GU J Sci, Part A, 8(2): 189-196 (2021)

Gazi University
Journal of Science
PART A: ENGINEERING AND INNOVATION
http://dergipark.gov.tr/gujsa

Araştırma Makalesi Research Article

Practical Equations for Calculating the Root Diameter of Bolts

Eray ÖZBEK[1*], Bengi AYKAÇ[1], Sabahattin AYKAÇ[1]

[1]*Gazi University, Faculty of Engineering, Civil Engineering Department, 06570 Ankara, Turkey*

Keywords

Bolt
Root Diameter
Minor Diameter
Thread
Steel Structure

Abstract

Since bolts can be removed and reassembled, they are often preferred by civil engineers in steel structures. Bolt root (minor) diameter, in other words, the least diameter of the bolt should be considered for most of the bolted connection design. In this case, the designer either takes the root diameter from the tables or calculates it using complex equations. Therefore, practical linear equations for both Standard Metric and Inch Based American bolts with sufficient accuracy were derived. It is claimed that these equations can save the designer from being dependent on the tables or memorizing complex equations.

Cite

Özbek, E., Aykaç, B., Aykaç, S. (2021). Practical Equations for Calculating the Root Diameter of Bolts. *GU J Sci, Part A*, *8*(2), 189-196.

Author ID (ORCID Number)

E. Özbek, 0000-0001-6738-7789
B. Aykaç, 0000-0002-6285-5667
S. Aykaç, 0000-0001-6269-8430

Article Process

Submission Date	08.07.2020
Revision Date	25.03.2021
Accepted Date	26.03.2021
Published Date	06.04.2021

1. INTRODUCTION

Bolting of steel structures is a very rapid field erection process that requires less skilled labor than does riveting or welding. Moreover, bolts can be removed and reassembled. They are produced by spirally threading a cylindrical steel bar and terminology is shown in Figure 1. During the threading, the cross section of the cylindrical rod inevitably narrows and reaches the smallest value at the root. However, screw thread features may vary depending on the location on the world. Most well-known and widely accepted ones are the ISO Standard Metric (ISO 68-1, 1998) and Inch Based American (ASME, 2011) screw threads. Both screw threads have the same 60° profile, but the characteristic dimensions of the Inch Based thread, major diameter and the pitch, are selected as an inch fraction rather than a millimeter (Figure 1).

Bolt root (minor) diameter, in other words, the least diameter of the bolt, should be considered for the bolts in tension and bolts in which threaded part is on the shear plane. In this case, although the designer can find the root diameter (d_3) with the help of a chart as in Table 1 or Table 2, it is not practical. On the other hand, while Eq.1 can be used for Standard Metric (TS 61-2, 2016), Eq.2 can be used for Inch Based American bolts (AISC, 2016).

$$d_3 = d - 1.2269\,P \qquad \text{(mm)} \tag{1}$$

$$d_3 = d - \frac{0,9743}{n} \qquad \text{(in)} \tag{2}$$

where d is the nominal diameter of the bolt, P is the pitch distance, and n is the threads per inch. As seen, these equations depend on the P and n value. However, P and n values are specific to each bolt and there is no strong correlation according to nominal bolt diameter. In other words, P and n values for each bolt should be memorized.

