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Utilizing Modern Experimentation Method to Quantify Jet-Breaker Dimension Effects on Drop Manhole Pool Height

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Abstract

Drop manholes are commonly employed in sewer and drainage systems to reduce pipes slope. The operation of these structures is dominated by their flow regime. Poor hydraulic performance of them under Regime R2 was improved with the jet-breaker, which intersects the inlet jet; yet its proper dimensions were needed to be precisely determined. In this paper, effects of jet-breaker length, width, sagitta, and angle on drop manhole pool free-surface height were experimentally studied under 80% filling ratio of the inlet pipe. The modern statistical Design of Experiment (DoE) methodology and dimensional analysis were utilized to design the experiments in accordance with the 24-1IV fractional factorial design. Consequently, nine specific jet-breakers were built and examined at two different angles, and under various flow rates. The statistical analysis of the results shown that manhole pool height was significantly decreased when jet-breaker length, width, and sagitta were 1, 1.4, and 0.7 times the inlet pipe diameter, respectively, and its angle was at 70°. The use of DoE resulted in 21% reduction in experimental runs, cost, and time, while it provided comprehensive data analysis and objective conclusion.

Keywords: Drop Manhole; Fractional Factorial; Jet-Breaker; Optimization; Pool Height.

1. Introduction

Drop manholes are widely used in steep slope sewer and drainage systems to decrease pipes slope and flow velocities. They are also utilized downstream of culverts, large spillway shafts, and to transport stormwater from the near-surface drainage network to underground storage tunnels [1]. These structures significantly affect many features of the sewer system operation [2]; the hydraulic performance of them may be affected by limited energy dissipation, excessive pool free-surface height, considerable air entrainment, and choking of the outlet [3]. Main hydraulic features of drop manholes depend on their operating condition [4].

Manhole flow regime, which is also referred as the operating condition, is primarily determined by the inlet jet impact location inside its shaft [5]. A dimensionless number was introduced by Granata et al. [6] to classify flow regimes inside the drop manholes, namely the impact number (I), as $\mathsf{I} = V_o/D_M\,(2s/g)^{1/2}$, where V_o is mean approach flow velocity, D_M manhole internal diameter, s drop height, and g the gravitational acceleration. Flow patterns inside the drop manholes are classified into regimes: R1, R2a, R2b, R2c, R3a, and R3b, and features of them are described in detail by De Marinis et al. [7] and Granata et al. [6]. Accordingly, regime transition from R1 to R2a approximately occurs for $\mathsf{I} \simeq 0.6$; the transition from R2c to R3a for $\mathsf{I} \simeq 0.95$–1, and from R3a to R3b for $\mathsf{I} \simeq 1.5$. Recently, Ma et al. [4] have defined four regimes inside drop manholes based on inlet or outlet control conditions, as I, II, III, and IV, which are more suitable to keep tracking of energy dissipation. The former regimes just occurred under Regime I of this arrangement. Also,

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Regimes I or II were recommended at design discharge of drop manholes. Incidentally, Under Regimes R2a, R2b, and R2c, the free-falling inlet jet totally or partially impacts on manhole outlet, and adverse working conditions occur [3]. Therefore, specific jet-breaker devices were introduced and studied by Granata et al. [3]; they advised the plane jet-breaker (PJB), which is a flat plate that intercepts the inlet jet under Regime R2 in the middle of drop manhole plane. However, not any investigations were pursued to evaluate the effects of jet-breaker dimensions on drop manhole performance, so this advantageous device still needs to be more studied and properly sized in order to be fully exploited.

The energy dissipation is the main parameter for assessing drop manhole performance. However, effects of the air demand and pool free-surface height on drop manhole operation have not been neglected [3]. A water pool is developed inside this structure and the water discharge from that into the downstream sewer. Its free-surface height must be smaller than the drop height, which is limited to approximately 3 to 5 m for drop manholes, to avoid overflows and undesired backwater effects to the approaching flow. Furthermore, water pool height has a significant impact on the choking of the outlet pipe, and when manhole outflow is under constrained conditions, the energy dissipation depends on it [5, 8]. Drop manhole pool free-surface height (h_p) increases with the impact number. In regime R1, h_p is not affected by the upstream filling ratio; it increases in regime R2, while small variations are observed in regime R3a. However, a considerable pool height increase is observed under regime R3b. The effects of the approach flow depth (h_o) and jet shape become important at the transition from regime R2 to R3. For a given value of I, the pool height increases with h_o [9]. Pool free-surface height of the drop manhole is studied by several researchers, such as Granata et al. [3], Zheng et al. [5], and Ma et al. [4], who suggested equations for predicting pool height. According to Granata et al. [3], a PJB only slightly affects the pool height; while, the sudden increase of the pool height under Regime R2c was no longer observed. They argued that h_p increases gradually, reaching Regime R3b at slightly higher values than observed in the absence of the PJB. In addition, they found that pool free-surface height is primarily governed by the flow regime inside the drop manhole and should be considered as a jet-breaker selection criterion. Regarding the importance of drop manhole pool free surface height and lack of investigation on jet-breaker dimensions effects on h_p, it is convincible to pursue further research in this field of study.

