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Artificial Roughness Dimensions and their Influence on Bed Topography Variations Downstream of a Culvert: An Experimental Study

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Abstract

Protecting the downstream side of culverts against the scouring phenomenon is deemed a vital point to consider when designing culverts, which are structures utilized as water passages. This study represented an attempt to investigate the effect of artificial roughness on the scouring happening at the downstream side of culverts. To this end, 37 tests with three variable parameters of height, length lateral to the flow, and the distance between rows of artificial roughness were conducted. The results revealed the greater role artificial roughness height played in mitigating the scouring than the rest of the parameters did compared to the control test. Furthermore, the greatest reduction of the scour depth was observed when height, length perpendicular to the flow, and the distance between rows of artificial roughness were respectively equal to 0.13, 0.26 and 0.8 times the culvert mouth height. More than 17% decrease in the maximum scour depth was found in tests conducted under these conditions compared to the control test. In addition, the greatest rise in sedimentation volume was observed when the dimensions were respectively 0.33, 0.33 and 0.66 times the culvert mouth height. This test indicated 9% increase in the sedimentation volume compared to the control test.

Keywords Culvert · Scouring · Artificial roughness · Sedimentation · Control test

1 Introduction

Applied in abundance, culverts are there to fulfill the purpose of transferring and leading the water flow through the embankments of roads, highways and railways in drainage basins. Culverts are in charge of providing protection for channels and the associated

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structures, as well as embankments, during floods and unanticipated currents; hence, sufficient care must be taken in design, implementation and management of these structures so that they would not only carry out their protective function but also endure longer. Local scouring at the culvert outlet is a common phenomenon, which is considered a deteriorative factor, threatening its durability; if it is not taken under control, the whole infrastructure could fail and breed irreparable damage. Since numerous parameters could contribute to the scouring downstream of culverts, reaching a proper estimation of the scouring status is truly complicated. Recent years have seen many studies conducted on scouring in culverts, where the effects of factors such as the culvert shape and the culver slope on the scouring variations were determined. A number of those are recounted below.

Mendoza et al. (1983) studied the effect of headwall on the culvert's outlet scouring. Abt et al. (1985) investigated the effect of the culvert slope on the scouring at the outlet of a culvert and concluded that raising this parameter entailed deeper scouring. In another study, Abt et al. (1987) examined the effect of the culvert's shape on its local scouring. Having investigated the effect of tailwater depth on the amount of scouring, Abida and Townsend (1991) reported that on the condition that the ratio of the tailwater depth to the culvert diameter was less than 0.2, the scour depth decreased as the tailwater depth declined. Lim (1995) explored local scouring at the outlet of a circular culvert. Day et al. (2001) analyzed the effect of model scale on scouring at the outlet mouth of culverts and obtained a number of equations to anticipate scour depth downstream of outlets using small-scale models. Hotchkiss and Larson (2005) studied the energy dissipated at the outlet of a culvert by employing two methods. Emami and Shciels (2010) compared local scouring under different flow conditions on a natural live bed. Crookston and Tulis (2012) investigated scouring at a culvert with an erodible bed. Sorourian et al. (2015) explored the scouring at sand beds at the outlet of partially blocked square culverts under unsteady flow conditions. Sorourian et al. (2016) addressed the effect of blockage on the local scouring of culverts. Results suggested that the blockage had a significant effect on the flow structure and the geometry of the scour hole at the culvert outlet. In a numerical study, Najafzadeh and Karegar (2019) predicted scour depths at the outlet of culverts using Gene Expression Programming (GEP), Evolutionary Polynomial Regression (EPR), and tree models. Abdel Aal et al. (2019) focused on reduction in the maximum scour depth downstream of the culvert outlet under different flow conditions. Zhang and Wu (2019) numerically examined the maximum scour depth at the outlet of rectangular and circular culverts. Gunal et al. (2019) conducted a study to compare the simulated results of a FLOW-3D model of a box culvert with the experimental results of Sorourian to evaluate the accuracy of the numerical model. In an empirical study, Horst (2019) examined the effect of the culvert's lateral wall with different shapes and materials on its scouring. Galan and Gonzalez (2020) explored the effect of shape, inlet obstruction and lateral walls on the scouring at the outlet of non-submerged culverts. Taha et al. (2020a, b) investigated the effects of different ratios of inlet blockage on the dimensions of the scour hole. Taha et al. (2020a, b) conducted numerical and experimental investigations of scour depth downstream under different blockage ratios. The numerical investigation was made possible using Flow-3D, which led to acceptable results in comparison with the experimental work. Karimpour and Gohari (2020) experimentally explored the effect of flow blockage at the entrance of a culvert on the downstream scouring by applying a set of hydraulic models. Tan et al. (2020) addressed the geometry of culverts, the properties of sediment particles and their effect on culvert scouring in an experimental study. Othman Ahmed et al. (2021) presented a numerical model in order to estimate the scour depth and its location downstream of a box culvert under unsteady flow conditions. In an experimental study, Miranzadeh et al. (2022) examined obstruction in box culverts and circular culverts under flooding conditions. Le et al. (2022)

conducted a numerical investigation of scouring at the outlet of a meandering channel with a culvert as a diversion structure. Nassar (2022) carried out experiments to study a new solution for the protection of a circular culvert's outlet against scouring. Mohammadi et al. (2023) evaluated different machine-learning algorithms for automatic culvert inspection.