*Corresponding Author, e-mail: erayozbek@gazi.edu.tr

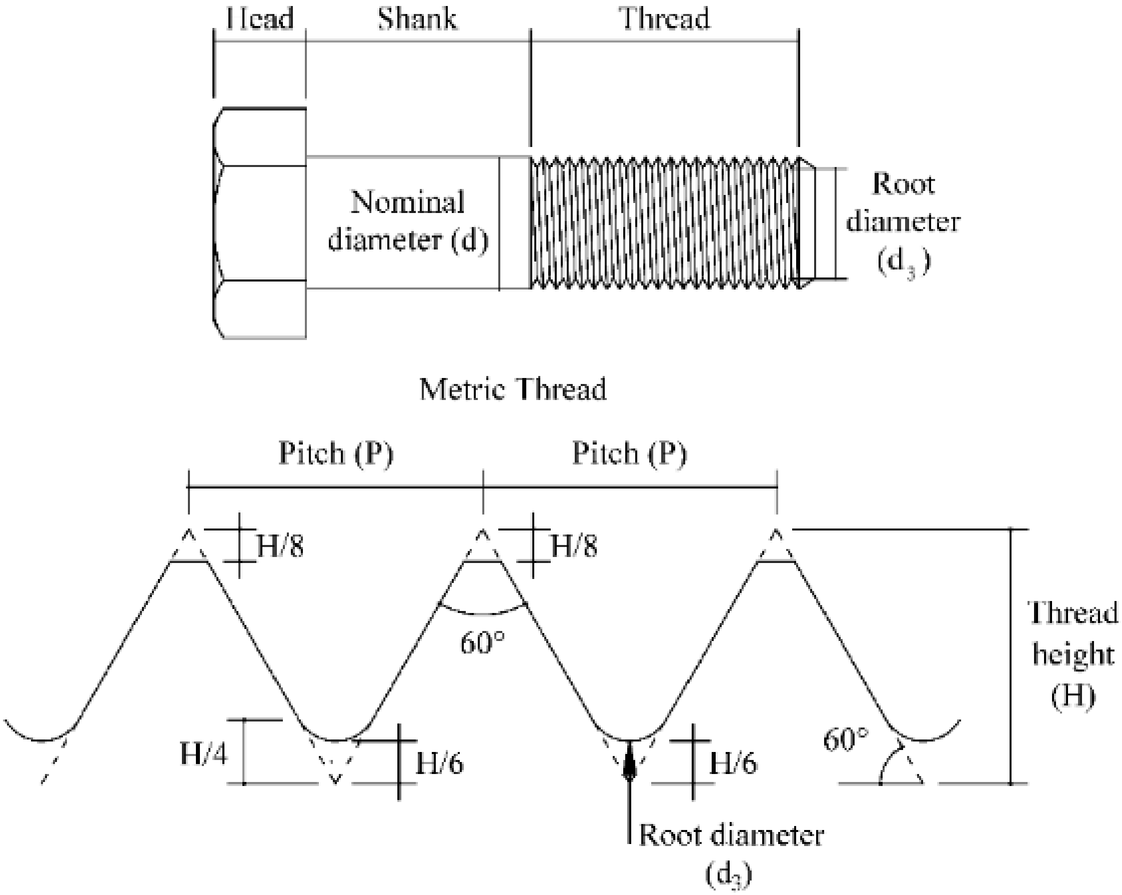

Figure 1. *Bolt Terminology and Standard Metric Bolt Profile*

Table 1. *ISO General Purpose Metric Screw Threads (TS 61-2, 2016)*

Nominal Diameter *d* (mm)	Pitch Length *P* (mm)	Root Diameter d_3 (mm)	Nominal Diameter *d* (mm)	Pitch Length *P* (mm)	Root Diameter d_3 (mm)
6	1.00	4.773	**27**	3.00	23.319
7	1.00	5.773	**30**	3.50	25.706
8	1.25	6.466	**33**	3.50	28.706
9	1.25	7.466	**36**	4.00	31.093
10	1.50	8.160	**39**	4.00	34.093
11	1.50	9.160	**42**	4.50	36.479
12	1.75	9.853	**45**	4.50	39.479
14	2.00	11.546	**48**	5.00	41.866
16	2.00	13.546	**52**	5.00	45.866
18	2.50	14.933	**56**	5.50	49.252
20	2.50	16.933	**60**	5.50	53.252
22	2.50	18.933	**64**	6.00	56.639
24	3.00	20.319	**68**	6.00	60.639