In this paper, effects of jet-breaker dimensions on drop manhole pool free-surface height were experimentally investigated. Experiments were planned according to the modern statistical Design of Experiment (DoE) methodology. Engineering experiments are often done by the best-guess (with engineering judgment) and one-factor-at-a-time (OFAT) approaches. These methods require many runs and cannot identify interactions between input variables (factors), both of them are inefficient and in fact can be disastrous. In contrast, DoE is a feasible time-effective and cost-effective approach to designing and analyzing experiments. It can be used for a wide range of researches and for various purposes, such as screening of input variables, extracting a regression model, and optimizing the response. This method of experimentation was introduced in the early 1920s when Ronald A. Fisher discovered factorial designs. However, its application in hydraulic engineering is in the preliminary stages and is still unfamiliar to many engineers [10]. Recently Sangsefidi et al. [11] utilized DoE method to describe the hydraulic performance of arced weirs. They found an appropriate model by a much lower number of experiments than traditional approaches.

Effects of jet-breaker length, width, sagitta, and angle (as design factors) on pool free-surface height (as response variable) were evaluated in this study and the suitable dimensions of the jet-breaker were achieved. A combined use of 2^{4-1}_{IV} fractional factorial design and dimensional analysis was utilized to design the experiments and analyze the result. Tests were performed under 80% filling ratio of manhole inlet pipe since according to Hager [12] this ratio should be generally adopted for sewer and drainage systems. Also, by conducting partial fold-over experiments, alias links between two-factor interactions were broken and their effects were completely revealed. According to the designed experiments, nine jet-breakers were built and about 135 tests were performed; the applied design caused about 21% reduction in the test total number than a similar full factorial design. Finally, the proper dimensions of the jet-breaker were suggested for minimizing the response variable. Also, it was evidenced that merely conclude from fractional factorial results could be erroneous.

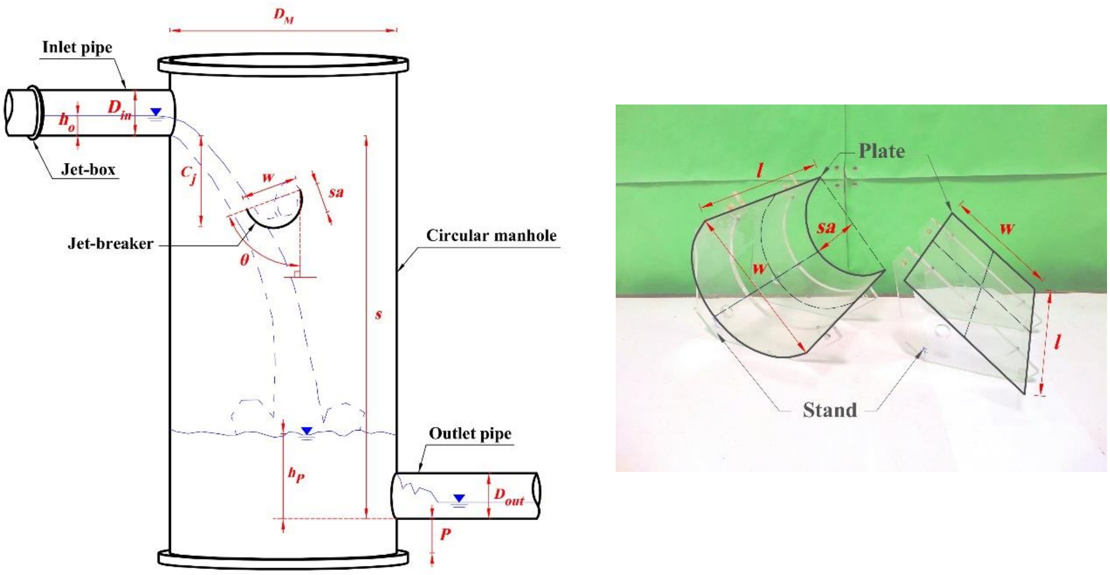
2. Materials and Method

2.1. Drop Manhole Pool Free-Surface Height

Drop manhole pool free-surface height is a function of many variables and h_P should be minimized. Christodoulou [13] related h_P to the dimensionless drop parameter, $(gs/V_o)^{1/2}$; he also mentioned that the water level depends on the angle between the inlet and outlet pipes (φ) and is affected by the downstream pipe slope (δ_{out}). Chanson [1] argued that h_P is governed by approach flow depth (h_o), outlet pipe diameters (D_{out}) and drop height (s). Moreover, Granata et al. [6] introduced an empirical relation between the pool height and g, V_o, h_o, D_M, s, D_{out}, and inlet pipe diameter (D_{in}). Therefore, pool free-surface height of a drop manhole with the jet-break, under the free-outflow condition, sufficient air supply, and plane bottom, could be expressed as a function of effective variables in accordance with Equation 1.

$$h_P = \Psi_1\left(V_o, h_o, D_{in}, \delta_{in}, D_M, s, P, \varphi, D_{out}, \delta_{out}, C_j, l, w, sa, \theta, g\right) \tag{1}$$

Where, δ_{in} is inlet pipe slope, P shaft pool depth, C_j distance between the jet-breaker center and inlet pipe invert; l, w, sa, and θ are jet-breaker length, chord (width), sagitta, and angle, respectively, while other variables are already defined (Figure 1).



(a) Drop manhole with jet-breaker **(b) Jet-breaker**

Figure 1 Dimensions of drop manhole and jet-breaker

2.2. Dimensional Analysis

According to Equation 1, a relatively large number of independent variables are required to describe drop manhole pool free-surface height (h_P). By means of dimensional analysis, these separated variables could be appropriately combined into independent dimensionless numbers in a smaller set. Dimensional analysis has been used in engineering, particularly fluid mechanics and hydraulics, for about hundred years. Many methods have been developed for doing this analysis, among which Rayleigh's method, Buckingham Π theorem, method of synthesis, and matrix method are popular [10]. Matrix method, which was used in this study, has two attractive features as: (i) desirable dimensionless variables could be inserted into the analysis, and (ii) all distinct sets of dimensionless variables are achievable. In spite of that, its calculations are relatively complicated [14].