Various parameters with an influence on the culvert's outlet scouring have been analyzed in the literature. Presence of artificial roughness with specific and orderly arrangements inside a culvert has an effect on the bed topography downstream of the culvert; however, this has not been studied so far. This study was an attempt to address the effect of artificial roughness on bed topography variations downstream of a culvert. To this end, the artificial roughness arrangements, including the geometric dimensions and the distance Between Rows of artificial roughness, were investigated.

2 Materials and Methods

The culvert dimensions were also selected based on the range of dimensions used in the literature as well as the available dimensions of the channel used in the study. The tests were conducted in a channel with a metal floor and glass walls. The channel's height and width were respectively 0.7 and 1 m. The upstream and downstream straight paths of the channel were respectively 6.5 and 5.1 m long. To carry out the experiments, a model culvert made of PVC with a length (L) of 1 m, width (B) of 1 m, mouth width (b) of 0.45 m and mouth height (h) of 0.15 m was first constructed and then implemented on the channel. Figure 1 displays both actual and schematic illustrations of the laboratory culvert.

Artificial roughness was designed and developed with PVC material and three variable parameters of height, length lateral to the flow, and distance between rows were considered. The length lateral to the flow of the artificial roughness was considered a constant value of 0.33 h. The laboratory culvert constructed for the purpose of the study was installed at a distance of 3 m from the upstream straight path of the laboratory channel. analyzed for bed topography variations. A 720-min-long test in the absence of artificial roughness was run at a discharge rate of 0.0215 m^3/s in order to determine the equilibrium time for the tests. The

Fig. 1 Schematic view of the culvert dimensions and actual view of the culvert

scour hole depth at 180 min into the test underwent the greatest variation compared to the total scouring. Given that the maximum variations in the scour depth compared to the total scouring occurred at the end of 180 min into the test, the equilibrium time (t_e) for the tests was considered to be 180 min.

3 Experiments

In order to conduct the tests in this study, the flow depth was made adjustable using the butterfly valve placed at the end of the channel. Further, a discharge rate of 0.0215 m^3/s was considered for the tests. Silica sediment particles with an average grading (d_{50}) of 0.0015 m were applied to the channel bed for a height of 0.326 m. 37 tests, including a control test and 36 tests on artificial roughness, were conducted by altering 3 variable parameters: height (H), length lateral to the flow (W) and distance between the rows (S). Accordingly, the tests were labeled in this format: $N_{\text{H-W-S}}$. The upstream and downstream beds of the culvert were first flattened in preparation for the tests. To conduct these tests, the artificial roughness was installed inside the culvert in 4 rows of 4 and 3 beginning from the culvert's outlet mouth side extending toward the inlet mouth. Figure 2 depicts a few illustrations of the artificial roughness arrangement inside the culvert.

Then the flow was maintained inside the channel with a discharge rate of 0.0215 m^3/s. When each test was completed, the channel bed was fully drained for 3 h. Data on the downstream side of the culvert were collected using a laser device. To this end, 0.025 × 0.025-m mesh grids along the initial 1 m and 0.05 × 0.025-m mesh grids along another 1.5 m in the downstream straight path were considered respectively at the length and width of the channel. Given the length of the culvert's downstream straight path (2.5 m) and the width of the channel (1 m), 70 longitudinal sections and 40 cross sections were collected for each test. Figure 3 depicts the spatial range of significant points regarding scouring and sedimentation downstream of the culvert.

Y in Fig. 3 represents the length of the culvert's downstream straight path. Two scour holes were developed along the channel's right wall, where the first hole (ds_1) fell within

