |
| 29  |                     | D/S            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 18.9    |
| 30  |                     | E/D            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 18.2    |
| 31  |                     | E/S            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 19      |
| 32  |                     | F/D            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 19.8    |
| 33  |                     | F/S            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 17.6    |
| 34  |                     | G/D            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 18.9    |
| 35  |                     | G/S            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 18.8    |
| 36  |                     | H/D            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 23.3    |
| 37  |                     | H/S            | 0   | 305  | 58.7 | 77   | 0    | 1825      | 21.1    |

(Continued)
| No. | Source                          | Coordinates | Width | Length | Thickness | Density | Void Ratio | Notes   |
|-----|--------------------------------|-------------|-------|--------|-----------|---------|------------|---------|
| 38  | Washa and Fluck (1952)         | A1/A4       | 852   | 203.2  | 257.2     | 304.8   | 0.016302   | 927     |
| 39  |                                | A2/A5       | 400   | 203.2  | 257.2     | 304.8   | 0.007654   | 927     |
| 40  |                                | A3/A6       | 0     | 203.2  | 257.2     | 304.8   | 0          | 927     |
| 41  |                                | B1/B4       | 400   | 152.4  | 157.2     | 203.2   | 0.016696   | 927     |
| 42  |                                | B2/B5       | 200   | 152.4  | 157.2     | 203.2   | 0.008348   | 927     |
| 43  |                                | B3/B6       | 0     | 152.4  | 157.2     | 203.2   | 0          | 927     |
| 44  |                                | C1/C4       | 516   | 304.8  | 101.6     | 127     | 0.016663   | 927     |
| 45  |                                | C2/C5       | 258   | 304.8  | 101.6     | 127     | 0.008331   | 927     |
| 46  |                                | C3/C6       | 0     | 304.8  | 101.6     | 127     | 0          | 927     |
| 47  |                                | D1/D4       | 516   | 304.8  | 101.6     | 127     | 0.016663   | 927     |
| 48  |                                | D2/D5       | 258   | 304.8  | 101.6     | 127     | 0.008331   | 927     |
| 49  |                                | D3/D5       | 0     | 304.8  | 101.6     | 127     | 0          | 927     |
| 50  |                                | E1/E4       | 284   | 304.8  | 58.7      | 76.2    | 0.015873   | 927     |
| 51  |                                | E2/E5       | 142   | 304.8  | 58.7      | 76.2    | 0.007937   | 927     |
| 52  |                                | E3/E6       | 0     | 304.8  | 58.7      | 76.2    | 0          | 927     |
| 53  | Ulitskij & Pusinov (1956)      | B-17        | 0     | 80     | 86.5      | 100     | 0          | 210     |
| 54  |                                | B-18        | 0     | 80     | 86.5      | 100     | 0          | 210     |
| 55  |                                | B-19        | 0     | 80     | 86.5      | 100     | 0          | 210     |
| 56  |                                | B-20        | 0     | 80     | 86.5      | 100     | 0          | 210     |
| 57  |                                | B-41        | 0     | 80     | 86.4      | 100     | 0          | 200     |
| 58  |                                | B-42        | 0     | 80     | 86.4      | 100     | 0          | 200     |
| 59  |                                | B-43        | 0     | 80     | 86.4      | 100     | 0          | 200     |
| 60  |                                | B-44        | 0     | 80     | 86.4      | 100     | 0          | 200     |
| 61  | Shkerbelis (1957)              | B-1         | 0     | 70     | 87        | 100     | 0          | 328     |
| 62  |                                | B-2         | 0     | 70     | 84.5      | 100     | 0          | 328     |
| 63  |                                | B-3         | 0     | 70     | 86.3      | 100     | 0          | 328     |
| 64  |                                | B-4         | 0     | 70     | 83        | 100     | 0          | 328     |
| 65  | P.C.A. (1950)                  | 20NA        | 0     | 152    | 254       | 305     | 0          | 270     |