In this method, the dimensionless numbers are calculated by means of four matrices, namely A, B, C, and D. Matrices A and B are called dimensional matrix (DM) in which the rows are the dimensions and the columns are the variables. Each element of this matrix is the exponent to which the particular dimension is raised in the particular variable. A is a square matrix whose order is equal to the rank of DM (R_{DM}) and must not be singular. The exponent of each variable in each dimensionless number are presented in each row of matrices C and D. The latter is an (N_V - R_{DM}) × (N_V - R_{DM}) square matrix, where N_V is the number of variables. The D matrix should be invertible and selected in a way that inserts desirable dimensionless variables into the analysis. The C matrix could be calculated according to Equation 2 in order to find the dimensionless set [14].

$$\mathbf{C} = -\mathbf{D}.(\mathbf{A}^{-1}.\mathbf{B})^{\mathrm{T}} \tag{2}$$

In case of fix D, intermixing the variables between the A and B matrices results in distinct sets of dimensionless variables [14].

Dimensional analysis was performed for pool free-surface height of the drop manhole with the jet-breaker by matrix method. Regarding its calculation difficulties, a code was provided with MATLAB 2016b and the analysis was conducted for variables in Equation 1, which have dimension and are not an angle. As a result, 23 distinct sets of dimensionless variables were obtained and the set with more applicable variables was selected. Consequently, Equation 1 could be expressed in dimensionless form as Equation 3.

$$\frac{h_P}{D_{\text{out}}} = \Psi_2\left(\frac{V_o}{D_M}\sqrt{\frac{s}{g}}, \frac{h_o}{D_{in}}, \frac{s}{D_M}, \frac{l}{D_{in}}, \frac{w}{D_{in}}, \frac{sa}{w}, \theta, \frac{C_j}{s}, \frac{P}{D_{out}}, \frac{s^2}{D_M D_{out}}, \frac{D_{out}}{D_{in}}, \delta_{in}, \varphi, \delta_{out}\right) \tag{3}$$

In this equation, the left-hand side term is the dimensionless pool free-surface height, the first right-hand side dimensionless variable is a variant of the impact number, the second variable is inlet pipe filling ratio, and the third one is dimensionless drop height. All dimensionless variables are well-known in the drop manhole field of study [4, 6, 13, 15], apart from the jet-breaker related variables, fourth to eighth terms, which are firstly introduced in this research. Equations 1 and 3 show, pool height which depended on 16 variables becomes a function of 14 dimensionless variables. Furthermore, this dimensionless equation could be used to establish dimensional similarity and extend the results to similar drop manholes. In the forthcoming analysis, the impact number (I) would be used instead of the first right-hand side term of Equation 3.

2.3. Statistical Design of Experiments

Engineering experiments are often done by either physical, numerical or both methods. Subjects of these investigations are generally: (i) evaluation and comparison of preliminary design configurations, (ii) selecting design factors levels which result in a robust design (a design that works well under a wide variety of field conditions), and (iii) determining key design factors that significantly impact the system [16]. The best-guess and OFAT approaches are frequently used in experimentation, but these approaches require many experimental runs and cannot identify interactions between input variables [17]. Effects of several factors on a system are generally studied by coupling the experimentation with statistical analysis.

By means of DoE methodology, experimentation would be coupled with statistics [10]. In comparison with the traditional approaches, DoE can introduce a stronger and more accurate model with a much lower number of experiments; it also comprises comprehensive analyzing procedures. These make it a time- and cost-saving approach for designing and analyzing the experiments. DoE can be employed for different objectives in almost all fields of engineering and science. In general, DoE could be used for learning about a process or a system, screening important design factors, determining factors interaction, building a mathematical model for prediction, and optimizing the response. A wide variety of experimental designs and their statistical analysis can be found in many excellent textbooks, including Ryan [18], Myers et al. [19], and Montgomery [17].

2.3.1. Design Factors and Response Variables

Before proceeding with the design of experiments by DoE, design factors and their levels should be selected appropriately. Since the effects of jet-breaker dimensions on drop manhole pool free-surface height were subject of this investigation, the jet-breaker related dimensionless numbers of Equation 3 were chosen as design factors. Table 1 represents these factors and their low, high, and center value, according to the two-level fractional factorial design, which was utilized in this research and is discussed in the next section. The low and high levels were chosen from a practical point of view and over a wide range, according to the unreplicated two-level factorial design requirements [17]. For some combinations of the design factor levels (i.e. experiments, which are under discussion in the subsequent section) nine runs were performed which each run corresponded to one flow rate (or one impact number). Flow rates were selected over a wide range that covered all flow regimes for each experiment. Other independent dimensionless numbers were kept constant; with exception of the impact number which was changed as various discharges were tested.