Fig. 2 Illustration of artificial roughness inside the culvert

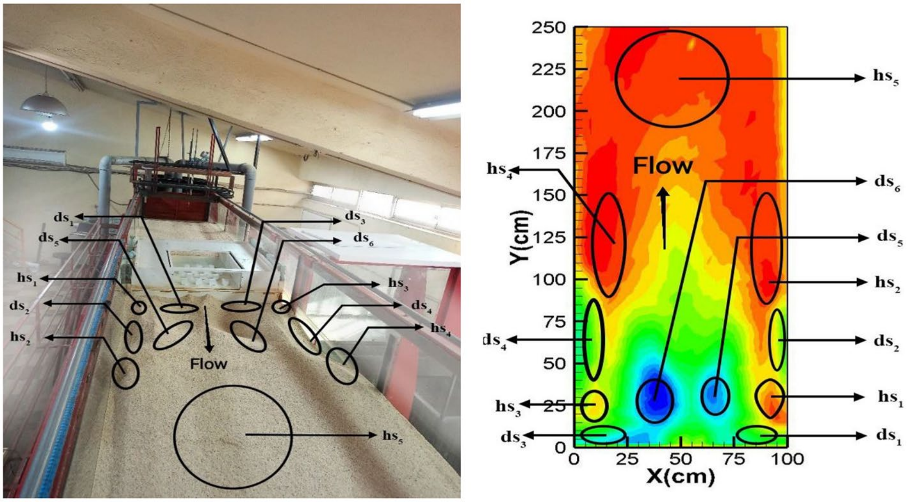


Fig. 3 Range of significant points downstream of the culvert

the range of 0 to 0.02 Y and the second hole (ds_2) fell within the range of 0.1 to 0.28 Y. In addition, two scour holes were developed along the channel's left wall, the first of which (ds_3) occurred within the range of 0 to 0.04 Y and the second of which (ds_4) occurred within the range of 0.1 to 0.30 Y. Two scour holes were developed within the range of 0.06 to 0.28 Y in alignment with the two right and left walls of the culvert, respectively denoted by ds_5 and ds_6. Two sediment peaks were developed in alignment with the channel's right wall, the first of which (hs_1) fell within the range of 0.05 to 0.14 Y and the second of which (hs_2) occurred within the range of 0.36 to 0.6 Y. Furthermore, two sediment peaks were developed along the channel's left wall. The first peak (hs_3) was observed within the range of 0.05 to 0.14 Y and the second one (hs_4) happened within the range of 0.38 to 0.64 Y. hs_5 is the sedimentation region at mid-channel, which is defined within the range of 0.76Y to Y. Considering all of the tests, which were conducted in this study for three intervals between the rows, 0.53 h, 0.66 h and 0.8 h, significant scouring and sedimentation points were developed within the mentioned ranges.

4 Results and Discussion

The flow impacted the bed materials in the form of a jet after leaving the culvert. The output jet caused a scour hole during the initial seconds of the test in the vicinity of the culvert's outlet mouth. As a consequence, the materials were transported in downstream direction. The hole developed after about two minutes into the test was divided into two scour holes aligned with the outlet walls of the culvert. Vortices formed around these holes. These were generated in a clockwise fashion near the channel's right wall and in a counterclockwise fashion near the left wall. The vortices carried the bed materials away from the vicinity of the walls and poured them into the scour holes. The flow velocity within the vortex region was lower than that in the channel's central points, and sedimentation thus occurred in the vortex region. The sedimentary zones of hs_1, hs_2, hs_3, and hs_4 were developed in the vortex regions.

Table 1 presents the maximum values of scour and sedimentation along with their locations. The maximum values of scour and sedimentation are nondimensionalized with the culvert's mouth height (h) in this table. The culvert's mouth height is 0.15 m. According to Table 1, the maximum scour hole occurs in Area ds_6 in every test except for the control test. The maximum scour hole occurred in Area ds_3 in the control test. The maximum scour hole depth decreased in more than 88% of the tests compared to the control test. The greatest decrease compared to the control test was observed in $N_{2\text{–}4\text{-}12}$ by over 17%. Over 58% of the tests showed an increase in sedimentation compared to the control test.

The highest increase compared to the control test was associated with $N_{2\text{–}5\text{-}12}$ by over 36%. In more than 69% of the tests, the greatest sedimentation occurred in Zone hs_4. Bed topography analyses of the tests, after completion, included scour holes and sediment peaks. In all of the tests, the scour holes which developed in alignment with two culvert walls fell within the range of 0.06 to 0.28 Y. In addition, Area ds_6 was greater than Area ds_5 in every test. The control test showed the maximum scour hole at the channel's left wall in proximity to the culvert's outlet mouth (ds_3). The sedimentation values at the channel's right wall were greater than those at the left wall. Furthermore, the sedimentation values at the end of the straight path downstream of the culvert were greater than those at its beginning. The maximum sedimentation value occurred in Zone hs_2. 12 tests were conducted with $S = 0.53$ h. Figure 4 depicts bed topography of the tests on this distance between the rows.