Table 2. *Inch Based American Screw Threads (AISC, 2016)*

Nominal Diameter *d* (in)	Threads per inch *n*	Root Diameter d_3 (in)	Nominal Diameter *d* (in)	Threads per inch *n*	Root Diameter, d_3 (in)
1/4	20	0.196	**1-3/4**	5	1.530
3/8	16	0.307	**2**	4.5	1.760
1/2	13	0.417	**2-1/4**	4.5	2.010
5/8	11	0.527	**2-1/2**	4	2.230
3/4	10	0.642	**2-3/4**	4	2.480
7/8	9	0.755	**3**	4	2.730
1	8	0.865	**3-1/4**	4	2.980
1-1/8	7	0.970	**3-1/2**	4	3.230
1-1/4	7	1.100	**3-3/4**	4	3.480
1-3/8	6	1.190	**4**	4	3.730
1-1/2	6	1.320			

note: 1 in = 25.4 mm

Thus, latest AISC (2016) manual recommends working with the nominal diameter instead of the root diameter for convenience. Additionally, effect of the root diameter is taken into account as reduced rupture strength (F_u) of the bolt material. Accordingly, 0.75 F_u taken as the nominal tensile strength of fasteners subjected to tension and 0.45 F_u taken as the nominal shear strength of fasteners when threads are not excluded from shear plane. Indeed, tensile strength of material is multiplied by 0.6 for shear strength according to Von Mises yield criterion. On the other hand, Turkish Specification ÇYHY (2016) adopted also the same approach with the same equations. However, it is thought that such an approach does not represent the actual behavior even if give safe results. Moreover, while AISC (2016) deals with the Unified Thread Standard (ASME, 2011), ÇYHY (2016) deals with the ISO Standard Metric screw thread (TS 61-2, 2016). Screw thread features of these standards are different as mentioned before. Compatibility of AISC (2016) approach is questionable for Standard Metric bolts.

Consequently, in order to use the material more efficiently and to recommend a practical and memorable equation, a numerical study was conducted. Equations were proposed for both Standard Metric and Inch Based American screw threads. Additionally, the accuracy of the equation was discussed and compared with the existing rule of thumb. This rule of thumb basically says to multiply nominal diameter by 0.86 to obtain root diameter ($d_3 = 0.86\ d$) for each case (Odabaşı, 2000; Salmon et al., 2008).

2. MATERIAL AND METHOD

Metric bolt nominal diameters and their corresponding actual root diameters were plotted together as shown in Figure 2. Nominal diameters include bolts from M6 to M68 and values were taken from Table 1. It was seen that increasing trend is in a steady rate. Best-fit straight line (linear trend line) was drawn to resemble the data. The equation of this line was calculated ($y=0.897x-0.8744$) and illustrated in Figure 2. A trend line is most reliable when its R-squared value is at or close to one. Accordingly, R-squared value calculated for this equation was 0.9998 (Figure 2). However, obtained equation was not easy to memorize. On the other hand, such precise equation is not required for the design of steel structures. Thus, obtained equation was rounded and simplified as in Eq. 3.