Table 1. Design factor levels and ranges in coded and actual values; variables are defined in Figure 1

Design Factors	Expression	Factor Levels		
		Low (-1)	Center (0)	High (+1)
A: (Jet-breaker length ratio)	l/D_{in}	1	1.5	2
B: (Jet-breaker width ratio)	w/D_{in}	0.6	1	1.4
C: (Jet-breaker sagitta ratio)	sa/w	0	0.25	0.5
D: (Jet-breaker angle)	θ	0°	35°	70°

In order to evaluate design factor effects on pool free-surface height (h_P), appropriate response variable should be designated. The average of the dimensionless pool free-surface heights of each experiment was considered as response variable according to Equation 4.

$$\overline{\left(\frac{h_P}{D_{out}}\right)} = \frac{\sum_{i=1}^{n}\left(\frac{h_P}{D_{out}}\right)_i}{n} \tag{4}$$

Where, *i* represents the run number of considered experiment and *n* is its total run number, which is nine for all experiments of this study.

2.3.2. Fractional Factorial Design

Factorial-based DoE is recognized as the most efficient and commonly used method for conducting multi-factored experiments. It works very well as factor screening tool and allows a large number of factors to be investigated in few experimental runs. This class of DoE could distinguish main and interaction effects of design factors which meaningfully affect response variable. The two-level factorial design with k design factors (i.e. a design which all of its design factors have only two levels and is called 2^k factorial design) requires a minimum of 2^k experiments to accommodate all possible combinations of factor levels (i.e. a full factorial design). The full factorial design could estimate all main and interaction effects without effect mixture (or aliasing) [16, 17].

At the early stage of this investigation, an estimate of design factors main effects and some insight regarding two-factor interactions were desirable. In fact, 5 of 15 degrees of freedom of 2^4 full factorial design (in this study k = 4) are associated with three-factor and higher interactions. However, it could be assumed that the high-order interactions are negligible [17]. Therefore, only a fraction of the full factorial design was needed to be performed. Consequently, a 2^{4-1} fractional factorial design with resolution IV was selected. This design is shown in Table 2 by FF mark. In resolution IV design, no main effect is aliased with any other main effect or with any two-factor interaction; but two-factor interactions are aliased with each other [17]. According to the selected design, significant design factors would be detected by only eight experiments instead of 16 experiments of the full factorial design, which would reduce both experimental cost and time by 50%. Significant effects could be investigated more thoroughly by subsequent additional experiments.

The Initial analysis of results in the following sections revealed one significant two-factor interaction. Therefore, partial fold-over experiments were considered to separate the two-factor interactions alias chain and were added to the designed experiments of Table 2 by PF mark. Moreover, two replications of the center point were added to the design to provide an independent estimate of experimental error and protection against second-order curvature effects [17]; center point experiments were conducted for the central level of design factors (Table 2). Furthermore, one additional experiment without the jet-breaker was considered as control experiment. As previously mentioned, each one of the experiments comprises nine similar runs which cover all flow regimes. In general, the utilized design caused the total run number of a similar full factorial design reduced from 171 runs (2^4 full factorial experiments + 2 center point experiments + 1 control experiment) to 135 runs (2^{4-1} fractional factorial experiments + 4 partial fold-over experiments + 2 center point experiments + 1 control experiment), which is approximately 21% decrease in cost, time, experimental work, and analytical effort.

Table 2. Design of experiments. Design factors are in coded values and defined in Table 1

Experiment Number	Design / experiment	Experiment Label	Coded design Factors			
			A	B	C	D
1	FF[1]	(1)	-1	-1	-1	-1
2	FF	ab	1	1	-1	-1
3	FF	ac	1	-1	1	-1
4	FF	bc	-1	1	1	-1
5	FF	ad	1	-1	-1	1
6	FF	bd	-1	1	-1	1
7	FF	cd	-1	-1	1	1
8	FF	abcd	1	1	1	1
9	PF[2]	abd	1	1	-1	1
10	PF	abc	1	1	1	-1
11	PF	bcd	-1	1	1	1
12	PF	acd	1	-1	1	1
13	CP[3]	Rep.[4] 1	0	0	0	0
14	CP	Rep. 2	0	0	0	0
15	Control	Control	-	-	-	-

[1] Fractional factorial design

[2] Partial fold-over design

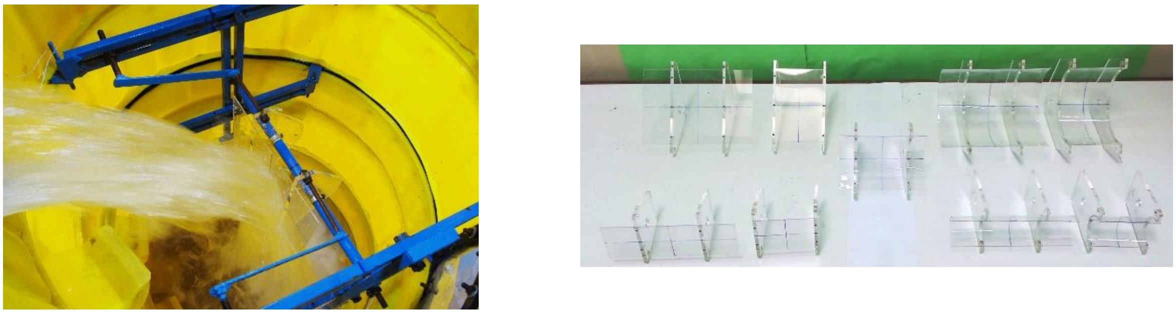
[3] Center point experiment

[4] Repetition

2.4. Experimental Setup and Facilities

The experiments of Table 2 were conducted at the Hydraulic Structures Laboratory of Shahid Bahonar University of Kerman, Kerman, Iran. A full-size circular polyethylene (PE) drop manhole, which was connected to the laboratory Measurement Distribution and Recirculation System (MDRS), was used to perform the experiments. Manhole internal diameter (D_M) is 1 m and its drop height (s) is 1.6 m, and both inlet and outlet pipes internal diameter (D_{in} and D_{out}) are equal to 0.18 m with slope (δ) of 0°; the downstream pipe ends with a free-outflow. Also, the angle between the inlet and outlet pipes (φ) is 180°, and shaft pool depth (P) is 0.14 m.