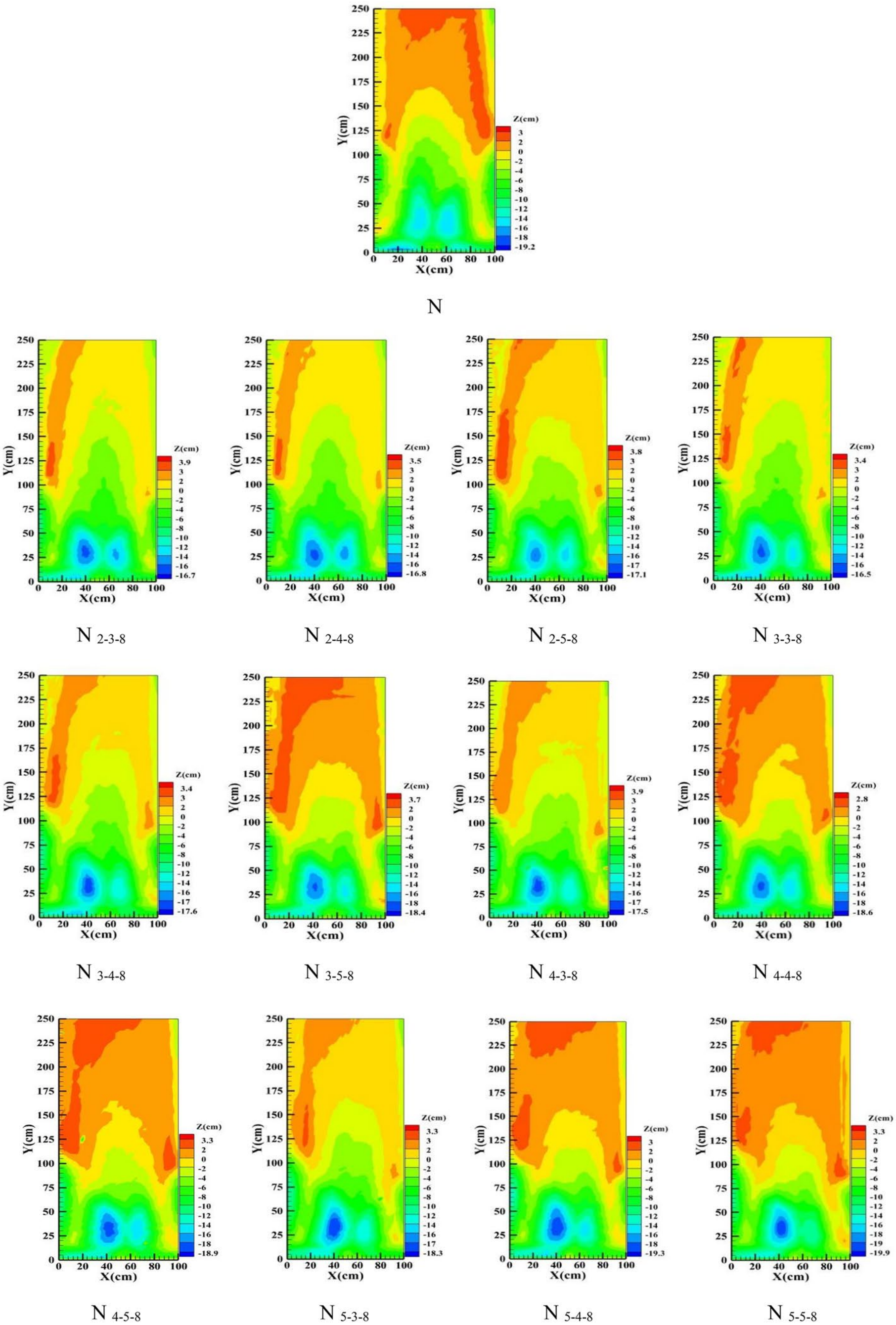
The scour holes which developed along the two culvert walls again fell within the range of 0.06 to 0.28 Y, similar to those obtained from the control test. In every test on this distance between the rows, Area ds_6 was larger than Area ds_5. In all of the tests conducted on this distance between the rows, the maximum scour hole occurred at mid-channel and oriented toward the left wall (ds_6), while in the control test, the maximum scour hole was developed at the left wall of the channel near the culvert's outlet mouth (ds_3). Presence of artificial roughness inside the culvert led to an increase in the flow height inside it. Increasing the height caused the flow to be shot to a farther distance away from the culvert's outlet mouth; consequently, it led to formation of the maximum scour hole at a greater distance from the outlet mouth compared to that in the control test. The maximum scour hole occurred at a farther distance from the culvert's outlet mouth in every test on this distance between the rows compared to the control test. The slope of variations in the maximum scour depths obtained from the tests was sharp during the initial minutes into the tests, but it grew milder after a few minutes. Over 83% of the tests on this distance caused an average of 8% reduction in scouring downstream of the culvert compared to the control test. With over 14% reduction of scouring compared to the control test, $N_{3\text{–}3\text{-}8}$ led to the highest decrease, and with 3.5% increase in scouring downstream of the culvert compared to the control test, $N_{5\text{–}5\text{-}8}$ had the highest increase among the tests on this distance. According to Fig. 4, it was determined that at this distance between the rows, the artificial roughness with a lower height played a better role in reducing scouring downstream of the culvert. The low height of artificial roughness led to less increase in the flow height than the large height of artificial roughness; therefore, the output flow jet impacted the bed with less strength, which meant a reduction in scouring. It can be observed from the bed topography that the sedimentation values at the left wall were greater than those at the right wall in contrast with those in the control test. More than 83% of the tests on this distance caused an average of 18% increase in sedimentation compared to the control test. With 30% increase in sedimentation, $N_{4\text{–}3\text{-}8}$ and $N_{2\text{–}3\text{-}8}$ showed the greatest increase among the

