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Effect of Water Depth Change on Manning Coefficient for Partially-Filled Circular Culverts

تأثير تغيير أعماق المياه على معامل ماننج للبرابخ الدائرية المملوءة جزئيا

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الملخص

يعتبر البربخ أفضل منشأ فى حالة تقاطع مجرى مائى مع طريق وذلك لانه اقل تكلفة فى الانشاء مقارنة بالكبارى ومن اهم المعادلات المستخدمه فى حساب التصرف هى معادلة ماننج والتى تتأثر جدا بقيمة معامل ماننج والذى يعتمد على عدة عوامل من اهمها العمق والتصرف ولكن الابحاث السابقة لم تهتم بدراسة معامل ماننج تحت عمق نسبى مقداره 25% من القطر الداخلى للماسورة لذلك تم التركيز خلال الدراسة الحالية على الاعماق اقل من أو تساوى 25% من العمق الكلى للماسورة.

ولتحقيق أهداف البحث تم إختيار اربعة برابخ دائرية الشكل اثنتان مصنوعة من الخرسانة المسلحة واثنتان من الحديد الزهر على ترع الفاروقية وبشبيش وميت السراج بالمحلة الكبرى – محافظة الغربية - جمهورية مصر العربية كنموذج للدراسة وباستخدام جهاز قياس سرعة وتصرف الكتروني تم قياس السرعة علي مناسيب مختلفة وتم التوصل الى مايلى:

1. معامل ماننج يتغير بتغير العمق النسبى للمياه داخل الماسورة.
2. القيم الناتجة لمعامل ماننج للبرابخ المختبرة توافقت مع القيم المرجعية لها.
3. تم استنتاج علاقة جديدة تربط بين معامل ماننج النسبى والعمق النسبى للاعماق النسبية الاقل من أو تساوى 25% للبرابخ المختلفة فى الميول ومادة الصنع وتم مقارنتها بالمعادلات المنستنتجة سابقا ووجدت ان نسب الخطأ بها أقل بكثير من المعادلات السابقة.

Abstract

Culvert is a structure used to convey surface runoff through embankments. The circular is the popular section for design pipes, such as culverts, drain tiles and sewers of small and medium sizes. Also it may be made of concrete, steel, corrugated metal and polyethylene. Manning's equation is most commonly used throughout the world for the purpose of computing flow velocities in open channel. Manning roughness coefficient is one of the effective factors on water velocity and discharge. The present study is about the determination of the relation between relative depth and relative roughness for circular culvert. For this purpose, field work was carried out on four pipe culverts on canals at El-Mahalla El kubra, Egypt. The culverts are of different diameters, slopes and materials. The velocity is recorded by using FlowTracker. Manning roughness coefficient greatly varied with the variation of relative depth, surface roughness and discharge. For four culverts, a total of 143 depth data points were collected at different discharges ranging from 0.004 to 4.750 m^3/sec. New equations are developed for relation between the relative depth (d/D) and the relative roughness (n/n_f) for flow depths less than 25% full for four pipe culverts on El Mahalla El Kubra, Egypt, when the water geometries are given.

Keywords:

Manning’s coefficient, Manning’s equation, open channel, culvert, pipe, relative depth, and relative roughness.

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1. Introduction

Manning's equation was introduced by the Irish Engineer Robert Manning in 1889, Chow [1]. It is an empirical equation that applies to uniform flow in open channels and is a function of the channel velocity, flow area and channel slope. Manning's equation formula is:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (1)$$

Where V = mean velocity, n = the Manning's roughness coefficient, R = the hydraulic radius and S = the bed slope.

Major factors affecting Manning's roughness coefficient are, surface roughness, vegetation, channel irregularity, channel alignment, silting and scouring, obstruction, size and shape of channel, stage and discharge, seasonal change, suspended material and bed load.

Yarnell and Woodward [2] carried out their research on clay and concrete drain tile with diameter from 4 to 12 inches with slopes from 0.05 to 1.5%. Their study was not based on Manning's roughness n but on the Kutter n and the Chezy C coefficient. **Camp [3]** developed the partial full flow investigations of Wilcox and Yarnell and Woodward with research investigation circular sewer pipe designed to flow partially full. He noted that the researches of Yarnell and Woodward include data indicating Manning's roughness values at pipes under partial flow greater than at full flow. Camp's work led to the curve, which shows the variation of Q/Q_{full}, V/V_{full}, and n/n_{full} as functions of the ratio of depth of flow to pipe diameter (y/D). V_{full} and Q_{full} can be calculated for full pipe flow conditions in a given pipe with the Manning equation. **In 1951, Straub and Morris [4]** carried out a research on corrugated circular and the pipe arch culverts. In circular case they applied their application on diameter pipe sections were 18, 24 and 36 inch with 193 ft long and lay on a slope of 0.2%. They noted that Manning's roughness coefficient decreased as diameters increased for a relative depth. From Straub and Morris curve's it was noticed that decreasing relative depth does not vary with relative roughness values. **In 1954, Cosens [5]** carried out a research on asbestos cement and vitrified clay with diameter 8 inch and slopes of 0.25 and 0.4%. He noted that the velocity at 50% capacity and full flow was not equal. He also noted that the slope of the energy grade line increases the roughness increasing. **In 1964, Neale and Price [6]** carried out their research on polyvinyl chloride pipe (PVC) with diameter 8 and 12 inch and slopes of 0.3, 0.6 and 1% under both partially full and full flow. From their curve it is clear that relative depth decreases while the relative roughness remains approximately constant and independent of the velocity. **In 1967, Pomeroy [7]** confirmed that the n value is a coefficient in an empirical equation and it is defined as a mathematical function of the variables of the equation. He calculated Manning's roughness for the individual depth measurements and took the average ignoring the data points for which the Froude numbers were between 0.9 and 1.4. He collected the data in 21 existing sewer lines. The total number of data points collected by him below 20% relative depth was 78 and the maximum relative depth attained during his experiment was 69.9%. He did not end up calculating full flow Manning's roughness for the sewers because full flow was never attained in those sewer lines.

In 1986, Barr and Das [8] proposed two explicit equations for h/D but did not indicate how velocity V showed be calculated. **Saatçı (1990, 1992) [9, 10]** proposed another two explicit solutions for θ and calculated the flow depth h/D and velocity V. **In 1993 Esen [11]** proposed new two explicit solutions calculated the flow depth h/D and velocity V. **In 1994 Li [12]** proposed two explicit solutions for θ and calculated the slope S. **1998, Zaghloul [13]** showed that the roughness value n for a pipe partially full is greater than the roughness value *n* for full flow conditions. **Giroud et al. (2000) [14]** proposed direct estimation of *V* (without calculating θ or *h/D* first). **Akgiray (2004) [15]** reviewed types of problems that require iterative calculations and explicit solutions proposed in the literature as:

I . Given *Q, D,* and *S*, find, *h/D* and (or) *V*; and

II .Given *Q, D,* and *V*, find, *h/D* and (or) *S*

He reexamined type I and type II problems and found that Camp's curve was well represented by a new and simpler alternative equation. He developed a single relation to replace the two Saatçı equations given before him. **Akgiray (2005) [16]** improved new equations for two other types of problem as:

- Given *V, D,* and *S,* find, *d/D* and (or) *Q*; and
- Given *Q, V,* and *S,* find, *d/D* and (or) *D*.