Plexiglass windows were built on one of the manhole side-walls in different elevations to carefully monitor flow patterns and inlet jet impact location. An iron frame was embedded inside the manhole to hold the jet-breaker and adjust its both position and angle precisely; with reference to Granata et al. [3], jet-breaker center was placed $s/4$ (i.e. C_j = 0.4 m) below inlet pipe invert, in manhole diametrical plane and orthogonal to inlet flow direction (Figure 2a). Nine plexiglass jet-breakers were built according to the designed experiments, which are shown in Figure 2b and their geometrical dimensions are displayed in Table 3. For each experiment, the relevant jet-breaker was properly installed in the manhole, then it was tested under various flow regimes.



(a) Jet-breaker inside manhole during 'ab' experiment at 20 l/s flow rate (I = 0.7)

(b) Tested jet breakers

Figure 2. Plexiglass jet-breakers

Table 3. Geometrical dimensions of tested jet-breakers

Jet-breaker Number	Jet-breaker Dimensions				Experiment(s) Label
	Length (l)	Width (w)	Sagitta (sa)	Angle (θ)	
#1	18 cm	10.8 cm	0 cm	0°	(1)
#2	36 cm	25.2 cm	0 cm	0° & 70°	ab & abd
#3	36 cm	10.8 cm	5.4 cm	0° & 70°	ac & acd
#4	18 cm	25.2 cm	12.6 cm	0° & 70°	bc & bcd
#5	36 cm	10.8 cm	0 cm	70°	ad
#6	18 cm	25.2 cm	0 cm	70°	bd
#7	18 cm	10.8 cm	5.4 cm	70°	cd
#8	36 cm	25.2 cm	12.6 cm	0° & 70°	abc & abcd
#9	27 cm	18 cm	4.5 cm	35°	Center Point

A jet-box was placed at the upstream of manhole inlet to maintain approach flow filling ratio at 80% (Figure 1a); it preserved the flow depth independent of flow rates. This device consisted of plexiglass plates of various filling ratios (the 80% plate was used in this study) which each one was fitted in the inlet pipe by pipe flange connections. At manhole pool, the average pool free-surface height (h_P) was measured by using a set of five piezometers connected to manhole bottom.

Water discharges were measured with an online electromagnetic flow meter with ±0.1 l/s precision. The tested flow rates were 11.4, 14.3, 17.1, 20, 22.8, 25.7, 28.5, 37.1, and 48.5 l/s which caused 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.3, and 1.7 impact numbers (I), respectively. Also, approach flow Froude number ($\mathsf{F}_o = Q/(gDh_o^4)^{1/2}$) varied between 0.67 and 2.86. More than 135 tests were conducted altogether and Figure 2a shows 'ab' experiment at Q = 20 l/s.

2.5. Research Methodology

First of all, fractional factorial (FF) and control experiments were randomly performed. In order to conduct each experiment, the relevant jet-breaker (Table 2 and Table 3) was properly installed inside the drop manhole. Then it was tested under nine predefined flow rates (or impact numbers) which were randomly applied. The flow rates were adjusted by a gate valve and the electromagnetic flow meter and afterward, the average pool free-surface height (h_P) was recorded according to the five piezometers which were connected to manhole bottom; the water height in each piezometer was measured by a ruler. Since the Initial analysis of results indicated the need for partial fold-over and center point experiments, so in the second place, these experiments were similarly performed. Finally, the results were analyzed and proper dimensions of the jet-breaker were revealed as presented in the following sections.

3. Results and Discussions

3.1. Fractional Factorial Experiments

The fractional factorial experiments (Table 2) were performed in random order together with control experiment and Figure 3 shows the dimensionless pool free-surface heights (h_P/D_{out}) of these experiments versus the impact number. Accordingly, several jet-breakers successfully reduced h_P/D_{out}, especially over R2 and R3a regimes. Moreover, some jet-breakers completely prevent the local peak at I = 0.8 where the inlet jet collides with manhole outlet. This figure reveals that pool free-surface height linearly increases with the impact number (or flow discharge).

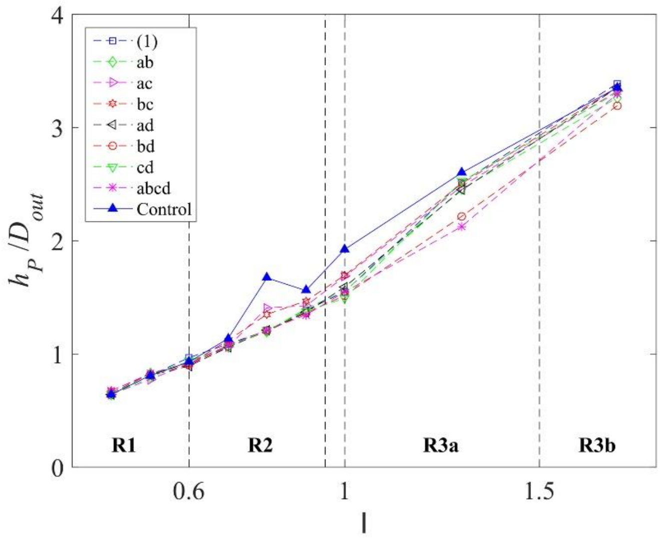


Figure 3. Dimensionless pool free-surface height (hP/Dout) versus impact number (I) for fractional factorial and control experiments (Table 2)