Table 1 Specifications and results tests

Name	$\frac{\text{ds max}}{\text{h}}$	Location Symbol ds $_{\text{max}}$	Change $\frac{\text{ds max}}{\text{h}}$ Compared from Test control (%)	$\frac{\text{Y}}{\text{h}}$	$\frac{\text{X}}{\text{h}}$	$\frac{\text{hs max}}{\text{h}}$	Location Symbol hs $_{\text{max}}$	Change $\frac{\text{h max}}{\text{h}}$ Compared from Test control (%)	$\frac{\text{Y}}{\text{h}}$	$\frac{\text{X}}{\text{h}}$
N	1.28	ds_3	-	0.16	5.33	0.2	hs_2	-	9.33	0.5
N $_{2–3\text{-}8}$	1.11	ds_6	-13.4	2.16	4	0.26	hs_4	30	7.66	6
N $_{2–4\text{-}8}$	1.11	ds_6	-12.5	1.83	4	0.233	hs_4	16.66	8.66	6
N $_{2–5\text{-}8}$	1.14	ds_6	-10.93	1.83	4	0.253	hs_4	26.16	9.66	5.83
N $_{3–3\text{-}8}$	1.1	ds_6	-14.06	2	4	0.226	hs_4	13.13	9.66	6
N $_{3–4\text{-}8}$	1.17	ds_6	-8.33	2.5	3.83	0.226	hs_4	13.13	9.33	5.83
N $_{3–5\text{-}8}$	1.22	ds_6	-4.16	2.16	3.83	0.2	hs_4	0	8.33	5.83
N $_{4–3\text{-}8}$	1.16	ds_6	-8.9	2	4	0.26	hs_2	30	6	0.5
N $_{4–4\text{-}8}$	1.24	ds_6	-3.12	2.16	4	0.186	hs_5	-6.66	16	5.33
N $_{4–5\text{-}8}$	1.26	ds_6	-1.56	2.33	3.83	0.22	hs_2	10	6.66	0.33
N $_{5–3\text{-}8}$	1.22	ds_6	-4.68	2.16	4	0.22	hs_4	10	8.33	5.66
N $_{5–4\text{-}8}$	1.28	ds_6	0.52	2	3.83	0.2	hs_2	0	6.33	0.5
N $_{5–5\text{-}8}$	1.32	ds_6	3.64	2.16	3.83	0.22	hs_2	10	6.16	0.5
N $_{2–3\text{-}10}$	1.1	ds_6	-13.54	2	4.16	0.206	hs_5	3.33	16	5
N $_{2–4\text{-}10}$	1.2	ds_3	-6.25	0.33	6.33	0.213	hs_4	6.5	9.33	6
N $_{2–5\text{-}10}$	1.08	ds_6	-15.62	2	4.16	0.24	hs_4	20	8	6
N $_{3–3\text{-}10}$	1.17	ds_6	-8.33	2	4	0.226	hs_4	13.33	8	6
N $_{3–4\text{-}10}$	1.12	ds_6	-11.97	2	4	0.22	hs_4	0	8.66	5.66
N $_{3–5\text{-}10}$	1.37	ds_6	7.29	2.33	4	0.213	hs_5	6.66	16	5.16
N $_{4–3\text{-}10}$	1.26	ds_6	-1.04	2.16	4.16	0.186	hs_4	-6.66	8.33	5.83
N $_{4–4\text{-}10}$	1.21	ds_6	-5.2	2	3.83	0.186	hs_5	-6.66	16.33	5.16
N $_{4–5\text{-}10}$	1.26	ds_6	-1.56	2.33	4	0.2	hs_4	0	8.33	6.16
N $_{5–3\text{-}10}$	1.18	ds_6	-7.81	2	4	0.18	hs_5	-10	16.33	5.33
N $_{5–4\text{-}10}$	1.27	ds_6	-0.52	2.33	3.83	0.193	hs_4	-3.33	8.66	6.16

Table 1 (continued)

Name	$\frac{\text{ds max}}{\text{h}}$	Location Symbol ds $_{\text{max}}$	Change $\frac{\text{ds max}}{\text{h}}$ Compared from Test control (%)	$\frac{\text{Y}}{\text{h}}$	$\frac{\text{X}}{\text{h}}$	$\frac{\text{hs max}}{\text{h}}$	Location Symbol hs $_{\text{max}}$	Change $\frac{\text{h max}}{\text{h}}$ Compared from Test control (%)	$\frac{\text{Y}}{\text{h}}$	$\frac{\text{X}}{\text{h}}$
N $_{5–5\text{-}10}$	1.34	ds_6	4.68	2.33	3.83	0.166	hs_4	-16.66	8.66	6.16
N $_{2–3\text{-}12}$	1.07	ds_6	-16.14	2	4	0.24	hs_4	20	9	6
N $_{2–4\text{-}12}$	1.06	ds_6	-17.18	2.16	4.16	0.22	hs_4	10	9	6
N $_{2–5\text{-}12}$	1.08	ds_6	-15.62	2	4.16	0.273	hs_4	36.66	8	5.83
N $_{3–3\text{-}12}$	1.08	ds_6	-15.62	2	4	0.22	hs_4	10	8.66	6
N $_{3–4\text{-}12}$	1.1	ds_6	-13.59	2.16	4	0.18	hs_4	-10	8	6
N $_{3–5\text{-}12}$	1.12	ds_6	-11.97	2	3.83	0.226	hs_4	-13.33	8.33	5.83
N $_{4–3\text{-}12}$	1.12	ds_6	-12.5	2.16	4.16	0.206	hs_4	3.33	8.33	5.16
N $_{4–4\text{-}12}$	1.2	ds_6	-6.25	2.33	4	0.22	hs_4	10	7.66	5.83
N $_{4–5\text{-}12}$	1.2	ds_6	-6.25	2.33	4	0.213	hs_4	6.5	8	5.83
N $_{5–3\text{-}12}$	1.13	ds_6	-11.45	2.33	4.16	0.2	hs_4	0	8.33	5.83
N $_{5–4\text{-}12}$	1.13	ds_6	-11.45	2	4	0.22	hs_4	10	8.66	5.83
N $_{5–5\text{-}12}$	1.2	ds_6	-5.72	2	4.16	0.186	hs_4	-6.66	16	5.16