$$\mathrm{d}_3 = 0.9\ (\mathrm{d} - 1) \qquad \text{(mm)} \tag{3}$$

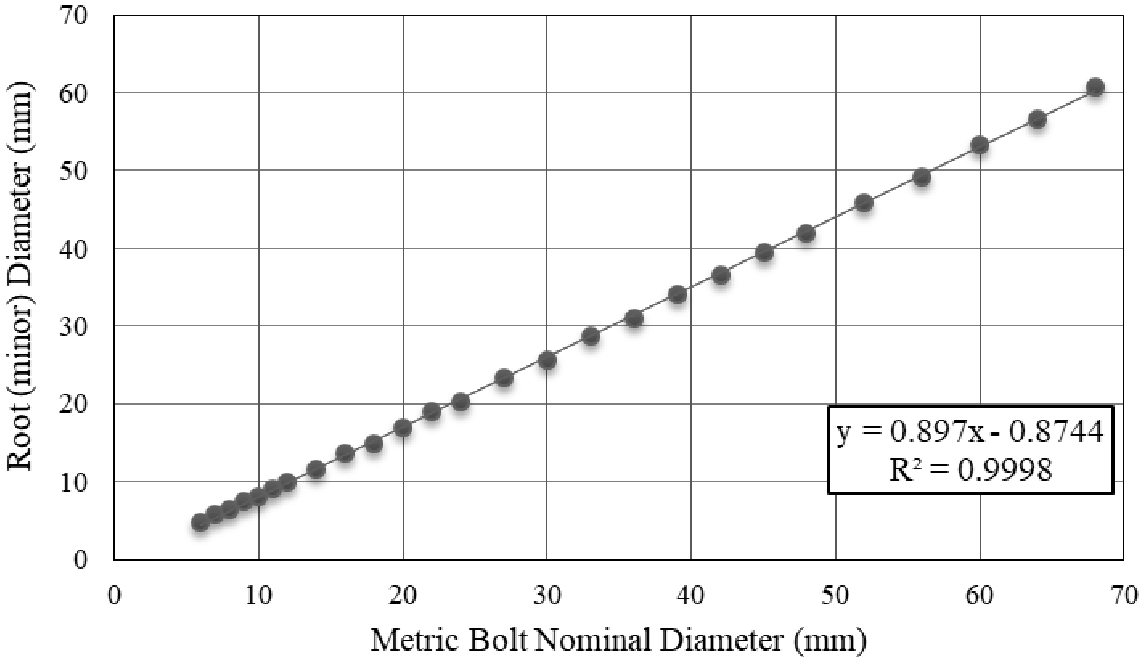

Figure 2. *Linear Trend Line of Metric Bolts*

Afore mentioned same procedure was applied to available Inch Based American bolts which were summarızed in Table 2. The equation of the trend line was calculated as *y=0.9381x-0.0739* with an R-squared value of 0.9994 and illustrated in Figure 3. Derived equation was again rounded and simplified as in Eq. 4.

$$\mathrm{d_3} = 0.94\left(\mathrm{d} - \frac{1}{12}\right) \quad \text{(in)} \tag{4}$$

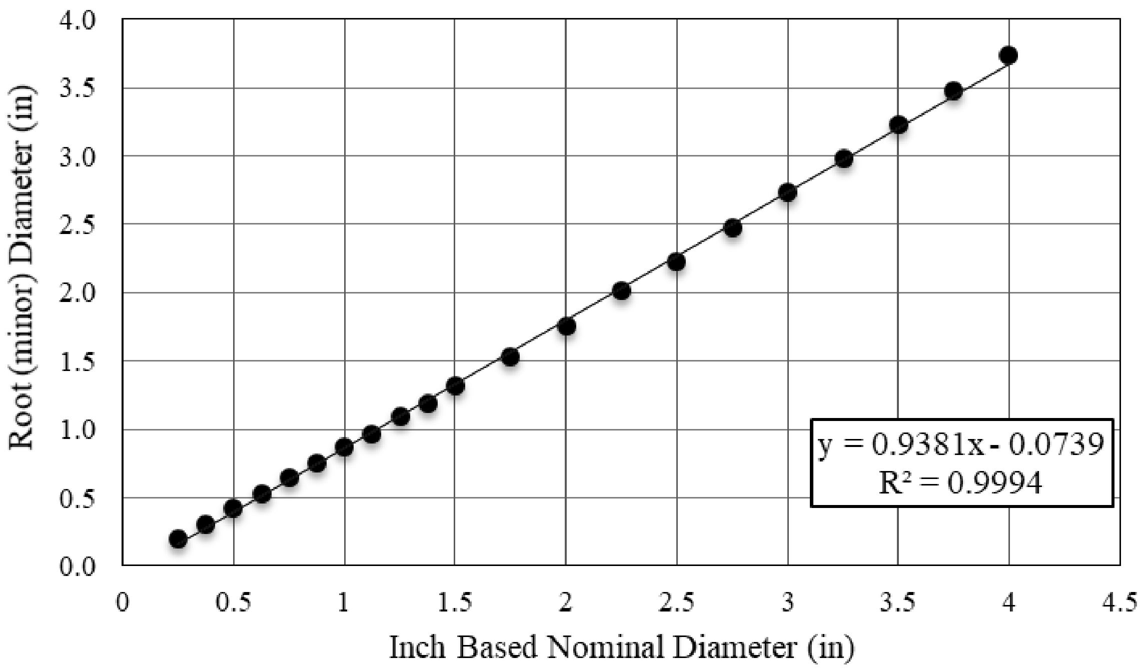

Figure 3. *Linear Trend Line of Inch Based American Bolts*

3. DISCUSSION AND CONCLUSIONS

Initially, root diameters were calculated by the proposed equations (Eq.3 and Eq.4) and the rule of thumb ($d_3=0.86\ d$). Thus, diagrams for both Standard Metric (Figure 4) and Inch Based American (Figure 5) screw threads were plotted and indicated together with the actual root diameters to make explicit comparisons. Additionally, results were summarized in Table 3 and Table 4. Percent error was computed as the actual root diameter minus the calculated root diameter, divided by the actual root diameter and multiplied by 100%. In other words, absolute value was not applied to be able to asses from an engineering point of view.