According to Equation 4, the averages of the dimensionless pool free-surface height values of each fractional factorial experiment were used to estimate design factor effects on drop manhole pool free-surface height. The estimated effects and alias chains are shown in Table 4. Moreover, the half-normal probability plot of the effects, which is a common tool for analyzing fractional factorial results, is presented in Figure 4. In this plot, points that significantly deviate from the straight line, which passes through the origin and close to the fiftieth percentile data value, are considered as significant effects [17].

Table 4. Estimated values of effects and alias chains of 2^{4-1}_{IV} design

Estimate	Alias Structure
[A] = -0.0041	[A] → A + BCD
[B] = -0.0109	[B] → B + ACD
[C] = 0.01067	[C] → C + ABD
[D] = -0.0252	[D] → D + ABC
[AB] = -0.0091	[AB] → AB + CD
[AC] = -0.0102	[AC] → AC + BD
[AD] = 0.0069	[AD] → AD + BC

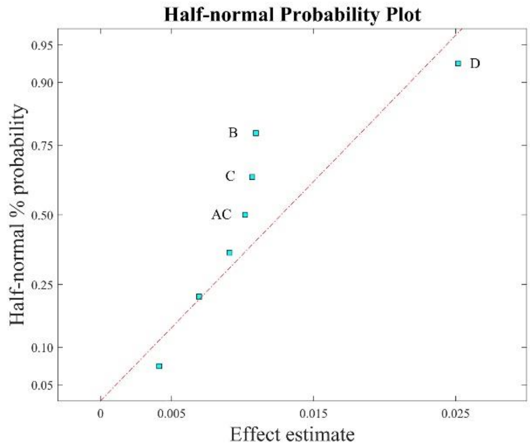


Figure 4. Half-normal probability plot of effects for pool free-surface height

According to Figure 4, the main effects of the factors B, C, and D, together with the AC interaction effect are large. Because of aliasing, these effects are really B + ACD, C + ABD, D + ABC, and AC + BD, respectively. Nevertheless, since it seems plausible that the three-factor and higher interactions are negligible, the B, C, and D could be considered as significant main effects. However, the AC interaction is puzzling since it could be either AC, BD, or both two-factor interactions which are significant. To find out which interactions are important the partial fold-over experiments of Table 2 would be required to de-alias all two-factor interaction effects. Results and analysis of these experiments are presented in the subsequent sections.

3.2. Partial Fold-Over Experiments

The center point and partial fold-over experiments of Table 2 were performed in random order. The dimensionless pool free-surface heights (h_P/D_{out}) of these experiments versus the impact number is shown in Figure 5. As former experiments, some jet-breakers decrease h_P/D_{out} over R2 and R3 flow regimes relative to the control experiment. Assuming that the three-factor and higher interactions are negligible, significant main and two-factor interaction effects could be revealed by analysis of variance (ANOVA) in the following section.

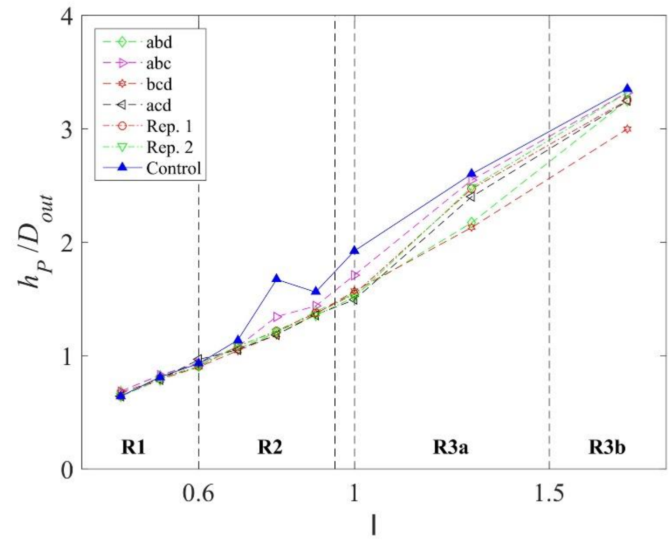


Figure 5. Dimensionless pool free-surface height (h_P/D_{out}) versus impact number (I) for partial fold-over, center point and control experiments (Table 2)

3.3. Analysis of Variance

The averages of the dimensionless pool free-surface heights of each experiment (Equation 4) were used as response variable to evaluate design factor effects. ANOVA results are summarized in Table 5. This table shows that factor D effect is statistically significant at 1% significance level ($\alpha = 0.01$) and the model and B, AB, BD, and CD effects are statistically significant at $\alpha = 0.05$. The statistical significance is determined by p-value, which shows the probability value and its smaller value leads to a more significant effect [17]. Moreover, the ANOVA results indicate that there is no evidence of second-order curvature in the response over the region of exploration since the curvature p-value is rather large. Additionally, the lack of fit (LOF), which is defined as the deviation of data from the fitted model, is not significant which means that there is a strong indication that the model fits with the data well [19].