N

N_{2-3-8} N_{2-4-8} N_{2-5-8} N_{3-3-8}

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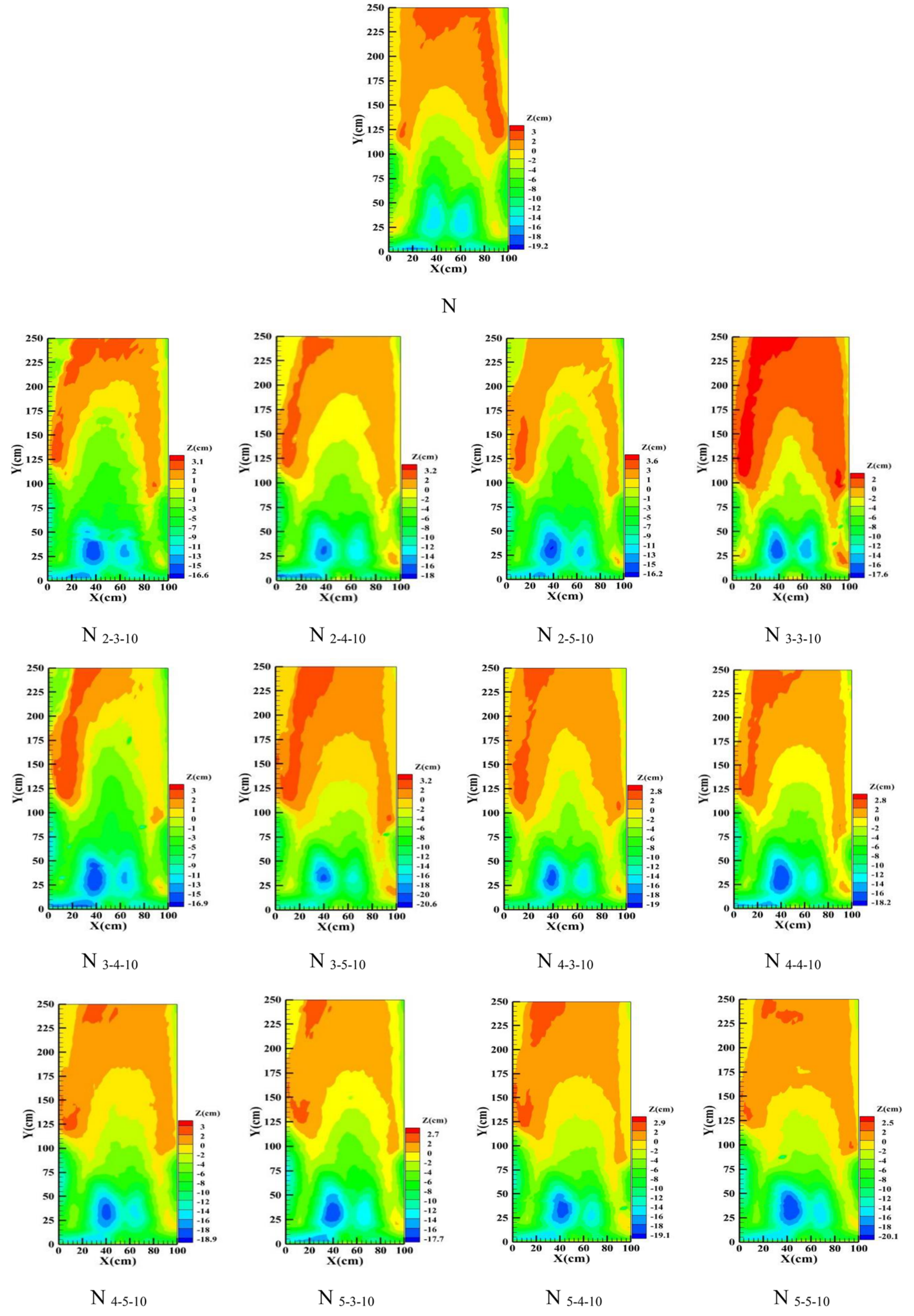
N_{4-5-8} N_{5-3-8} N_{5-4-8} N_{5-5-8}