| 66  |                                | 40NA        | 0     | 152    | 254       | 305     | 0          | 270     |
| 67  |                                | 60NA        | 0     | 152    | 254       | 305     | 0          | 270     |
| 68  | Sattler (1956)                 | a1/a2       | 0     | 100    | 134       | 160     | 0          | 116     |
| 69  |                                | b           | 0     | 1000   | 56        | 74.5    | 0          | 116     |
| 70  | Haddad (1960)                  | 1a          | 0     | 180    | 318       | 350     | 0          | 360     |
| 71  |                                | 2a          | 0     | 180    | 310       | 350     | 0          | 360     |

(Continued)
|   | Yu and Winter (1960) |   | Figarovskij (1962) |   | Hajnal—Konyi (1958-1963) |   | Ulitskij et al. (1963) |   | Branson and Metz (1963) |
|---|---------------------|---|--------------------|---|--------------------------|---|-----------------------|---|---------------------|
| 72|                     | A | 0                  | 305 | 258.8                   | 305 | 0                     | 298 | 25.4               |
| 73|                     | B | 0.002534           |      | 0.005068                |      | 0.002997              |      | 0.003005           |
| 74|                     | C | 0                  | 305 | 258.8                   | 305 | 0                     | 298 | 24.3               |
| 75|                     | D | 0                  | 610 | 245.9                   | 305 | 0                     | 298 | 25.4               |
| 76|                     | E | 0                  | 305 | 249.2                   | 305 | 0                     | 298 | 29.4               |
| 77|                     | F | 0                  | 305 | 157.2                   | 203 | 0                     | 298 | 29.4               |
| 78|                     | P1-1k | 0                  | 180 | 233                    | 250 | 0                     | 251 | 18.3               |
| 79|                     | P1-2k | 0                  | 180 | 233                    | 250 | 0                     | 251 | 18.3               |
| 80|                     | P2-1k | 0                  | 180 | 228                    | 250 | 0                     | 159 | 17.5               |
| 81|                     | P2-2k | 0                  | 180 | 228                    | 250 | 0                     | 159 | 17.5               |
| 82|                     | P3-1k | 0                  | 180 | 229                    | 250 | 0                     | 164 | 25.4               |
| 83|                     | P3-2k | 0                  | 180 | 229                    | 250 | 0                     | 164 | 25.4               |
| 84|                     | BI-1 | 0                  | 105 | 177                    | 202 | 0                     | 295 | 34.6               |
| 85|                     | BI-2 | 0                  | 101 | 178                    | 203 | 0                     | 295 | 34.6               |
| 86|                     | BI-3 | 0                  | 103 | 178                    | 201 | 0                     | 295 | 34.6               |
| 87|                     | BI-1 | 0                  | 102 | 180                    | 205 | 0                     | 325 | 34.6               |
| 88|                     | BI-2 | 0                  | 104 | 175                    | 200 | 0                     | 325 | 34.6               |
| 89|                     | BI-3 | 0                  | 102 | 187                    | 212 | 0                     | 295 | 34.6               |
| 90|                     | BI-1 | 0                  | 102 | 187                    | 212 | 0                     | 295 | 34.6               |
| 91|                     | BI-2 | 0                  | 102 | 185                    | 210 | 0                     | 295 | 34.6               |
| 92|                     | BI-3 | 0                  | 102 | 185                    | 210 | 0                     | 295 | 34.6               |
| 93|                     | BIII-1 | 50                 | 103 | 162                    | 204 | 0.002997             | 315 | 34.6               |
| 94|                     | BIII-2 | 50                 | 104 | 160                    | 206 | 0.003005             | 315 | 34.6               |
| 95|                     | BIII-3 | 50                 | 101 | 165                    | 205 | 0.003                 | 315 | 34.6               |