Table 5. Analysis of variance results for pool free-surface height

Source of variation	Estimate	Sum of Squares	Degrees of Freedom	F_0	P-Value
Intercept	1.4847	-	-	-	-
model	-	0.0200	10	19.3244	0.0164
A	-0.0051	0.0002	1	2.1137	0.2420
B	-0.0119	0.0012	1	11.6528	0.0420
C	0.0098	0.0008	1	7.8743	0.0675
D	-0.0261	0.0058	1	56.3672	0.0049
AB	0.0118	0.0011	1	10.6915	0.0468
AC	0.0023	0.0000	1	0.4247	0.5611
AD	0.0059	0.0003	1	2.7045	0.1986
BC	0.0010	0.0000	1	0.0815	0.7939
BD	-0.0125	0.0013	1	12.1310	0.0400
CD	-0.0208	0.0035	1	33.5810	0.0102
Curvature	-	0.0000	1	0.1778	0.7017
LOF*	-	0.0002	1	1.6476	0.4213
PE**	-	0.0001	1	-	-
Total	-	0.0203	13	-	-
Residual	-	0.0003	3	-	-

* Lack of fit
** Pure Error

ANOVA results revealed that it is the BD interaction which is significant but not the AC interaction. Furthermore, this analysis shows that the AB and CD interactions are also significant while the fractional experiments and the half-normal probability plot of effects (Figure 4) did not detect them. The estimated effects of the AB and CD interactions are 0.0118 and -0.0208, respectively, since these interactions are combined in utilized fractional factorial design (Table 4), their effects were canceled out and not indicated. Therefore, just performing fractional factorial experiments and concluding from them could be misleading.

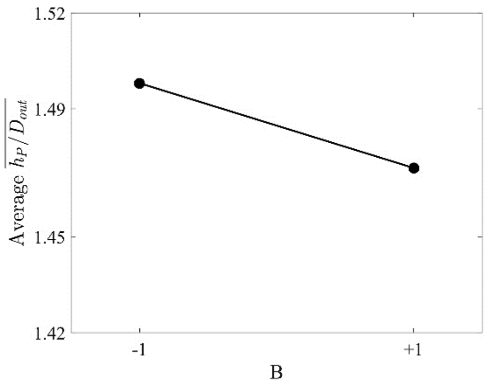
The estimate column values of the ANOVA tables (Table 5) are in fact the regression model coefficients. According to these values and significant effects, the regression models for the response variable over the ranges of the design factors are presented in Equation 5.

$$\frac{h_P}{D_{out}} = 1.4847 - 0.0051(\mathrm{A}) - 0.0119(\mathrm{B}) + 0.0098(\mathrm{C}) - 0.0261(\mathrm{D}) + 0.0118(\mathrm{AB}) - 0.0125(\mathrm{BD}) - 0.0208(\mathrm{CD}) \quad (5)$$

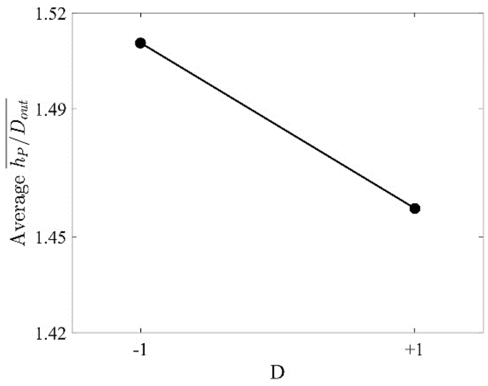
Where A, B, C, and D are design factors, which defined previously in Table 1. The factors A and C were considered in order to preserve the model hierarchy. The model accounted for 96.0% variability in the response, hence its R-squared (R^2) was 0.960. As well, the adjusted R^2 (R^2_{Adj}) was 0.914 and its closeness to R^2 indicate that the correct terms were used in the model. In the next section, the significant effects are closely studied.

3.4. Factor Effects and Optimum Levels

The impacts of the significant main effects (i.e. jet-breaker width ratio (factor B) and jet-breaker angle (factor D)) on the response variable are shown in Figure 6.



(a) Effect of jet-breaker width ratio (factor B)

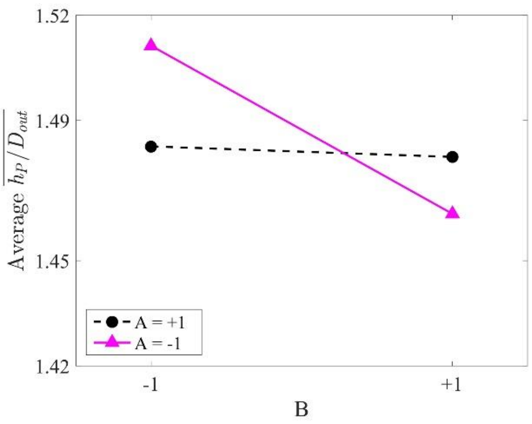


(b) Effect of jet-breaker angle (Factor D)

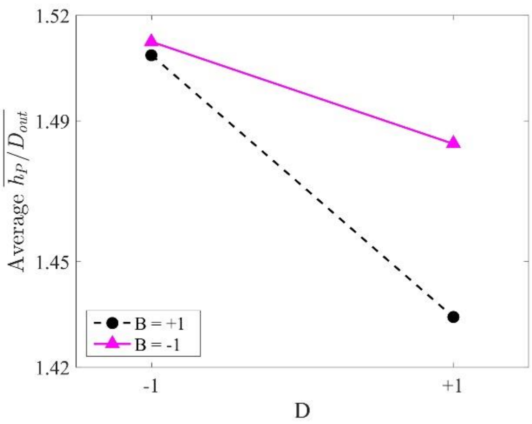
Figure 6. Impact of significant main effects on drop manhole dimensionless pool free-surface height

According to this figure, factor D effect is stronger than factor B effect. Moreover, different levels of the factor D more alter the dimensionless pool free-surface height. Furthermore, the minimum value of pool free-surface height happened when both B and D are at their high levels. Consequently, jet-breaker width (w) equal to 1.4D_{in} and jet-breaker angle (θ) at 70° are favorable. However, since the factors B and D are involved in significant interaction effects, their main effect plots might be under false pretenses and their proper levels should be determined from their interaction plots.

