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RESEARCH ARTICLE

INNOVATIVE PROTECTION AGAINST THE SCOUR AT OUTLETS OF CYLINDRICAL CULVERTS AND APPLICATION USING MULTI EXPRESSION PROGRAMMING TECHNIQUE (MEP)

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ABSTRACT

The present experimental study suggested a pool to resist the localized scour downstream of cylindrical culverts. The study was conducted with a range of intensity number of discharges $F_p = [0.44{:}0.98]$. The proposed pool decreased the scour by 70%. The pool of the comparative depth = 0.29 gives the minimal geometrics of the scour hole. The pool length has a significant influence on the scour depth. Multi Expression Programming (MEP) is utilized to develop predicting equations of the erosion geometrics. The proposed models were compared with Multiple Linear Regression (MLR). The average precision of the equations improved by 8% more than multiple linear regression equations (MLR).

KEYWORDS

scour, tube, pool, culverts, and artificial intelligence.

1. INTRODUCTION

Estimating the scour at the exit of culverts is an essential need in the engineering applications. Generally, predicting the scour is very difficult. The earlier researches may be divided into the following categories:

- The studies discussed hydraulic conditions;
- The studies discussed the protection tools;
- The studies modeled the erosion around the structures; and
- The studies applied artificial intelligence.

There are many studies discussed hydraulic conditions affected the erosion. A studied the scour patterns at the exit of circular jets (Jame et al., 2013). A group researcher also studied the erosion of two types of jets (Mehraein et al., 2011). It was discovered that jet features affected the erosion profile. Jahromi and Nasserian demonstrated that the increase of flow depth at channel boundary diminished the erosion features (Jahromi and Nasserian, 2010). Nédélec and Gay discussed the consequence of outlets of drainage tubes in the open channels (Nedelec and Gay, 2008). The tube slope was discovered as an item affected the transition zone. In some research paper showed that densimetric Froude number, soil and end depths were significant items (Faraque et al., 2008). A group researchers pointed out the slope of culvert increased the scour by 10% to 40% (Abt et al., 1985).

There are many studies discussed the protection tools against erosion. There also some of researcers utilized different intermediate and end sills to improve the basin performance at the exit of culverts (Tiwari and Seema, 2013; Tiwari et al., 2013). In meanwhile, a group researcher diminished the erosion by cross vanes (Kerenyi et al., 2003). Saleh investigated the hydraulic jump formed in stilling basins with a pool (Saleh, 2006). The influence of the pool's length and depth on the jump features were studied. Verma and Goel proposed experimentally an efficient stilling basin at the exit of a tube culvert (Verma and Goel, 2003). A group researchers pointed out that 68% of the erosion was diminished using a vertical deflector for the flow at the exit of culverts (Negm et al., 2014). In other research study, they explored the headwall's effects on erosion at the exit of culverts (Mendoza et al., 1983). The formulas defining the scour cavity were presented.

Many expressions were proposed correlating scour features. Melville and Lim submitted an equation of the erosion (Melville and Lim, 2013). The equation pointed out the comparative erosion was three times as the jet Froude number. Some researchers numerically simulated the erosion in a plunge pool by a two-dimensional jet (Jia et al., 2001). In other hand, researchers have pointed out that eighty-one percent of the extreme scour has existed at thirty-one minutes of a 316minitues-test for the uniform sand (Ruff et al., 1982). Guven and Gunal specified that the genetic programming accuracy to expect the scour downstream hydraulic structures was better than other techniques (Guven and Gunal, 2008). A study showed that genetic algorithms gave high accuracy results for the erosion depth downstream sills (Zahiri et al., 2014). Azamathulla and Yusoff used gene-expression programming as a tool to approximate the erosion depth below pipelines (Azamathulla and Yusoff, 2013). It was a very good tool to approximate the erosion depth.

Some researchers examined scour experiments below different, skewed pipelines (Azamathulla et al., 2014). A regression model was built to guess the erosion depth below the different skewed pipelines. The developed regression model gave a low accuracy result (R2 = 0.55). there also researcher applied Support Vector Machines to approximate the erosion depth (Nassar et al., 2009). The results indicate that the precision of the models generated by support vector machines were better than the traditional statistical equations. Mohamed applied Stochastic Gradient Boosting (SGB) to simulate free jumps downstream expansions (Mohamed, 2010). It was found that it is possible to apply SGB in practical applications. Large group of researchers investigated ANN technique as a tool to predict 2-D sediment (Negm et al., 2003; Negm et al., 2007). It was

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found that ANN technique gave acceptable results compared the collected field data.

Multi Expression Programming technique (MEP) software is a free software for scientific applications (Mihai, 2016). It is utilized as a prediction tool. The features of the technique were presented (Oltean and Grosan, 2003; Oltean and Grosan, 2004). Oltean Mihai reported the main steps of the MEP algorithm. As seen, there are no available studies that proposed a hard pool at the exit of the tube culvert to minify the scour. The paper examines the existing of a hard pool at the exit of tubes. Multi Expression Programming (MEP) is utilized to develop predicting equations of the erosion geometric. The proposed models were compared with Multiple Linear Regression (MLR).