In 2009, From American Concrete Pipe Association [17] presented a method for determination the values of the partial flow depth and velocity in circular concrete pipe. **In 2010, Mangin [18]** used the previous data to develop an equation to predict water depth inside of partially circular culverts independently from the Manning's equation. The new equation predicts depth more frequently and with greater accuracy than the Manning's equation for the data analyzed and is therefore, a more consistent method when used to design and assess culverts for fish passage. This equation to predict depth *(d)* for a circular culvert, based on discharge *(Q)*, slope *(S)*, diameter *(D)*, gravity *(g)* and absolute material roughness *(Ks)*, has been developed. The new equation reduces the absolute mean error in calculating water depth by 37% compared to the previously published data. **In 2012, Devkota [19]** said that previous researchers have found that the Manning's roughness for partial flows is greater than full flow but inadequate data were collected for flows less than 20% full. So he tried to collect water depth data in HDPE culverts and to derive a relation between Manning's roughness and relative depth with a 4ft x 2ft flume of 60ft length, three test culverts of diameter 1ft, 2ft and 3.5ft were tested with the discharge ranging from 0.2 to 10.3cfs at bed slopes of 0.2 to 2%. He showed that the Manning's roughness coefficient varied with diameter, relative depth, slope and discharge. Also he showed that with the increase in the slope of energy grade line, the Manning's roughness coefficient also increases. Devkota [19] found that between 20% and 40% relative depth the partial flow roughness was found to be roughly equal to the full flow roughness. The results further indicate that the peak Manning's roughness coefficient for partial flow in the 1, 2 and 3.5ft diameter culvert was 0.011 and occurred at about 27.5% of the full flow. The fact that below 20% depth, the Manning's roughness coefficient is smaller than the design roughness (full flow roughness) causes the flow velocity to be higher than predicted or designed. Similarly from 20 to 40% full, the culvert has higher roughness indicating lower velocity than otherwise would be predicted.

In 2012, Toews and Clark [20] carried out their research on CMP (corrugated metal pipe) culvert with diameter 0.8 m of 21 m long and the culvert was supported on a series of adjustable yokes to allow slope adjustment. They measured relative depths ranged from 0.03 to 0.67 for each of the tested slopes (0.04, 0.14, 0.27, 0.49 and 0.75%). Therefore a set of equations were developed, using a least squares regression for the variation in Manning's n. They noted that their equations did not give satisfactory results for the flow depth below relative depth of 0.2 so that they used Mangin's dimensionless parameters S and $Q\big/\sqrt{gD^5}$. In 2012**, Bengtson [21]** gave an equation for relative roughness value n/n_f for a pipe partially full.

The goal of this study is to investigate the effect of variation of water depth in types of culvert materials available and to determination a relation between Manning’s roughness coefficient and relative depth. The water depth profile was measured within culverts with varying discharge, slope and diameter. Discharge and depth thus collected were used to calculate Manning’s roughness coefficient. The coefficients were then compared to the full flow roughness reported for steel and concrete culverts by Chow [1].

2. Field Work

Manning's roughness coefficient in culvert changes with water depth, discharge, diameter, slope and culvert's surface roughness. The field work was used to conduct experiments that would determine the variation of Manning's roughness coefficient with relative depth. Concrete and steel culverts were studied because it is the most common types of culvert materials. Most of the previous investigators did not use the steel culvert in their researches. Culverts under consideration are constructed at EL-Farokya, Beshbesh and Meet EL-Serag canals. The tested culverts are circular. The diameters of the test culverts were 1.0, 1.4, 1.7, 2.0m with four different slopes 0.001, 0.003, 0.0017 and 0.00125 respectively.

The measurements quantities were discharge and water depth in the culvert. Upstream the canal intake, control gate was installed to limit the discharge of water into the culvert. The tested culverts are defined with each location km on canal, material, diameter, length, upstream and downstream bed level and slope as shown in Table (1).

Table (1) Illustration of Bed Slopes and Locations of Culverts

Culvert Site	1	2	3	4
Canal Name	EL-Farokya	Beshbesh	Met EL-Serag	Met EL-Serag
Km	2.400	3.250	6.750	5.000
Material	Concrete	Concrete	Steel	Steel
Diameter (m)	1.0	1.4	1.7	2.0
Length (m)	10	6	6	8
Upstream Bed Level	(2.51)	(1.82)	(2.16)	(2.27)
Downstream Bed Level	(2.50)	(1.80)	(2.15)	(2.26)
Slope	0.001	0.003	0.0017	0.00125

2.1. Experimental Measurements

Field data have been collected at four different sites. For the first culvert, thirty-one sections were chosen, for the second culvert, thirty-nine sections were chosen.

As, for third culvert, forty-one sections were chosen and thirty-three sections were chosen for fourth one. The field measurements were water depths and velocities.

2.1.1. Water depth

Water surface varied with the control discharge gate. For each discharge, water depth was measured.

For these experiments, water depth in the culvert was measured by scalar rod. Measurements are taken when the situation is steady and the water levels are stable.

2.1.2. Mean Velocity

The culvert cross section was divided into sections, as shown in Fig. (1).

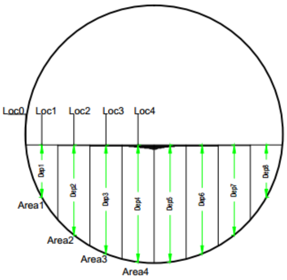

Figure (1) Divisions the Culvert Cross Section into Station

In the present study, the mean sectional station velocity was determined by measuring the velocity at 0.6 of the depth in each vertical ($V_{mean} = V_{0.6}$), or, where more reliable results were required, by taking the average of the velocities at 0.2 and 0.8 the depth ($V_{mean} = \left(V_{0.2} + V_{0.8}\right)/2$). For the culvert cross section, series of velocity measurements were taken at different locations for each water depth using the FlowTracker. The mean velocity was determined at that station for more depths.

2.1.3 Experimental Results

Field data have been collected at four different culverts sites.

