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

Faiq M. S. Al-Zwainy[1]*, Rana I. K. Zaki[1], Atheer Mahmood Al-saadi[2] and Huda F. Ibraheem[3]

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*Corresponding author: Faiq M. S. Al-Zwainy, College of Engineering, Al-Nahrain University, Republic of Iraq
E-mail: faiq_faiqmohmed@yahoo.com

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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.

Subjects: Intelligent Systems; Concrete & Cement; Structural Engineering

Keywords: time-dependent deflection; beams; reinforced concrete; statistical analysis; artificial neural networks; variability; parametric study

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

Faiq M. S. Al-Zwainy

ABOUT THE AUTHOR

Dr. Faiq Al-zwainy was born in Iraq. He obtained his bachelor's degree in civil engineering in Al-Mustansiriya University, Baghdad, Iraq, in 1996; his master's degree in 2000 from Al-Mustansiriya University; and his PhD in 2009 at Baghdad University (BU). He is Member of PMI (Project Management Institute). Currently, he is Assistant Professor Dr. in College of Engineering/ Al-Nahrain University, Iraq. His research interest includes artificial neural network in structural engineering. The experimental work of this research was implemented in Iraq. This research aims to provide a statistical approach for predicting the time-dependent deflection of reinforced concrete beams.

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.

Marí, Bairán, 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):

$$\lambda = \mathcal{E}(1 + 50\rho') \tag{1}$$

where

$$\rho' = \left(\frac{As'}{bd}\right) \tag{2}$$

ρ’ is the ratio of compression reinforcement at mid-span for simple and continuous beams and at support for cantilevers; As’ 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 ξ 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_g for the calculation of immediate deflection:

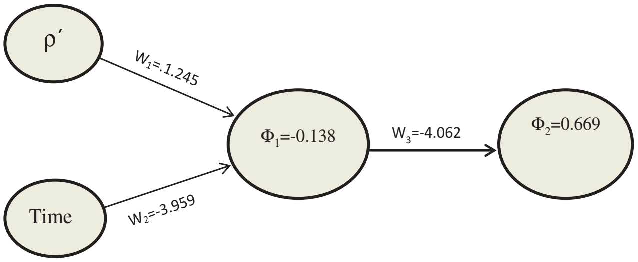

Figure 1. Structure of the ANNs, weights, and threshold-level details for the optimal model division (81 14 5).

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

where

$$Mcr = \frac{frIg}{yt} \tag{4}$$

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, λ, 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,

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

Data Division			Training Error %	Testing Error %	Coefficient of Correlation (r)%
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

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				
81	14	5	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) Learning Rate = (0.2) Momentum Term = (0.8) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid)	1	11.3	11.56	91.4
2		2	10.9	11.6	64.2
3		3	10.9	11.6	64.4
4		4	10.8	11.1	63.7
5		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) Learning Rate (0.2) No. of Nodes (1) Transfer function in the hidden layer (Sigmoid) Transfer function in the output layer (Sigmoid)	0.1	11.3	11.7	75.2
	0.2	11.26	10.4	76.9
	0.3	11.3	10.5	54.4
	0.4	13.9	13.5	73.7
	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

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 11.54, 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 5. Effects of learning rate on ANN performance (optimal model)

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
	0.2	11.3	11.56	91.4
	0.3	10.9	10.7	85.3
	0.4	11.4	10.7	78.6
	0.5	11.3	12	79.5
	0.6	11.5	7.6	87.7
	0.7	11.5	9.7	54
	0.8	11.7	9	74.5
	0.9	12	11.4	71.3
	0.95	11	13.7	86

Table 6. Effects of transfer function on ANN performance (optimal model)

Parameters Effect	Transfer Function		Training Error%	Testing Error%	Coefficient Correlation (r)%
	Hidden Layer	Output Layer			
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
	sigmoid	tanh	13.8	10.2	72.14
	tanh	sigmoid	10.4	12.4	74.6
	tanh	tanh	15.6	10.7	63

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:

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

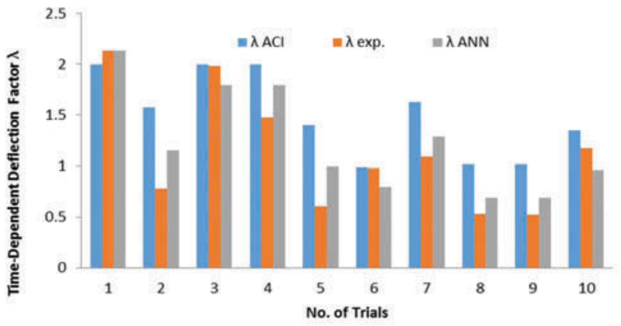

Figure 3. Histograms of computed time-dependent deflection according to ACI and ANN to actual measured time-dependent deflection for division (80 5 15).