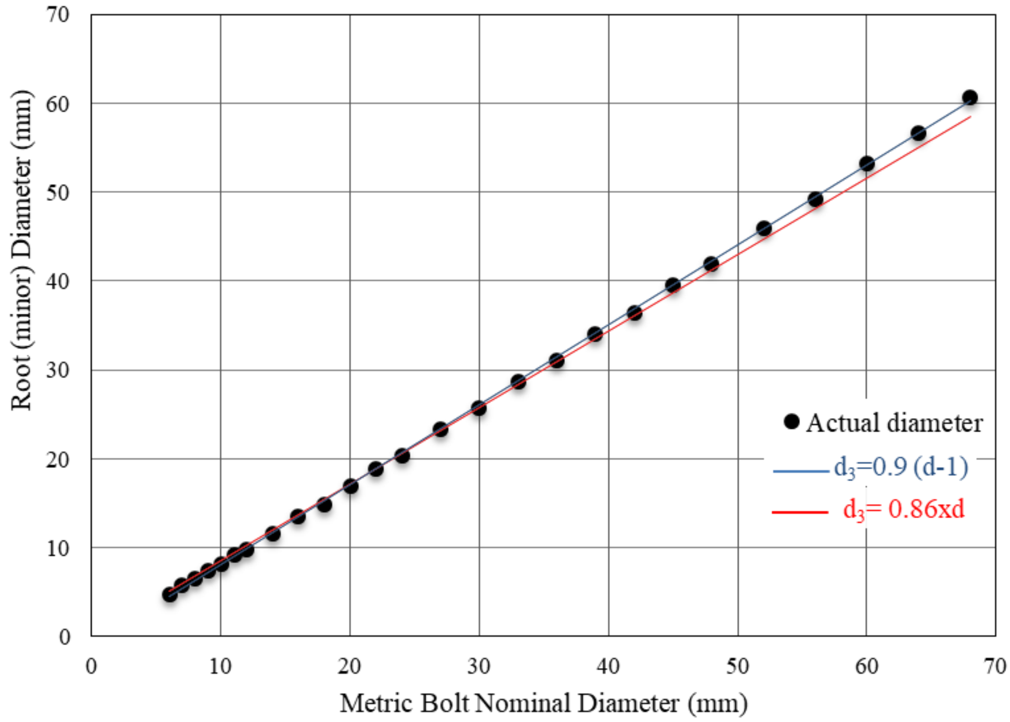

Figure 4. *Comparison Diagram for Metric Bolts*

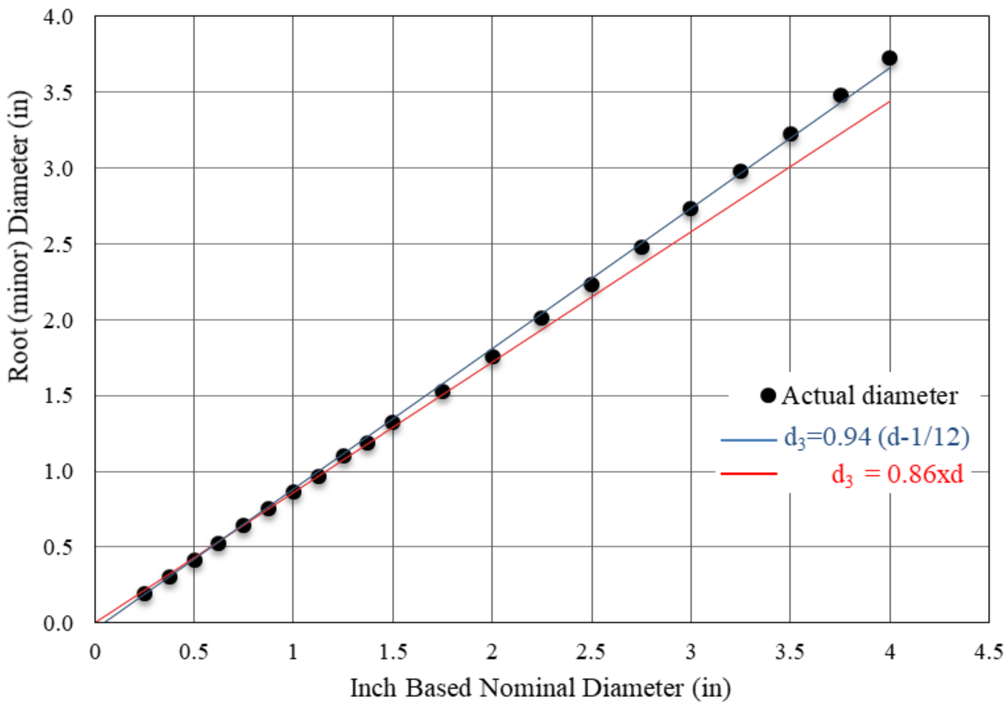

Figure 5. *Comparison Diagram for Inch Based American Bolts*

For Standard Metric screw threads, while proposed equation error varied between the values of +6.5% and -2.5%, the rule of thumb equation varied between +3.6% and -8.6%. Accordingly, proposed equation varied in more closer and smaller range. On the other hand, ÇYHY (2016) permits minimum of M12 bolts for structural steel connections. If diameters smaller than the M12 were excluded from the evaluation, error varied between +0.6% and -2.5% for the proposed equation. These values are +3.6% and -4.7% for the rule of thumb approach (Table 3). In addition, superiority of the proposed equation is more obvious for bolts larger than M36 (Figure 4). Error mean value, standard deviation, and coefficient of variation were calculated as -1.0, 3.2, and 311.4% for the rule of thumb, respectively. Estimation power of the Eq.3 was better and the same statistical values were 0.3, 2.1, and 683.1%.