All measurements are tabulated in Tables (2) to (5)

Table (2) Measurements of Water Depths and Mean Velocities for Concrete Culvert

D = 1.0m, Q_f = 2.053m^3/s and S = 0.001				D = 1.0m, Q_f = 2.053m^3/s and S = 0.001			
Run No.	d (m)	d/D	V_{mean} (m/s)	Run No.	d (m)	d/D	V_{mean} (m/s)
1	0.05	0.05	0.2997	17	0.50	0.50	0.8313
2	0.10	0.10	0.4281	18	0.53	0.53	0.8553
3	0.12	0.12	0.4665	19	0.55	0.55	0.8685
4	0.15	0.15	0.5262	20	0.57	0.57	0.8628
5	0.20	0.20	0.5865	21	0.60	0.60	0.8748
6	0.22	0.22	0.6111	22	0.63	0.63	0.9147
7	0.25	0.25	0.6438	23	0.65	0.65	0.8904
8	0.28	0.28	0.6639	24	0.67	0.67	0.9114
9	0.30	0.30	0.6903	25	0.70	0.70	0.9057
10	0.33	0.33	0.7218	26	0.74	0.74	0.9429
11	0.35	0.35	0.7227	27	0.76	0.76	0.9282
12	0.37	0.37	0.7479	28	0.80	0.80	0.9789
13	0.40	0.40	0.7524	29	0.86	0.86	0.9915
14	0.42	0.42	0.7503	30	0.90	0.90	1.0338
15	0.45	0.45	0.7824	31	0.97	0.97	1.0533
16	0.47	0.47	0.8073				

Table (3) Measurements of Water Depths and Mean Velocities for Concrete Culvert

D = 1.4m, Q_f = 0.82m^3/s and S = 0.003				D = 1.4m, Q_f = 0.82m^3/s and S = 0.003			
Run No.	d (m)	d/D	V_{mean} (m/s)	Run No.	d (m)	d/D	V_{mean} (m/s)
1	0.07	0.05	0.4116	21	0.62	0.44	0.9545
2	0.10	0.07	0.4871	22	0.65	0.46	0.9747
3	0.12	0.09	0.5330	23	0.67	0.48	1.0116
4	0.15	0.11	0.5952	24	0.70	0.50	1.0248
5	0.20	0.14	0.6114	25	0.73	0.52	1.0646
6	0.23	0.16	0.6447	26	0.75	0.54	1.0871
7	0.27	0.19	0.6815	27	0.79	0.56	1.1067
8	0.30	0.21	0.7179	28	0.82	0.59	1.1302
9	0.33	0.24	0.7442	29	0.86	0.61	1.1132
10	0.35	0.25	0.7732	30	0.87	0.62	1.1346
11	0.38	0.27	0.7947	31	0.90	0.64	1.1466
12	0.40	0.29	0.8322	32	0.97	0.69	1.2032
13	0.43	0.31	0.8481	33	1.00	0.71	1.1838
14	0.45	0.32	0.8541	34	1.15	0.82	1.2448
15	0.47	0.34	0.8583	35	1.20	0.86	1.3013
16	0.50	0.36	0.8935	36	1.25	0.89	1.3153
17	0.52	0.37	0.8975	37	1.30	0.93	1.3319
18	0.55	0.39	0.9131	38	1.35	0.96	1.3355
19	0.58	0.41	0.9480	39	1.39	0.99	1.3353
20	0.60	0.43	0.9385				

Table (4) Measurements of Water Depths and Mean Velocities for Steel Culvert

D = 1.7m, Q_f = 3.19m^3/s and S = 0.0017				D = 1.7m, Q_f = 3.19m^3/s and S = 0.0017			
Run No.	d(m)	d/D	V_{mean}(m/s)	Run No.	d (m)	d/D	V_{mean}
1	0.10	0.06	0.5662	21	0.74	0.44	1.0873
2	0.12	0.07	0.5842	22	0.78	0.46	1.1728
3	0.14	0.08	0.6036	23	0.80	0.47	1.1870
4	0.17	0.10	0.6353	24	0.85	0.50	1.1777
5	0.20	0.12	0.6885	25	0.88	0.52	1.1958
6	0.27	0.16	0.7871	26	0.92	0.54	1.2138
7	0.30	0.18	0.8029	27	0.96	0.56	1.2140
8	0.32	0.19	0.8180	28	1.00	0.59	1.2318
9	0.36	0.21	0.8338	29	1.10	0.65	1.2478
10	0.40	0.24	0.8704	30	1.15	0.68	1.2856
11	0.43	0.25	0.8446	31	1.20	0.71	1.3416
12	0.46	0.27	0.8703	32	1.25	0.74	1.3421
13	0.50	0.29	0.8883	33	1.32	0.78	1.3579
14	0.53	0.31	0.8974	34	1.38	0.81	1.3738
15	0.55	0.32	0.9245	35	1.43	0.84	1.3950
16	0.58	0.34	0.9618	36	1.48	0.87	1.4157
17	0.60	0.35	0.9778	37	1.52	0.89	1.4316
18	0.63	0.37	0.9964	38	1.55	0.91	1.3766
19	0.65	0.38	1.0433	39	1.60	0.94	1.3961
20	0.70	0.41	1.0799	40	1.67	0.98	1.4111

Table (5) Measurements of Water Depths and Mean Velocities for Steel Culvert

D = 2.0m, Q_f = 4.75m^3/s and S = 0.00125				D = 2.0m, Q_f = 4.75m^3/s and S = 0.00125			
Run No.	d (m)	d/D	V_{mean} (m/s)	Run No.	d (m)	d/D	V_{mean} (m/s)
1	0.07	0.04	0.4635	18	0.76	0.38	1.2283
2	0.10	0.05	0.5644	19	0.83	0.42	1.3168
3	0.12	0.06	0.6250	20	0.90	0.45	1.3283
4	0.15	0.08	0.7056	21	0.95	0.48	1.3681
5	0.18	0.09	0.7660	22	1.00	0.50	1.3950
6	0.20	0.10	0.8046	23	1.10	0.55	1.4552
7	0.22	0.11	0.8414	24	1.15	0.58	1.4306
8	0.25	0.13	0.9052	25	1.20	0.60	1.4720
9	0.30	0.15	0.9847	26	1.30	0.65	1.4898
10	0.33	0.17	1.0241	27	1.40	0.70	1.4894
11	0.35	0.18	1.0532	28	1.50	0.75	1.4921
12	0.40	0.20	1.1086	29	1.65	0.83	1.4892
13	0.42	0.21	1.1251	30	1.70	0.85	1.4978
14	0.45	0.23	1.1673	31	1.80	0.90	1.4796
15	0.50	0.25	1.2076	32	1.90	0.95	1.5140
16	0.60	0.30	1.2700	33	1.98	0.99	1.5144
17	0.70	0.35	1.2579				

3. Mathematical Model

From Manning's formula, Manning's roughness coefficient is a function of discharge Q, depth d, diameter D and slope S. Velocities and depths thus collected were used to calculate Manning's roughness coefficient. To apply the Manning’s equation, it is need to calculate the cross section geometric properties, cross section area (A), wetted perimeter (P), and hydraulic radius (R).

3.1. Geometric Parameters

There are two materials were used in culvert pipe: concrete and steel with four different diameters (1, 1.4, 1.7, 2m) with four slopes (0.001, 0.003, 0.0017 and 0.00125). Geometric parameters calculated were cross section area, wetted perimeter and hydraulic radius. Geometric parameters are shown in Tables (6) to (9).