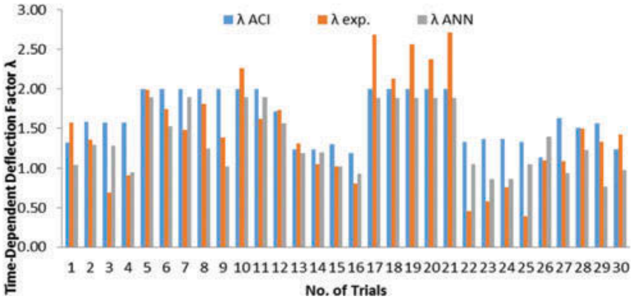

Figure 4. Histograms of computed time-dependent deflection according to ACI and ANN to actual measured time-dependent deflection for division (65 20 15).

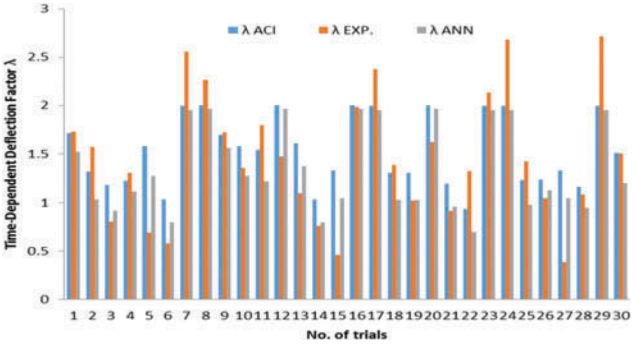

Table 7. Mean and standard deviation value for a limited sample for each conducted division of ANNs

	$\lambda_{ACI}/\lambda_{EXP.}$	$\lambda_{ANN}/\lambda_{EXP}$ (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

$$\lambda_{(8114\ 5)} = \frac{1.6067}{1 + e^{-(0.669 - 3.4.062\ \tanh X_1)}} + 0.527 \tag{5}$$

and

$$X_1 = 0.06 + 177.857\rho - 20\%' - 0.00228T \tag{6}$$

Table 8. Results of the comparative study

Input data		Output data	
ρ'	Time (Days)	λ ACI	λ 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%

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 (.$\lambda_{ANN}/\lambda_{exp}$), 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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Author details
Faiq M. S. Al-Zwainy[1]
E-mail: faiq_faiqmohmed@yahoo.com
Rana I. K. Zaki[1]
E-mail: ranaismailkhalil@gmail.com
Atheer Mahmood Al-saadi[2]
E-mail: atheer@yahoo.com
Huda F. Ibraheem[3]
E-mail: hudafarhan@yahoo.com
[1] Civil Engineering Department, College of Engineering, Al-Nahrain University, Republic of Iraq.
[2] Ministry of Construction and Housing, Republic of Iraq.
[3] Section of Quality Assurance, College of Economy and Management, Al-Iraqia University, Republic of Iraq.

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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	0.006131	473	19.3
6		6	35.6	50.8	114.3	127	0.006131	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*)

38	Washa and Fluck (1952)	A1/A4	852	203.2	257.2	304.8	0.016302	927	25
39		A2/A5	400	203.2	257.2	304.8	0.007654	927	25
40		A3/A6	0	203.2	257.2	304.8	0	927	25
41		B1/B4	400	152.4	157.2	203.2	0.016696	927	20.8
42		B2/B5	200	152.4	157.2	203.2	0.008348	927	20.8
43		B3/B6	0	152.4	157.2	203.2	0	927	20.8
44		C1/C4	516	304.8	101.6	127	0.016663	927	20.3
45		C2/C5	258	304.8	101.6	127	0.008331	927	20.3
46		C3/C6	0	304.8	101.6	127	0	927	20.3
47		D1/D4	516	304.8	101.6	127	0.016663	927	22.1
48		D2/D5	258	304.8	101.6	127	0.008331	927	22.1
49		D3/D5	0	304.8	101.6	127	0	927	22.1
50		E1/E4	284	304.8	58.7	76.2	0.015873	927	20.6
51		E2/E5	142	304.8	58.7	76.2	0.007937	927	20.6
52		E3/E6	0	304.8	58.7	76.2	0	927	20.6
53	Ulitskij & Pusinov (1956)	B-17	0	80	86.5	100	0	210	9.9
54		B-18	0	80	86.5	100	0	210	9.9
55		B-19	0	80	86.5	100	0	210	9.9
56		B-20	0	80	86.5	100	0	210	9.9
57		B-41	0	80	86.4	100	0	200	11.2
58		B-42	0	80	86.4	100	0	200	11.2
59		B-43	0	80	86.4	100	0	200	11.2
60		B-44	0	80	86.4	100	0	200	11.2
61	Shkerbelis (1957)	B-1	0	70	87	100	0	328	12.5
62		B-2	0	70	84.5	100	0	328	12.5
63		B-3	0	70	86.3	100	0	328	12.5
64		B-4	0	70	83	100	0	328	12.5
65	P.C.A. (1950)	20NA	0	152	254	305	0	270	12.2
66		40NA	0	152	254	305	0	270	26.9
67		60NA	0	152	254	305	0	270	37.4
68	Sattler (1956)	a1/a2	0	100	134	160	0	116	26.7
69		b	0	1000	56	74.5	0	116	26.7
70	Haddad (1960)	1a	0	180	318	350	0	360	26.2
71		2a	0	180	310	350	0	360	26.2