Fig. 4 The topography in tests with S = 0.53 h



N

N_{2-3-10} N_{2-4-10} N_{2-5-10} N_{3-3-10}

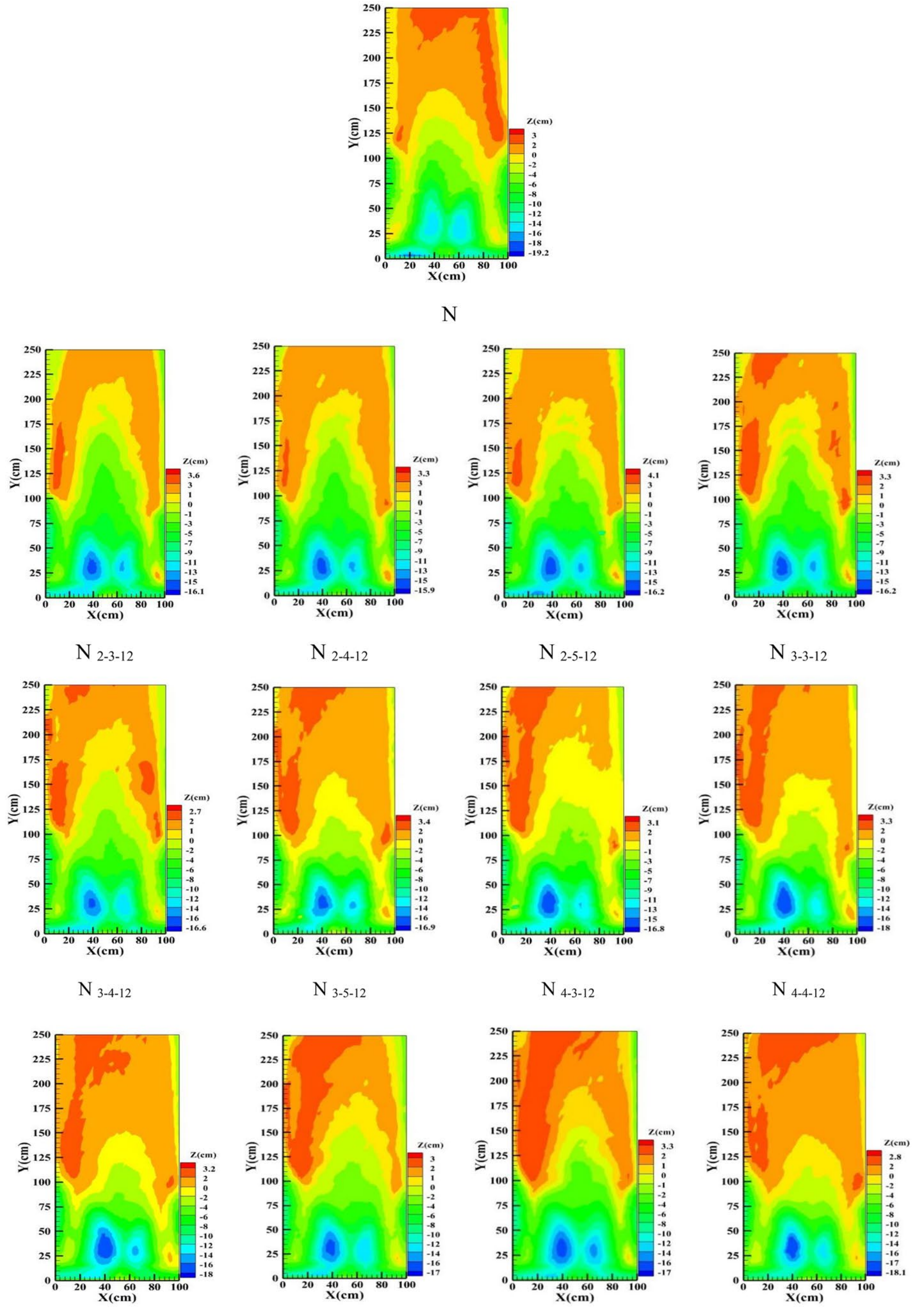
N_{3-4-10} N_{3-5-10} N_{4-3-10} N_{4-4-10}

N_{4-5-10} N_{5-3-10} N_{5-4-10} N_{5-5-10}

Fig. 5 The topography of the tests for S = 0.66 h tests on this distance. It was only N $_{4–4\text{-}8}$ with over 6% reduction compared to the control test that led to sedimentation reduction. 12 tests were conducted with $S=0.66$ h. The bed topography tests on this distance between the rows are presented in Fig. 5.

All of the tests conducted on this distance between the rows, except for N $_{3–5\text{-}10}$, caused an average of 7% reduction in the scouring downstream of the culvert compared to the control test. In every test conducted on this distance, except for N $_{2–4\text{-}10}$, the maximum scour hole was developed at mid-channel toward the left wall (ds_6). However, in N $_{2–4\text{-}10}$, like the control test, the maximum scour hole occurred at the left wall in the vicinity of the culvert's outlet mouth (ds_3). The slope of variations in the maximum scour point was sharper during the initial minutes of the tests. The maximum scouring point in all of the tests conducted on this distance between the rows of artificial roughness, except for N $_{2–4\text{-}10}$, was found at a larger distance from the culvert's outlet mouth compared to the control test. With over 15% reduction, N $_{2–5\text{-}10}$ had the greatest decrease, and with more than 4% increase, N $_{5–5\text{-}10}$ had the greatest increase among the tests conducted on this distance between the rows. Bed topography indicated that the sedimentation values at the left wall were greater than those at the right wall in contrast to the control test. Over 41% of the tests on this distance showed an average of 8.5% reduction in sedimentation compared to the control test, the highest amount of which occurred in N $_{5–5\text{-}10}$ by over 16.5%. In addition, over 41% of the tests caused an average of 10% increase in sedimentation compared to the control test, the greatest value of which was found in N $_{2–5\text{-}10}$. 12 tests were conducted with $S=0.8$ h. The bed topography of these tests are presented in Fig. 6.