Table (6) Geometric Parameters for Concrete Culvert with 1.0m Diameter

No. of Sec.	d (m)	A (m^2)	P (m)	R (m)	No. of Sec.	d (m)	A (m^2)	P (m)	R (m)
1	0.05	0.0147	0.4510	0.0326	17	0.50	0.3927	1.5708	0.2500
2	0.10	0.0409	0.6435	0.0635	18	0.53	0.4227	1.6308	0.2592
3	0.12	0.0534	0.7075	0.0755	19	0.55	0.4426	1.6710	0.2649
4	0.15	0.0739	0.7954	0.0929	20	0.57	0.4625	1.7113	0.2703
5	0.20	0.1118	0.9273	0.1206	21	0.60	0.4920	1.7722	0.2776
6	0.22	0.1281	0.9764	0.1312	22	0.63	0.5212	1.8338	0.2842
7	0.25	0.1535	1.0472	0.1466	23	0.65	0.5404	1.8755	0.2881
8	0.28	0.1800	1.1152	0.1614	24	0.67	0.5594	1.9177	0.2917
9	0.30	0.1982	1.1593	0.1709	25	0.70	0.5872	1.9823	0.2962
10	0.33	0.2260	1.2239	0.1847	26	0.74	0.6231	2.0715	0.3008
11	0.35	0.2450	1.2661	0.1935	27	0.76	0.6405	2.1176	0.3024
12	0.37	0.2642	1.3078	0.2020	28	0.80	0.6736	2.2143	0.3042
13	0.40	0.2934	1.3694	0.2142	29	0.86	0.7186	2.3746	0.3026
14	0.42	0.3130	1.4101	0.2220	30	0.90	0.7445	2.4981	0.2980
15	0.45	0.3428	1.4706	0.2331	31	0.97	0.7785	2.7934	0.2787
16	0.47	0.3627	1.5108	0.2401					

Table (7) Geometric Parameters for Concrete Culvert with 1.4m Diameter

No. of Sec.	*d* (m)	*A* (m^2)	*P* (m)	*R* (m)	No. of Sec.	*d* (m)	*A* (m^2)	*P* (m)	*R* (m)
1	0.07	0.029	0.631	0.046	21	0.62	0.658	2.039	0.323
2	0.10	0.049	0.758	0.064	22	0.65	0.700	2.099	0.333
3	0.12	0.064	0.832	0.077	23	0.67	0.728	2.139	0.340
4	0.17	0.106	0.997	0.107	24	0.70	0.770	2.199	0.350
5	0.20	0.135	1.085	0.124	25	0.73	0.812	2.259	0.359
6	0.23	0.165	1.169	0.141	26	0.75	0.840	2.299	0.365
7	0.27	0.203	1.260	0.161	27	0.79	0.895	2.380	0.376
8	0.30	0.242	1.348	0.179	28	0.82	0.937	2.440	0.384
9	0.33	0.277	1.419	0.195	29	0.86	0.992	2.522	0.393
10	0.35	0.301	1.466	0.205	30	0.87	1.005	2.543	0.395
11	0.38	0.338	1.534	0.220	31	0.90	1.046	2.605	0.402
12	0.40	0.363	1.579	0.230	32	0.97	1.138	2.753	0.413
13	0.43	0.401	1.645	0.244	33	1.00	1.176	2.819	0.417
14	0.45	0.427	1.688	0.253	34	1.15	1.353	3.177	0.426
15	0.47	0.454	1.730	0.262	35	1.20	1.404	3.313	0.424
16	0.50	0.494	1.793	0.275	36	1.25	1.451	3.465	0.419
17	0.52	0.520	1.835	0.284	37	1.30	1.491	3.641	0.409
18	0.55	0.561	1.897	0.296	38	1.35	1.522	3.866	0.394
19	0.58	0.603	1.958	0.308	39	1.39	1.538	4.161	0.370
20	0.60	0.630	1.998	0.315					

Table (8) Geometric Parameters for Steel Culvert with 1.7m Diameter

No. of Sec.	***d* (m)**	***A* (m^2)**	***P* (m)**	***R* (m)**	**No. of Sec.**	***d* (m)**	***A* (m^2)**	***P* (m)**	***R* (m)**
1	0.10	0.054	0.833	0.065	21	0.74	0.948	2.450	0.387
2	0.12	0.071	0.914	0.077	22	0.78	1.016	2.530	0.402
3	0.14	0.089	0.990	0.090	23	0.80	1.050	2.570	0.408
4	0.17	0.118	1.094	0.108	24	0.85	1.135	2.670	0.425
5	0.20	0.150	1.190	0.126	25	0.88	1.186	2.730	0.434
6	0.27	0.232	1.394	0.166	26	0.92	1.254	2.811	0.446
7	0.30	0.270	1.474	0.183	27	0.96	1.321	2.891	0.457
8	0.32	0.296	1.526	0.194	28	1.00	1.389	2.972	0.467
9	0.36	0.351	1.626	0.216	29	1.10	1.554	3.178	0.489
10	0.40	0.407	1.722	0.237	30	1.15	1.634	3.284	0.498
11	0.43	0.451	1.792	0.252	31	1.20	1.713	3.392	0.505
12	0.46	0.496	1.860	0.267	32	1.25	1.789	3.503	0.511
13	0.50	0.557	1.949	0.286	33	1.32	1.891	3.666	0.516
14	0.53	0.604	2.014	0.300	34	1.38	1.974	3.815	0.517
15	0.55	0.636	2.057	0.309	35	1.43	2.038	3.947	0.516
16	0.58	0.684	2.121	0.322	36	1.48	2.098	4.090	0.513
17	0.60	0.716	2.163	0.331	37	1.52	2.141	4.214	0.508
18	0.63	0.765	2.225	0.344	38	1.55	2.172	4.315	0.503
19	0.65	0.798	2.267	0.352	39	1.60	2.216	4.508	0.492
20	0.70	0.881	2.369	0.372	40	1.67	2.261	4.888	0.463

Table (9) Geometric Parameters for Steel Culvert with 2.0m Diameter

No. of Sec.	*d* (m)	*A* (m^2)	*P* (m)	*R* (m)	No. of Sec.	*d* (m)	*A* (m^2)	*P* (m)	*R* (m)
1	0.07	0.035	0.753	0.046	18	0.76	1.095	2.657	0.412
2	0.10	0.059	0.902	0.065	19	0.83	1.232	2.800	0.440
3	0.12	0.077	0.990	0.078	20	0.90	1.371	2.941	0.466
4	0.15	0.107	1.110	0.096	21	0.95	1.471	3.042	0.484
5	0.18	0.140	1.219	0.115	22	1.00	1.571	3.142	0.500
6	0.20	0.164	1.287	0.127	23	1.10	1.770	3.342	0.530
7	0.22	0.188	1.352	0.139	24	1.15	1.870	3.443	0.543
8	0.25	0.227	1.445	0.157	25	1.20	1.968	3.544	0.555
9	0.30	0.295	1.591	0.186	26	1.30	2.162	3.751	0.576
10	0.33	0.339	1.673	0.203	27	1.40	2.349	3.965	0.592
11	0.35	0.369	1.726	0.214	28	1.50	2.527	4.189	0.603
12	0.40	0.447	1.855	0.241	29	1.65	2.772	4.557	0.608
13	0.42	0.480	1.904	0.252	30	1.70	2.846	4.692	0.607
14	0.45	0.529	1.977	0.268	31	1.80	2.978	4.996	0.596
15	0.50	0.614	2.094	0.293	32	1.90	3.083	5.381	0.573
16	0.60	0.793	2.319	0.342	33	1.98	3.136	5.883	0.533
17	0.70	0.980	2.532	0.387					