Table 3. *Results of the Proposed Equation for Metric Bolts*

Nominal diameter (mm)	Actual d_3 (mm)	d_3 with proposed equation (mm)	Error in proposed equation (%)	$d_3= 0.86d$ (mm)	Error in $d_3= 0.86d$ equation (%)
6	4.773	4.5	5.7	5.2	-8.1
7	5.773	5.4	6.5	6.0	-4.3
8	6.466	6.3	2.6	6.9	-6.4
9	7.466	7.2	3.6	7.7	-3.7
10	8.160	8.1	0.7	8.6	-5.4
11	9.160	9.0	1.7	9.5	-3.3
12	9.853	9.9	-0.5	10.3	-4.7
14	11.546	11.7	-1.3	12.0	-4.3
16	13.546	13.5	0.3	13.8	-1.6
18	14.933	15.3	-2.5	15.5	-3.7
20	16.933	17.1	-1.0	17.2	-1.6
22	18.933	18.9	0.2	18.9	0.1
24	20.319	20.7	-1.9	20.6	-1.6
27	23.319	23.4	-0.3	23.2	0.4
30	25.706	26.1	-1.5	25.8	-0.4
33	28.706	28.8	-0.3	28.4	1.1
36	31.093	31.5	-1.3	31.0	0.4
39	34.093	34.2	-0.3	33.5	1.6
42	36.479	36.9	-1.2	36.1	1.0
45	39.479	39.6	-0.3	38.7	2.0
48	41.866	42.3	-1.0	41.3	1.4
52	45.866	45.9	-0.1	44.7	2.5
56	49.252	49.5	-0.5	48.2	2.2
60	53.252	53.1	0.3	51.6	3.1
64	56.639	56.7	-0.1	55.0	2.8
68	60.639	60.3	0.6	58.5	3.6