| 96|                     | SB3/B | 0                  | 101.6 | 101.6                | 127 | 0                     | 88  | 35.4               |
| 97|                     | SB3/M | 0                  | 101.6 | 101.6                | 127 | 0                     | 88  | 31.3               |
| Page | Description                       | Data                                                                 |
|------|-----------------------------------|----------------------------------------------------------------------|
| 109  | Pauw and Mayers (1964)            | R1 0 177.8 165.1 216 0 178 33.8                                     |
| 110  |                                   | R2 0 177.8 165.1 216 0 178 33.6                                     |
| 111  |                                   | R3 0 177.8 165.1 216 0 178 33.6                                     |
| 112  |                                   | R4 0 177.8 165.1 216 0 178 33.6                                     |
| 113  | Moertena and Pfeffermann (1965)   | P2 0 120 247 285 0 243 23.8                                         |
| 114  |                                   | P6 0 120 247 286 0 243 23.8                                         |
| 115  |                                   | P3a 0 121 244 282 0 151 20                                           |
| 116  |                                   | P6a 0 121 246 284 0 151 20                                           |
| 117  | Corley and Sozen (1966)           | C1 0 76 136 153 0 728 24                                             |
| 118  |                                   | C2 0 76 91.5 110 0 728 24                                             |
| 119  |                                   | C3 0 76 91.5 110 0 728 24                                             |
| 120  | Lutz et al. (1967)                | SR 0 101.6 171.5 203.2 0 170 34.1                                    |
| 121  |                                   | DR 258 101.6 177.8 203.2 0.014282 170 34.1                            |
| 122  | Hollington (1970)                 | 1-12 63 457 219 241 0.000629 1028 29.9                                |
| 123  |                                   | 13-15 63 457 219 241 0.000629 822 29.9                                |
| 124  |                                   | 16-18 284 457 213 241 0.002918 804 29.9                               |
| 125  |                                   | 19-21 535 457 213 241 0.005496 832 29.9                               |
| 126  |                                   | 19A-21A 63 457 219 241 0.00629 705 29.9                               |
| 127  |                                   | 22-24 63 457 219 241 0.00629 832 29.9                                |
| 128  |                                   | 25-27 63 457 219 241 0.00629 817 29.9                                |
| 129  |                                   | 28-30 63 457 219 241 0.00629 813 29.9                                |
| 130  |                                   | 31-33 63 457 219 241 0.00629 817 45.1                                |
| 131  |                                   | 34-36 63 457 219 241 0.00629 797 24                                  |
| 132  |                                   | 37-39 535 457 213 241 0.005496 804 24                                 |
| 133  |                                   | 40-42 63 457 219 241 0.00629 790 24                                  |
| 134  |                                   | 43-45 63 457 219 241 0.00629 785 45.7                                |
| 135  |                                   | 46-48 63 457 168 191 0.000821 783 29.9                               |
| 136  |                                   | 49-51 381 457 164 191 0.005084 783 29.9                               |
| 137  |                                   | 52-54 63 457 168 191 0.000821 778 29.9                               |
| 138  |                                   | 55-57 63 457 168 191 0.000821 778 45.1                                |
| 139  |                                   | 67-69 63 457 219 241 0.00629 510 29.9                                |
| 140  |                                   | 82-83 63 457 219 241 0.00629 155 29.9                                |
| 141  | Dilger and Abele (1974)           | B.89-5.3 64 203 174 203 0.001812 280 29.3                            |
| 142  |                                   | B.8-10 64 203 174 203 0.001812 208 18.8                             |
| 143  |                                   | B.11-10 64 203 174 203 0.001812 211 21.5                             |