3.2. Manning Roughness Coefficient

Manning's roughness coefficient can be calculated from Manning's equation, Eq. (1) and for full flow as:

$$n_f = \frac{(D/4)^{2/3} S^{1/2}}{V_f} \qquad (2)$$

With the four different values of bed slope obtained from four different four culverts and the water depths. Manning's roughness coefficient *n* for each discharge in each of the four tested culverts was calculated. The calculated Manning roughness's for the four culverts are presented in Table (10).

Table (10) Values of Manning’s Roughness Coefficient for Steel and Concrete Culverts Flowing Partly Full

n	Concrete Culvert	
	D=1.0m	*D*=1.4m
n_{min}	0.0107	0.0169
n_{max}	0.0155	0.0270
n_f	0.0128	0.0221
n	Steel Culvert	
	D=1.7m	*D*=1.7m
n_{min}	0.0117	0.0117
n_{max}	0.0206	0.0206
n_f	0.0174	0.0174

The obtained values are in a good agreement with the values recommended by Chow [1]. The concrete surface was somewhat very smooth, as the value implied that the roughness. The concrete reference Manning's coefficient *n* values was in between 0.011 and 0.022, the smoothest surface finishing tested herein. It was very evident as the finishing surface of the culvert became rougher, the *n* value increased. The largest *n* value was 0.0270 and belonged to the concrete culvert. This value was even larger than the standard values of concrete.

3.3. Equations of Relative Manning Coefficient with Relative Water Depth for Circular Open Channels

In 1998, Zaghloul [13] showed that the roughness value n for a pipe partially full is greater than the roughness value n_f for full flow conditions. The variation of the relative roughness with the relative depth by Zaghloul is:

$$\frac{n}{n_f} = 0.9987 + 3.4616(d/D) - 14.7108(d/D)^2 + 27.2574(d/D)^3 - 23.4963(d/D)^4 + 7.4909(d/D)^5 \qquad (3)$$

In (2004), Akgiray [15] found that Camp’s curve was well represented by the following equation:

$$\frac{n}{n_f} = 1 - 0.8627X^5 + 0.4281X^4 + 0.7626X^3 - 1.02X^2 + 0.8057X \qquad (4)$$

Where $X = 1 - d/D$

In (2012), Devkota [6] showed that a linear trend represents the relation between the relative Manning's roughness coefficient and relative depth, as:

$$\frac{n}{n_f} = 46.821(d/D)^5 - 121.61(d/D)^4 + 119.76(d/D)^3 - 56.528(d/D)^2 + 12.458(d/D) \qquad (5)$$

In 2012, Toews and Clark [20] divided the equation into two parts:

$$n/n_f = 0.878(d/D)^{-0.175} \qquad d/D \le 0.5 \qquad (6)$$

$$n/n_f = 1 \qquad d/D > 0.5 \qquad (7)$$

In 2012, Bengtson [21] developed equations for n/n_f as a function of d/D, over the range from $0 < d/D < 1$, as:

$$n/n_f = 1 + (d/D)/(0.3) \qquad 0 \le d/D \le 0.03 \qquad (8)$$

$$n/n_f = 1.1 + (d/D - 0.03)(12/7) \qquad 0.03 \le d/D \le 0.1 \qquad (9)$$

$$n/n_f = 1.22 + (d/D - 0.1)(0.6) \qquad 0.1 \le d/D \le 0.2 \qquad (10)$$

$$n/n_f = 1.29 \qquad 0.2 \le d/D \le 0.3 \qquad (11)$$

$$n/n_f = 1.29 - (d/D - 0.3)(0.2) \qquad 0.3 \le d/D \le 0.5 \qquad (12)$$

$$n/n_f = 1.25 - (d/D - 0.5)(0.5) \qquad 0.5 \le d/D \le 1 \qquad (13)$$

4. Results and Analysis

One of the most difficulties with open channel flow is variations in roughness of cross section. Manning’s roughness coefficient is widely used and extremely important parameter for use in water flow computation including flow velocity and depth. The Manning's roughness coefficient also is affected by the relative depth. Relative depth is the ratio of depth to diameter (*d/D*). The relative Manning's roughness is the term used to define the ratio of Manning's roughness for partial flow to full flow (n/n_f). The goal of this study is to investigate the effect of the variation of water depth in the different types of culvert materials and to determination a relation between Manning’s roughness coefficient and relative depth. The water depth profile was measured within culverts with varying discharge, slope and diameter. Discharge and depth thus collected were used to calculate Manning’s roughness coefficient. The coefficients were then compared to the full flow roughness reported for steel and concrete culverts.

4.2 Manning Roughness Coefficient with Relative Depth

For the concrete culverts 1.0m and 1.4m diameter, Manning's roughness coefficients were calculated, Figures (2) to (5). Similarly for the steel culvert 1.7m and 2.0m diameter, Manning's roughness coefficients were calculated.

For the four tested culverts, Manning's roughness coefficients were calculated, Figures (2) to (5). From Figure (2), the values of the Manning’s roughness coefficient for the concrete culvert 1.0m diameter varied from 0.0107 to 0.0155 for relative depths of 5% to 97%. The maximum Manning's roughness coefficient occurred at a relative depth of 70%. The discharge range is from 0.0044 to 0.82m^3/sec at slope 0.001. Similarly, the value of the Manning’s Roughness Coefficient for the concrete culvert 1.4m diameter varied from 0.0169 to 0.0270 for relative depths of 5% to 99.3%, Figure (3). The maximum Manning's roughness coefficient occurred at a relative depth of 42.9%. The discharge range is from 0.0118 to 2.053 m^3/sec and slope 0.003. The Manning’s roughness value for the steel culvert 1.7m diameter ranged between 0.0117 and 0.0206 for relative depths of 5.8% to 98.2%, Figure (4). The maximum Manning's roughness coefficient was observed at a relative depth of 31%. The Manning’s roughness value for the steel culvert 2.0m diameter ranged between 0.0098 and 0.017 for relative depths of 3.5% to 99%, Figure (5). The maximum Manning's roughness coefficient occurred at a relative depth of 82.5%. With these results, the Manning's roughness coefficient varied with diameter and water depth.