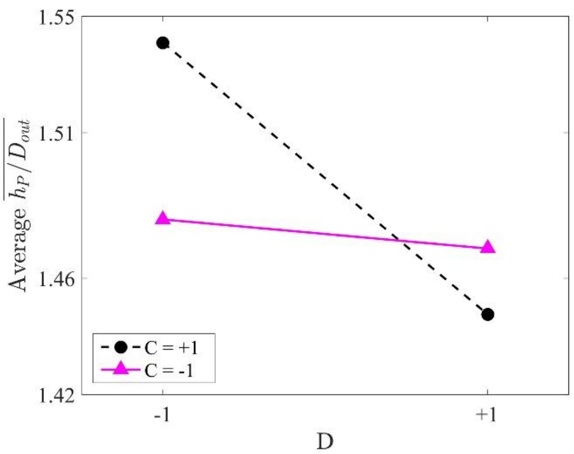
The impact of significant interaction effects (i.e. AB, BD, and CD) on the average of drop manhole dimensionless pool free-surface heights are demonstrated in Figure 7.



(a) Interaction plot of jet-breaker length ratio and width ratio (AB)



(b) Interaction plot of jet-breaker width ratio and angle (BD)



(c) Interaction plot of jet-breaker sagitta ratio and angle (CD)

Figure 7. Impact of significant interaction effects on drop manhole dimensionless pool free-surface height

As Figure 7a reveals, the factor B (jet-breaker width ratio) has marginal effect on response variable when the factor A (jet-breaker length ratio) is at the high level (i.e. level +1), while its effect is considerable at the low level (i.e. level -1) of the factor A. This shows that the factor A is dominating factor and it high level suppress factor B effect. Despite that, the factor B reveals its effect when the factor A it is at level -1. The low level of the factor A and the high level of the factor B result in a lower response and are optimum levels for these design factors. In spite of that, the effect of the factor A is negligible when the factor B is at its high level. According to Figure 7b, factor B effect is marginal at the low level of the factor D (jet-breaker angle) but it is remarkable at factor D high level. Moreover, it demonstrates that jet-breaker angel is an effective factor regardless of factor B level. This figure shows that a lower pool free-surface height is gained when both factors B and D are at their high levels. With reference to Figure 7c, at the low level of the factor D, the factor C (jet-breaker sagitta ratio) increase causes pool free-surface height increase; however, causes pool free-surface height decrease at the high level of the factor D. The high levels of the factors C and D cause a lower response, whereas factor C effect is negligible at the high level of the factor D. Also, this figure shows that jet-breaker angle effect is negligible when the jet-breaker is flat but its effect becomes considerable when the jet-breaker is curved.

In short, drop manhole pool free-surface height decreases significantly when jet-breaker length ratio is equal to 1, width ratio is equal to 1.4, sagitta ratio is equal to 0.5, and its angle is at 70°. Practically, the direct impact of the inlet jet with drop manhole pool is further prevented at high levels of jet-breaker width ratio and angle, so the pool would be less turbulent and more smoothly discharged, which result in a lower pool height. It should be mentioned that these dimensions of the jet-breaker just reduced drop manhole pool free-surface height (h_P) and not necessarily improve its overall hydraulic performance.

4. Conclusion

Drop manholes are extensively employed in steep-slope urban area to reduce pipes slope and flow velocities. Their performance was improved by the plane jet-breaker which intercepts the inlet jet under Regime R2 and was firstly introduced by Granata et al. [3]. In this study, a combined use of dimensional analysis and modern statistical Design of Experiment (DoE) methodology was utilized to evaluate jet-breaker length, width, sagitta, and angle effects on drop manhole pool free-surface height. The experiments were designed in accordance with 2^{4-1}_{IV} fractional factorial design, and the partial fold-over experiments were considered to de-alias two-factor interaction effects. With reference to the designed experiments, nine various jet-breakers were built and tested under nine different impact numbers. About 135 tests were conducted and in comparison with a similar full factorial design, the number of experimental runs declined about 21%. The statistical analysis of the results revealed that jet-breaker length equal to D_{in} (inlet pipe diameter), jet-breaker width equal to $1.4D_{in}$, jet-breaker sagitta equal to the half of jet-breaker width, and jet-breaker angel at 70° would significantly decrease drop manhole dimensionless pool free-surface height (h_P/D_{out}). In addition, this research indicates that meaningful effects might not be detectable by just resolution IV fractional factorial design since significant two-factor interaction effects could cancel out each other. In spite of that, by augmenting the fractional factorial design with the partial fold-over experiments all significant main and two-factor interaction effects could be efficiently revealed. Moreover, the efficiency and applicability of DoE in the experimental investigation of hydraulic structures was demonstrated.

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7. Conflicts of Interest

The author declares no conflicts of interest.

8. References

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