| 144  |                                   | B.28-10 64 203 174 203 0.001812 228 19.5                             |
| 145  |                                   | B.70-10 64 203 174 203 0.001812 270 25.9                             |
| 146  |                                   | B.120-10 64 203 174 203 0.001812 195 27.3                             |
| 147  |                                   | B.81-15 64 203 174 203 0.001812 281 29.4                             |

(Continued)
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 148 | Hajek et al. (1983–1984) program No.7 | 1K 12/13 | 0 | 1200 | 100 | 120 | 0 | 1132 | 29 |
| 149 |   | 2K 5/6 | 0 | 1200 | 100 | 120 | 0 | 1132 | 29 |
| 150 | Jaccoud and Favre (1982) | A1 | 57 | 600 | 100 | 120 | 0.00095 | 380 | 21.1 |
| 151 |   | A2 | 57 | 600 | 100 | 120 | 0.00095 | 380 | 24.9 |
| 152 |   | A3 | 57 | 600 | 100 | 120 | 0.00095 | 380 | 20.2 |
| 153 |   | A5 | 57 | 600 | 100 | 120 | 0.00095 | 380 | 33.4 |
| 154 |   | C13 | 57 | 750 | 134 | 160 | 0.000567 | 538 | 32.9 |
| 155 |   | C14 | 57 | 750 | 134 | 160 | 0.000567 | 538 | 30.9 |
| 156 |   | C24 | 57 | 750 | 134 | 160 | 0.000567 | 538 | 32 |
| 157 |   | C15 | 57 | 750 | 134 | 160 | 0.000567 | 538 | 29.3 |
| 158 | Ding Dajung et al. (1984–1985) | b-2 | 0 | 119 | 81.9 | 99 | 0 | 2220 | 30 |
| 159 |   | b-3 | 0 | 122 | 79.3 | 99 | 0 | 2220 | 30 |
| 160 |   | L-1 | 0 | 62 | 117 | 152 | 0 | 561 | 30 |
| 161 |   | L-2 | 0 | 156 | 119 | 152 | 0 | 561 | 30 |
| 162 |   | L-3 | 0 | 247 | 112.5 | 152 | 0 | 561 | 30 |
| 163 |   | L-4 | 0 | 81 | 173.8 | 201 | 0 | 561 | 30 |
| 164 |   | L-5 | 0 | 80 | 173 | 202 | 0 | 561 | 30 |
| 165 |   | L-6 | 0 | 85 | 171 | 201 | 0 | 561 | 30 |
| 166 | D. Van Nieuwenburg et al. (1984) | III-43 | 0 | 150 | 233 | 280 | 0 | 1600 | 34.3 |
| 167 |   | III-67 | 0 | 150 | 233 | 280 | 0 | 1600 | 34.3 |
| 168 |   | III-77 | 0 | 150 | 233 | 280 | 0 | 1600 | 34.3 |
| 169 |   | IV-52 | 462 | 150 | 248 | 280 | 0.012419 | 800 | 32 |
| 170 |   | IV-70 | 462 | 150 | 248 | 280 | 0.012419 | 800 | 32 |
| 171 |   | IV-80 | 462 | 150 | 248 | 280 | 0.012419 | 1000 | 32 |
| 172 |   | IV-90 | 462 | 150 | 248 | 280 | 0.012419 | 1000 | 32 |
| 173 | Bakoss et al. (1982) | B2 | 0 | 100 | 130 | 150 | 0 | 528 | 39 |
| 174 | Christiansen (1981–1988) | L3/L4 | 39 | 170 | 252 | 280 | 0.00091 | 3052 | 27.6 |
| 175 |   | L7 | 226 | 170 | 249 | 280 | 0.005339 | 3028 | 23.6 |
| 176 |   | L8 | 226 | 170 | 249 | 280 | 0.005339 | 2856 | 23.6 |
| 177 |   | L9/L10 | 452 | 170 | 249 | 280 | 0.010678 | 3123 | 31 |
| 178 | Clarke (1986) | A1 | 0 | 100 | 132 | 154 | 0 | 208 | 25.9 |
| 179 |   | A2 | 0 | 100 | 130 | 152 | 0 | 208 | 25.9 |
| 180 |   | B1 | 157.1 | 100 | 132 | 152 | 0.011902 | 208 | 25.9 |
| 181 |   | B2 | 157.1 | 100 | 134 | 154 | 0.011724 | 208 | 25.9 |

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|    | Paulson et al. (1991) | A0   | 0  | 127 | 210 | 254 | 0   | 360 | 90  |
|----|----------------------|------|----|-----|-----|-----|-----|-----|-----|
| 182|                      | A1   | 200| 127 | 210 | 254 | 0   | 360 | 90  |
| 183|                      | A2   | 400| 127 | 210 | 254 | 0   | 360 | 90  |
| 184|                      | B1   | 0  | 127 | 210 | 254 | 0   | 360 | 66  |
| 185|                      | B2   | 200| 127 | 210 | 254 | 0   | 360 | 66  |
| 186|                      | B3   | 400| 127 | 210 | 254 | 0   | 360 | 66  |
| 187|                      | C0   | 0  | 127 | 210 | 254 | 0   | 360 | 37  |
| 188|                      | C1   | 200| 127 | 210 | 254 | 0   | 360 | 37  |
| 189|                      | C2   | 400| 127 | 210 | 254 | 0   | 360 | 37  |
| 190| Gilbert (2008)      | B1-a | 0  | 250 | 300 | 333 | 0   | 400 | 32  |
| 191|                      | B2-a | 0  | 250 | 300 | 333 | 0   | 400 | 32  |
| 192|                      | B3-a | 0  | 250 | 300 | 333 | 0   | 400 | 32  |
| 193|                      | S2-a | 0  | 400 | 344 | 88  | 100 | 0   | 315 | 33.6|
| 194|                      | S3-a | 0  | 400 | 344 | 88  | 100 | 0   | 315 | 33.6|
| 195| Mias et al. (2011)  | HL1S10| 0  | 140 | 190 | -   | 190 | 0   | 360 | 56  |
| 196|                      | HL2S10| 0  | 140 | 190 | -   | 190 | 0   | 360 | 56  |
| 197| Gudonis et al. (2015)| DT-12| 0  | 100 | 88  | 100 | 0   | 315 | 33.6|
| 198|                      | DT-13| 0  | 100 | 88  | 100 | 0   | 315 | 33.6|
| 199|                      | DT-14| 0  | 100 | 88  | 100 | 0   | 315 | 33.6|
| 200|                      | DT-15| 0  | 100 | 88  | 100 | 0   | 315 | 33.6|