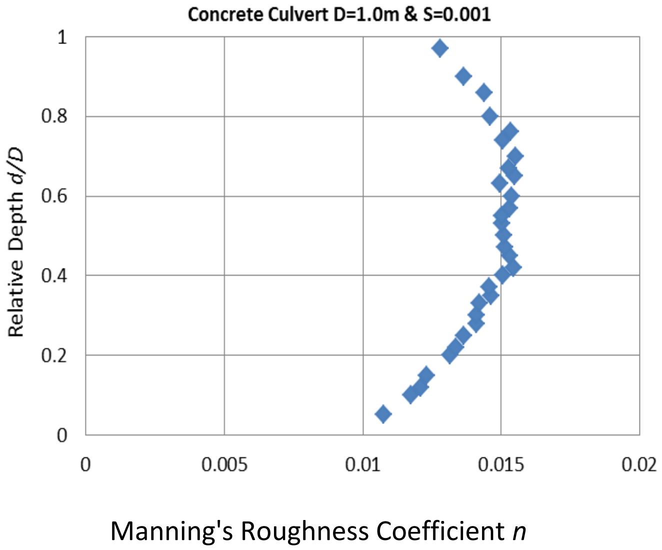

Figure (2) Manning's Roughness versus Relative Depth in Concrete Culvert *D*=1.0m

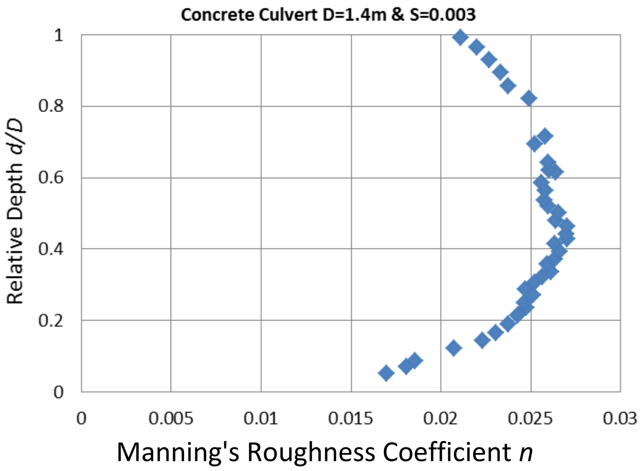

Figure (3) Manning's Roughness versus Relative Depth in Concrete Culvert *D*=1.4m

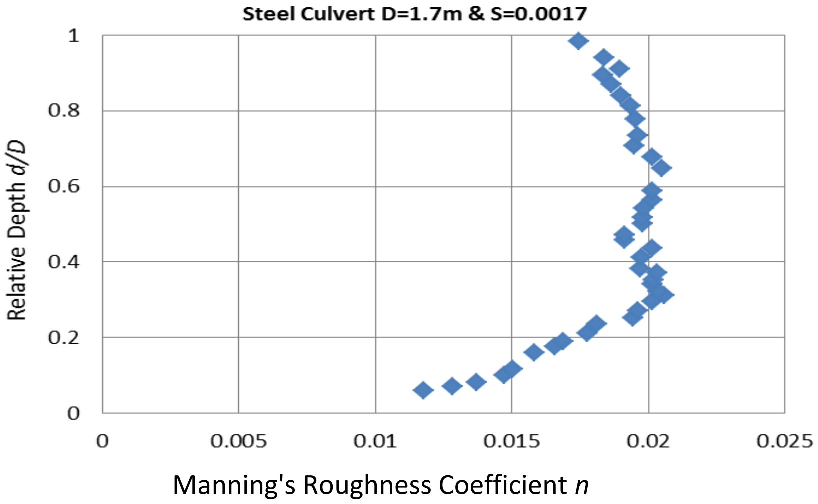

Figure (4) Manning's Roughness versus Relative Depth in Steel Culvert the *D*=1.7m

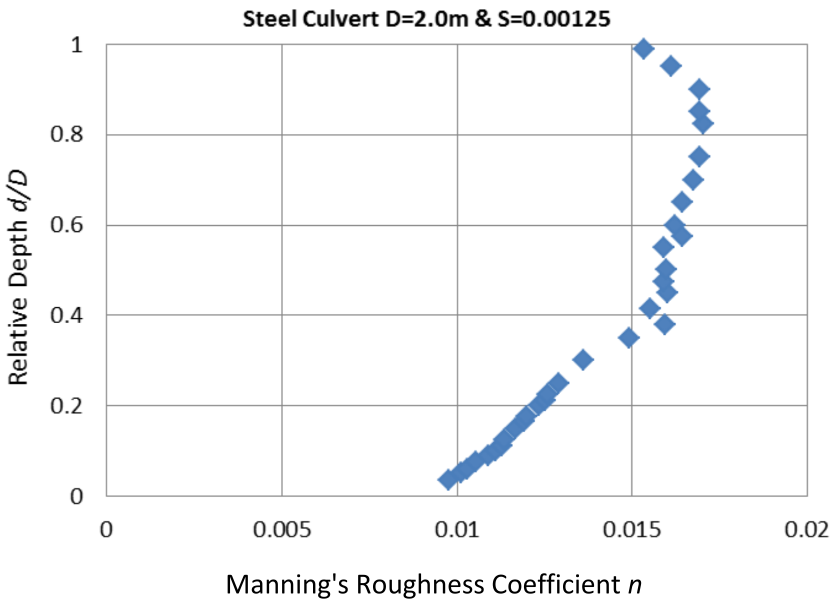

Figure (5) Manning's Roughness versus Relative Depth in Steel Culvert the *D*=2.0 m

4.3 Relative Manning Roughness Coefficient with Relative Depth

A plot of relative Manning's roughness versus relative water depth for four tested culverts is shown in Fig. (6). From curve, for below 25% full, the relative roughness for steel culvert is less than relative roughness for the concrete culvert and the Manning’s roughness coefficient *n* increased with the relative water depth (*d/D*) increased. Below 25% full, the Manning’s roughness coefficient *n* increased with the relative water depth *(d/D)* increase.

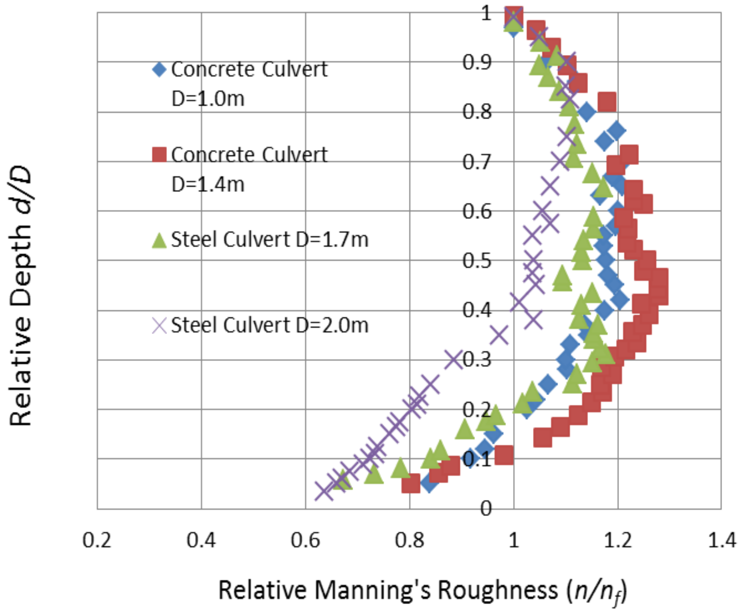

Figure (6) Relative Manning's Roughness versus Relative Depth in Four Test Culverts

A plot of relative Manning’s roughness coefficient versus relative depth for concrete culvert 1.0m and 1.4m diameter are shown in Fig. (6). Manning’s roughness coefficient increases with the increase in diameter of the culvert. From curves, for below 10% relative depth the relative Manning’s roughness value is from 80 to 100%. The results presented that the value of the Manning’s roughness coefficient for the steel culvert varied from 0.0098 to 0.0206.