Table 4. *Results of the proposed equation for Inch Based American Bolts*

Nominal diameter (in)	Actual d_3 (in)	d_3 with proposed equation (in)	Error in proposed equation (%)	$d_3= 0.86d$ (in)	Error in $d_3= 0.86d$ equation (%)
1/4	0.196	0.157	20.1	0.215	-9.7
3/8	0.307	0.274	10.7	0.323	-5.0
1/2	0.417	0.392	6.1	0.430	-3.1
5/8	0.527	0.509	3.4	0.538	-2.0
3/4	0.642	0.627	2.4	0.645	-0.5
7/8	0.755	0.744	1.4	0.753	0.3
1	0.865	0.862	0.4	0.860	0.6
1-1/8	0.970	0.979	-0.9	0.968	0.3
1-1/4	1.100	1.097	0.3	1.075	2.3
1-3/8	1.190	1.214	-2.0	1.183	0.6
1-1/2	1.320	1.332	-0.9	1.290	2.3
1-3/4	1.530	1.567	-2.4	1.505	1.6
2	1.760	1.802	-2.4	1.720	2.3
2-1/4	2.010	2.037	-1.3	1.935	3.7
2-1/2	2.230	2.272	-1.9	2.150	3.6
2-3/4	2.480	2.507	-1.1	2.365	4.6
3	2.730	2.742	-0.4	2.580	5.5
3-1/4	2.980	2.977	0.1	2.795	6.2
3-1/2	3.230	3.212	0.6	3.010	6.8
3-3/4	3.480	3.447	1.0	3.225	7.3
4	3.730	3.682	1.3	3.440	7.8

note: 1 in = 25.4 mm

For Inch Based American screw threads, while proposed equation error varied between +20.1% and -2.4%, the rule of thumb equation varied between +7.8% and -9.7%. At first, a deviation of +20.1% can be considered to be quite high. However, AISC (2016) does not take into account bolt diameters smaller than the ½ in (12.7 mm). If bolts smaller than the ½ in (12.7 mm) were excluded from the discussion, error varied between +6.1% and -2.4% for the proposed equation. These values are +7.8 % and -3.1% for the rule of thumb approach (Table 4). Superiority of the proposed equation was more obvious in terms of statistical variations. Error mean value, standard deviation, and coefficient of variation were calculated as 2.6, 4.3, and 162.6% for the rule of thumb, respectively. Estimation power of the Eq.4 was better and the same statistical values were 0.2, 5.2, and 2766%. It should be noted that coefficient of variation is 17 times higher for the proposed equation.

Consequently, it is claimed that both practical and memorable linear equations could be proposed with a sufficient accuracy for the root dimensions of Standard Metric and Inch Based American bolts. Here, sufficient accuracy refers to the design of structural steel connections and in this case error percentage can be considered negligible. However, if the design of special structures or devices needs more precise data, actual values should be taken from the tables.

Proposed equations resulted much better than the well-known rule thumb. Latest specifications, AISC (2016) and ÇYHY (2016), consider available least ratio of the root diameter to nominal diameter for convenience. The proposed equations can be easily adapted to specifications in order to use the material more efficiently. Since the cross section is proportional to the square of the diameter, the cost can be reduced significantly.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

REFERENCES

AISC (2016). 15th Ed. Steel Construction Manual. American Institute of Steel Construction, USA.

ASME (2011). ASME B1.1-1989. Unified Inch Screw Threads (UN. UNR. and UNJ Thread Forms). The American Society of Mechanical Engineers, New York, USA.

ÇYHY (2016). Çelik Yapıların Tasarım, Hesap ve Yapımına Dair Esaslar. Ministry of Environment and Urbanization, Ankara, Turkey.

ISO (1998). ISO 68-1. ISO General Purpose Screw Threads, Basic Profile Part 1: Metric Screw Threads. The International Organization for Standardization, Geneva, Switzerland.

Odabaşı, Y. (2000). Ahşap ve Çelik Yapı Elemanları (3rd ed.). Beta Press & Publications, İstanbul, Turkey.

Salmon, C. G., Johnson, J. E., & Malhas, F. A. (2008). Steel Structures: Design and Behavior (5th ed.). Pearson Education, New Jersey, USA.

TSE (2016). TS 61-2. Vida Dişleri- ISO Genel Amaçlı. Metrik- Bölüm 2, Normal Adımlı- Anma Çapı 1 mm - 68 mm Olan Vida Dişleri için Anma Ölçüleri. Turkish Standards Institution, Ankara, Turkey.