In all of the tests conducted on this distance between the rows, the maximum scour hole occurred at mid-channel toward the left wall (ds_6), while in the control test, the maximum scour hole was developed at the left wall near the culvert's outlet mouth (ds_3). The maximum scour point of all the tests on this distance between the rows occurred at a farther distance from the culvert's outlet mouth than that in the control test. The slope of variations in the maximum scour point was sharper during the initial minutes of the tests than that during the remaining time. All of the tests conducted on this distance between the rows caused an average of 12% reduction in scouring downstream of the culvert compared to the control test. With more than 17% reduction, N $_{2–4\text{-}12}$ had the greatest reduction and with over 5.5% decrease, N $_{4–5\text{-}12}$ showed the least reduction compared to the control test. Over 66% of the tests on this distance caused an average of more than 13% increase in sedimentation compared to the control test, and the highest increase was found in N $_{2–5\text{-}12}$, where more than 36% increase was reported. The most functional distance between the rows for reducing scour downstream of the culvert was the greatest distance used in this study, i.e., $S=0.8$ h, where all the tests on this distance caused an average of over 12% reduction compared to the control test. The minimum artificial roughness height used in this study caused an average of over 13% reduction in scouring compared to that in the control test, which shows the best performance among all the heights. The minimum artificial roughness length lateral to the flow used in this study caused an average of over 10% reduction in scouring compared to the control test, which is indicative of the best performance among all the lengths lateral to the flow. The scour volume in over 61% of the tests increased by an average of more than 18% compared to the control test. The greatest scour volume increase occurred in N $_{5–4\text{-}12}$ by over 42%. In addition, the greatest reduction in scour volume was reported in N $_{4–5\text{-}10}$ with more than 34% decrease compared to the control test. In every test on the distance between the rows with $S=0.8$ h, the scour volume increased by an average of over 24% compared to that in the control test. More than 83% of the tests caused a 20% increase in the scour area on average compared to the control test. The greatest scour area increase compared to the control test occurred in N $_{4–3\text{-}12}$ by more than 31%. In all of the tests on



N

N_{2-3-12} N_{2-4-12} N_{2-5-12} N_{3-3-12}

N_{3-4-12} N_{3-5-12} N_{4-3-12} N_{4-4-12}

N_{4-5-12} N_{5-3-12} N_{5-4-12} N_{5-5-12}

Fig. 6 The topography of the tests for S = 0.8 h the distance between the rows with S = 0.8 h, the scour area increased by an average of 29% compared to the control test. In excess of 91% of the tests conducted in this study caused an average of above 16% reduction in sedimentation volume compared to that reported in the control test. The greatest reduction occurred in N $_{2–4\text{-}12}$ by more than 29% compared to the control test. The smallest increase in sedimentation volume in comparison with the control test happened in N $_{5–3\text{-}10}$ by 1%. In all of the tests with S = 0.53 h and S = 0.8 h, the sedimentation volume decreased compared to the control test. Above 91% of the tests caused an average of more than 16% reduction in sedimentation area in comparison with the control test. The greatest reduction occurred in N $_{5–4\text{-}12}$ by over 33%. In all of the tests with S = 0.53 h and S = 0.8 h, the sedimentation area decreased compared to the control test. The greatest decrease in area was reported in the test on the distance between the rows with S = 0.8 h by 21% on the average.

5 Conclusion

This study investigated the effect of present artificial roughness on bed topography downstream of a culvert and helped select the optimal dimensions. The following results were obtained from the investigation.

- Among the variable parameters explored in this study, the artificial roughness height showed a greater influence regarding scour reduction than the rest of the parameters compared to the control test.
- The most functional distance between the rows for scour reduction downstream of the culvert was the one mostly used in this study, i.e., S = 0.8 h; all of the tests conducted on this distance caused an average of 12% decrease in scouring relative to the control test.
- The minimum artificial roughness height used in this study led to an average of over 13% decrease in scouring compared to the control test, proving to have the best performance among all the examined heights.
- The minimum artificial roughness length lateral to the flow used in this study entailed over 10% reduction in scouring on the average in comparison with the control test, which was the best performance among all the lengths lateral to the flow explored in this study.
- The optimum dimensions leading to a reduction in the scouring downstream of the culvert were those used in N $_{2–4\text{-}12}$, showing over 17% reduction in comparison with the control test.
- The greatest sedimentation increase compared with the control test was observed in N $_{2–5\text{-}12}$ by more than 36%.
- The greatest reduction in the volume of sedimentation occurred in N $_{2–4\text{-}12}$ by above 29% compared to the control test.
- The greatest reduction in the scour volume was reported in N $_{4–5\text{-}10}$ by over 33% compared to the control test.
- The greatest sedimentation area reduction happened in N $_{5–4\text{-}12}$ by over 33% compared to the control test.

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Declarations

Ethical Approval This paper has neither been published nor been under review for publication elsewhere.

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