A reversed plot of the data with the trend line is shown in Figure (7) for relative depth less than 25%. The axis of the plot of relative Manning’s roughness coefficient versus relative depth was reversed to determine a trend line that shows the relation between the variations of relative Manning’s roughness coefficient with relative depth in partially filled concrete and steel culverts.

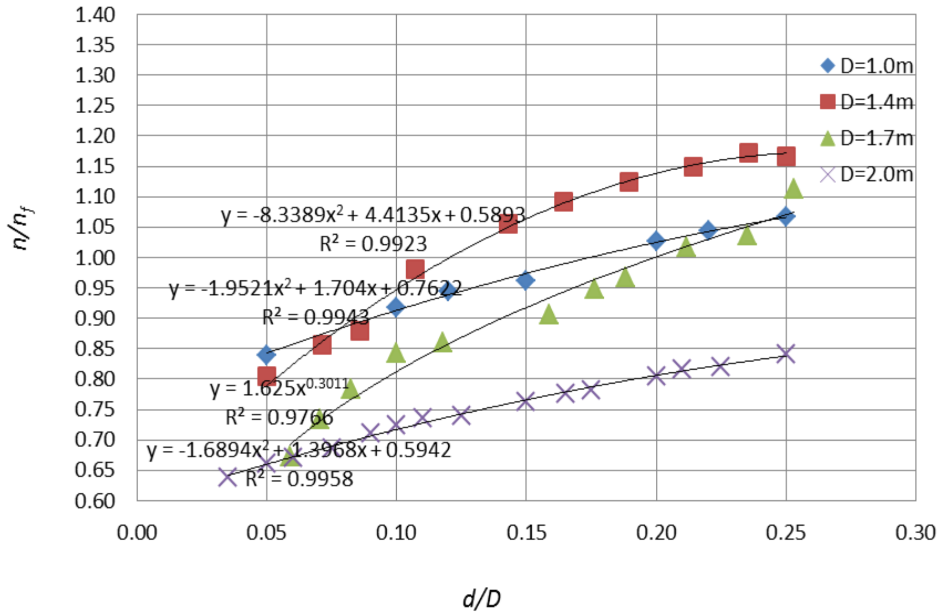

Figure (7) Trend line representing the Relation between Relative Manning’s Roughness Coefficient and Relative depth in Four Test Culverts for ($d/D \leq 0.25$)

The equations for the variation of relative Manning’s roughness coefficient for four tested culverts are shown below:

For concrete culvert with diameter 1.0m, as:

$$n/n_f = -1.9521(d/D)^2 + 1.704(d/D) + 0.7622 \tag{14}$$

For concrete culvert with diameter 1.4m, as:

$$n/n_f = -8.3389(d/D)^2 + 4.4135(d/D) + 0.5893 \tag{15}$$

For steel culvert with diameter 1.7m, as:

$$n/n_f = 1.625(d/D)^{0.3011} \tag{16}$$

For steel culvert with diameter 2.0m, as:

$$n/n_f = -1.6894(d/D)^2 + 1.3968(d/D) + 0.5942 \tag{17}$$

Tables (11) to (14) were presented comparison between previous equations to calculate relative Manning's roughness coefficient with proposed equations (Equations (14) to (17). From these tables, it was cleared that the proposed equations were more accurate than any previous equations. For Eq. (14) and (15) the maximum percentage error is 1.2 and 1.8%,respectively. For Eq. (16) and (17) the maximum percentage error is 3.5 and 1.0% respectively. The most accurate previous equation is Devkota's equation.

Table (11) Presents a Comparison between the Results of Field Work with Zaghloul, Akgiray, Devkota, Toews and Clark and Bengtson for Relative Manning Roughness *n/n_f* in Concrete Culvert 1.0m Diameter

d/D act	*n/n_f act*	Zaghloul	%Error	Akgiray	%Error	Devkota	%Error	Toews and Clark	%Error	Bengtson	%Error	Eq. (14)	%Error
0.05	0.840	1.138	-35.5	1.180	-40.5	0.496	40.9	1.483	-76.6	1.167	-38.9	0.843	-0.3
0.10	0.918	1.223	-33.2	1.226	-33.6	0.789	14.1	1.314	-43.1	1.220	-32.9	0.913	0.5
0.12	0.945	1.245	-31.7	1.240	-31.3	0.864	8.6	1.272	-34.7	1.232	-30.4	0.939	0.7
0.15	0.962	1.268	-31.7	1.257	-30.6	0.943	2.0	1.224	-27.2	1.250	-29.9	0.974	-1.2
0.20	1.027	1.285	-25.1	1.275	-24.1	1.009	1.8	1.164	-13.3	1.280	-24.6	1.025	0.2
0.22	1.043	1.287	-23.4	1.279	-22.6	1.020	2.3	1.144	-9.7	1.290	-23.7	1.043	0.0
0.25	1.066	1.286	-20.6	1.283	-20.3	1.024	4.0	1.119	-5.0	1.290	-21.0	1.066	0.0

Table (12) Presents a Comparison between the Results of Field Work with Zaghloul, Akgiray, Devkota, Toews and Clark and Bengtson for Relative Manning's n/nf in Concrete Culvert 1.4m Diameter

d/D act	*n/n_f act*	Zaghloul	%Error	Akgiray	%Error	Devkota	%Error	Toews and Clark	%Error	Bengtson	%Error	Eq. (15)	%Error
0.05	0.804	1.138	41.6	1.180	-46.8	0.496	38.3	1.483	-84.5	1.134	-41.1	0.789	1.8
0.07	0.855	1.180	-38.0	1.202	-40.5	0.642	24.9	1.393	-62.9	1.171	-36.9	0.862	-0.8
0.09	0.879	1.203	-36.9	1.215	-38.2	0.722	17.9	1.350	-53.6	1.196	-36.0	0.906	-3.1
0.11	0.981	1.231	-25.5	1.232	-25.6	0.818	16.6	1.298	-32.3	1.224	-24.8	0.966	1.5
0.14	1.056	1.263	-19.6	1.253	-18.7	0.928	12.2	1.234	-16.8	1.246	-17.9	1.050	0.6
0.16	1.091	1.275	-16.8	1.263	-15.8	0.969	11.2	1.204	-10.4	1.259	-15.3	1.089	0.2
0.19	1.125	1.283	-14.1	1.272	-13.1	1.001	11.0	1.175	-4.5	1.274	-13.2	1.126	-0.1
0.21	1.149	1.287	-12.0	1.278	-11.2	1.017	11.5	1.150	0.0	1.290	-12.3	1.152	-0.3
0.24	1.172	1.287	-9.8	1.282	-9.3	1.023	12.7	1.131	3.5	1.290	-10.1	1.166	0.5
0.25	1.167	1.286	-10.2	1.283	-9.9	1.024	12.3	1.119	4.1	1.290	-10.5	1.171	-0.4