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72	Yu andWinter (1960)	A	0	305	258.8	305	0	298	25.4
73		B	200	305	258.8	305	0.002534	298	26.8
74		C	400	305	258.8	305	0.005068	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	Figarovskij (1962)	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	Hajnal—Konyi (1958–1963)	1	0	127	158.8	190.5	0	1783	19.8
85		2	0	127	160.3	190.5	0	1783	19.8
86		4	0	127	160.3	190.5	0	1783	19.8
87		5	0	127	158.8	190.5	0	1783	19.8
88		6	0	127	160.3	190.5	0	1783	19.8
89		7	0	127	158.8	190.5	0	1787	37
90		8	0	127	160.3	190.5	0	1787	37
91		9	0	127	158.8	190.5	0	1787	37
92		10	0	127	160.3	190.5	0	1787	37
93		11	0	127	158.8	190.5	0	1787	37
94		12	0	127	160.3	190.5	0	1787	37
95	Ulitskij et al. (1963)	BI-1	0	105	177	202	0	295	34.6
96		BI-2	0	101	178	203	0	295	34.6
97		BI-3	0	103	178	201	0	295	34.6
98		B’I-1	0	102	180	205	0	325	34.6
99		B’I-2	0	104	175	200	0	325	34.6
100		B’I-3	0	101	176	201	0	325	34.6
101		BII-1	0	102	187	212	0	295	34.6
102		BII-2	0	102	187	212	0	295	34.6
103		BII-3	0	102	185	210	0	295	34.6
104		BIII-1	50	103	162	204	0.002997	315	34.6
105		BIII-2	50	104	160	206	0.003005	315	34.6
106		BIII-3	50	101	165	205	0.003	315	34.6
107	Branson and Metz (1963)	SB3/B	0	101.6	101.6	127	0	88	35.4
108		SB3/M	0	101.6	101.6	127	0	88	31.3

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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	148	38.9
112		R4	0	177.8	165.1	216	0	148	38.7
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	123	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	0.000629	705	29.9
127		22–24	63	457	219	241	0.000629	832	29.9
128		25–27	63	457	219	241	0.000629	817	29.9
129		28–30	63	457	219	241	0.000629	813	29.9
130		31–33	63	457	219	241	0.000629	817	45.1
131		34–36	63	457	219	241	0.000629	797	24
132		37–39	535	457	213	241	0.005496	804	24
133		40–42	63	457	219	241	0.000629	790	24
134		43–45	63	457	219	241	0.000629	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	0.000629	510	29.9
140		82–83	63	457	219	241	0.000629	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

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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 andFavre (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)	1B2	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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182	Paulson et al. (1991)	A0	0	127	210	254	0	360	90
183		A1	200	127	210	254	0.007499	360	90
184		A2	400	127	210	254	0.014998	360	90
185		B1	0	127	210	254	0	360	66
186		B2	200	127	210	254	0.007499	360	66
187		B3	400	127	210	254	0.014998	360	66
188		C0	0	127	210	254	0	360	37
189		C1	200	127	210	254	0.007499	360	37
190		C2	400	127	210	254	0.014998	360	37
191	Gilbert (2008)	B1-a	0	250	300	333	0	400	32
192		B2-a	0	250	300	333	0	400	32
193		B3-a	0	250	300	333	0	400	32
194		S2-a	0	400	-	161	0	400	32
195		S3-a	0	400	-	161	0	400	32
196	Miàs et al. (2011)	HL1S10	0	140	-	190	0	360	56
197		HL2S10	0	140	-	190	0	360	56
198	Gudonis et al. (2015)	DT-12	0	100	88	100	0	315	33.6
199		DT-13	0	100	88	100	0	315	33.6
200		DT-14	0	100	88	100	0	315	33.6
201		DT-15	0	100	88	100	0	315	33.6