Table (13) Presents a Comparison between the Results of Field Work with Zaghloul, Akgiray, Devkota, Toews and Clark and Bengtson for Relative Manning Roughness n/nf in Steel Culvert 1.7m Diameter

d/D act	*n/n_f act*	Zaghloul	%Error	Akgiray	%Error	Devkota	%Error	Toews and Clark	%Error	Bengtson	%Error	Eq. (16)	%Error
0.06	0.672	1.157	-72.0	1.189	-76.9	0.560	16.7	1.442	-114.4	1.149	-70.9	0.692	-3.0
0.07	0.733	1.179	-60.8	1.201	-63.8	0.637	13.1	1.396	-90.4	1.170	-59.5	0.731	0.2
0.08	0.783	1.198	-53.0	1.212	-54.7	0.704	10.1	1.359	-73.5	1.190	-51.9	0.766	2.2
0.10	0.842	1.223	-45.2	1.226	-45.6	0.789	6.3	1.314	-56.0	1.220	-44.9	0.812	3.5
0.12	0.861	1.242	-44.3	1.239	-43.9	0.856	0.5	1.277	-48.3	1.246	-44.7	0.853	0.9
0.16	0.907	1.272	-40.3	1.261	-39.0	0.960	-5.9	1.212	-33.6	1.259	-38.8	0.934	-3.0
0.18	0.948	1.280	-35.0	1.268	-33.8	0.987	-4.1	1.189	-25.5	1.274	-34.4	0.964	-1.7
0.19	0.967	1.283	-32.7	1.272	-31.5	1.000	-3.4	1.176	-21.6	1.289	-33.2	0.983	-1.6
0.21	1.018	1.287	-26.5	1.278	-25.5	1.016	0.1	1.152	-13.2	1.290	-26.8	1.018	-0.1
0.24	1.037	1.287	-24.2	1.281	-23.6	1.023	1.3	1.131	-9.1	1.290	-24.4	1.051	-1.4
0.25	1.114	1.286	-15.4	1.283	-15.2	1.024	8.1	1.117	-0.3	1.290	-15.8	1.074	3.5

Table (14) Presents a Comparison between the Results of Field Work with Zaghloul, Akgiray, Devkota, Toews and Clark and Bengtson for Relative Manning Roughness n/nf in Steel Culvert 2.0m Diameter

d/D act	n/n_f act	Zaghloul	%Error	Akgiray	%Error	Devkota	%Error	Toews and Clark	%Error	Bengtson	%Error	Eq. (17)	%Error
0.04	0.637	1.103	-73.1	1.162	-82.4	0.372	41.6	1.579	-147.8	1.109	-74.0	0.641	-0.6
0.05	0.660	1.138	-72.4	1.180	-78.6	0.496	24.9	1.483	-124.6	1.134	-71.7	0.660	0.1
0.06	0.671	1 .159	-72.7	1.191	-77.4	0.568	15.3	1.437	-114.0	1.151	-71.5	0.672	-0.1
0.08	0.687	1.186	-72.8	1.205	-75.5	0.663	3.4	1.382	-101.2	1.177	-71.4	0.689	-0.4
0.09	0.711	1.209	-70.2	1.218	-71.4	0.743	-4.6	1.338	-88.3	1.203	-69.3	0.706	0.6
0.10	0.723	1.223	-69.0	1.226	-69.5	0.789	-9.0	1.314	-81.6	1.220	-68.6	0.717	0.9
0.11	0.735	1.234	-68.0	1.234	-67.9	0.829	-12.8	1.292	-75.8	1.226	-66.9	0.727	1.0
0.13	0.740	1.249	-68.8	1.243	-68.0	0.880	-18.9	1.263	-70.7	1.235	-66.9	0.742	-0.3
0.15	0.762	1.268	-66.5	1.257	-65.1	0.943	-23.9	1.224	-60.7	1.250	-64.1	0.766	-0.6
0.17	0.776	1.275	-64.3	1.263	-62.8	0.970	-25.0	1.203	-55.1	1.259	-62.2	0.779	-0.3
0.18	0.782	1.279	-63.6	1.267	-62.0	0.985	-25.9	1.191	-52.3	1.265	-61.7	0.787	-0.6
0.20	0.805	1.285	-59.7	1.275	-58.4	1.009	-25.4	1.164	-44.6	1.280	-59.0	0.806	-0.1
0.21	0.816	1.287	-57.6	1.277	-56.4	1.015	-24.4	1.154	-41.3	1.290	-58.0	0.813	0.4
0.23	0.819	1.287	-57.1	1.280	-56.2	1.021	-24.6	1.140	-39.1	1.290	-57.4	0.823	-0.4
0.25	0.842	1.286	-52.8	1.283	-52.4	1.024	-21.6	1.119	-32.9	1.290	-53.2	0.838	0.5

5. Conclusions

From the rustles of the presented study the following conclusions are:

1. The Manning's roughness coefficient varied with diameter and relative depth;

2. The obtained values of the Manning's roughness coefficient *n* for sections are in a good agreement with the references values;

3. New relations between the relative depth (*d/D*) and the relative roughness (n/n_f) for the test culverts are presented for $d/D \leq 0.25$;

4. The new equations were compared by previous equations and it gives least error;

5. For $d/D \leq 0.25$ the partial flow roughness is less than the full flow roughness; and

6. Below 25% full, the relative roughness for steel culvert is less than relative roughness for the concrete culvert.

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List of notation

A	Water area;
d	Water depth;
D	Diameter of circular channel;
g	Gravitational acceleration;
Ks	Absolute material roughness;
n	Manning's roughness coefficient;
n_f	Manning's roughness coefficient for full flow;
$n_{\max}$	Maximum Manning's roughness coefficient;
$n_{\min}$	Minimum Manning's roughness coefficient;
P	Wetted perimeter;
R	Hydraulic radius;
Q	Discharge;
S	Bed slope;
V	Mean flow velocity at section;
$V_{0.2}$	Flow velocity at 0.2 depth;
$V_{0.6}$	Flow velocity at 0.6 depth;
$V_{0.8}$	Flow velocity at 0.8 depth;
V_{mean}	Mean flow velocity at section;
X	Dimensionless variable ($X = 1 - h/D$); and
y	Vertical water depth.