2. Dimensional Analysis Approach

The dimensionless equation (1) is obtained to describe items affecting the erosion. Erosion geometries include X/ϕ and h/ϕ, which are the comparative length and depth of erosion cavity at the exit of tubes, respectively.

$$\frac{X}{\phi}\ and\ \frac{h}{\phi} = f\left(\frac{Q}{\sqrt{g\phi^5}}, \frac{h_{up}}{\phi}, \frac{h_{out}}{\phi}, \frac{h_t}{\phi}, \frac{d_{84}}{\phi}, \frac{d_{16}}{\phi}, \frac{X_r}{\phi}, \frac{h_p}{\phi}, \frac{X_p}{\phi}\right) \quad (1)$$

Where: $Q/\sqrt{g\phi^5} = F_p$ is the intensity number of discharge; ϕ is tube inner diameter; g is gravity acceleration; Q is the passing flow rate through the tube; h_{up}/ϕ is the comparative flow depth upstream the tube intake; h_{out}/ϕ is the comparative depth at tube's exit; h_t/ϕ is the comparative depth at channel's end; d_{84}/ϕ and d_{16}/ϕ are the comparative soil items; X_r/ϕ is the comparative secured bed length; h_p/ϕ is the comparative pool depth; X_p/ϕ is the comparative pool length. The constant dimensionless items are omitted. Items that may affect the erosion at the exit of tubes are shown in the next figure.

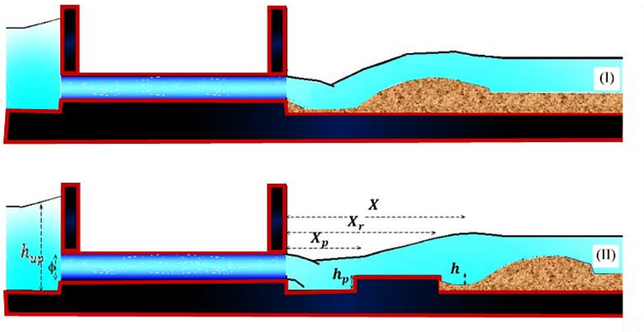

Figure 1: Sectional elevations sketches for lab's models [a] mobile bed case [b] solid pool case

3. Arrangement of Lab Works

3.1 The flume and measuring tools

- The models were built in a horizontal channel of 50cm depth, 30cm width while the channel's length is 1560cm. The lab work was conducted at the hydraulics lab at the faculty of engineering, Zagazig University.
- The downstream water surface was kept constant from the bed.
- The measuring of flow discharges and water surfaces were done by an orifice meter installed in the main feeding pipeline and 2- point gauges, respectively.

3.2 The models and soil

- The exit of a 0.09m diameter tube was kept over the channel bed by 0.1 m, see figure (1). The channel cross-section of the tube's exit is filled with sandy mobile soil particles with depth of 0.1 m, see the figure (2).
- $d_{50} = 0.88\ mm$, and the standard deviation of soil particles = $\sqrt{d_{84}/d_{16}}$= 2.59.

3.3 The test times

Few tests were done to detect the influence of the time. It was discovered that 74.6% of the extreme relative erosion depth attained at 600 minutes occurs by the end of the first half hour. As a result, the test time is taken as 30 minutes. Many investigations have taken the same experimental period (Ruff et al., 1982; Negm et al., 2014).

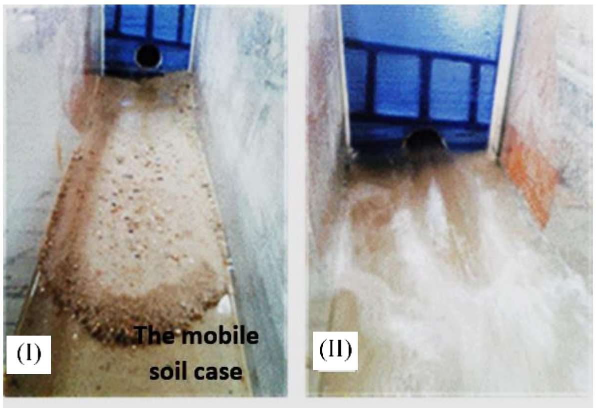

Figure 2: Photos for the models [I] the deformed bed [II] the flow at the exit of culvert

4. The Experimental Phases

The erosion geometries are recorded for six tests for the mobile bed case without the pool. The models of the first experimental phase consisted of a pool with h_p/ϕ=0.89 and four different proportional lengths X_p/ϕ = 1.77, 3.55, 5.55 and 7.33. The pool was formed within a hard bed of X_r/ϕ = 11.11, see figure 2.

The second phase consisted of a pool with X_p/ϕ = 5.55 and four proportional depths as h_p/ϕ =0.29, 0.41, 0.58 and 0.89.

5. Pool Length Influence

The correlation between the intensity number of the discharge F_p versus h/ϕ and X/ϕ for X_p/ϕ = 1.77, 3.55, 5.55 and 7.33 are demonstrated in figures (3a and 3b), respectively. The varying of X_p/ϕ has a small influence upon X/ϕ, see figure 3b. In the opposite side, the changing of X_p/ϕ has a significant effect upon h/ϕ, see figure 3a. The pool case of X_p/ϕ = 5.55 reduces the average depth of erosion by 50% with regard to the mobile bed case. The pool case of X_p/ϕ =5.55 gives the minimal h/ϕ comparably to the mobile bed case.

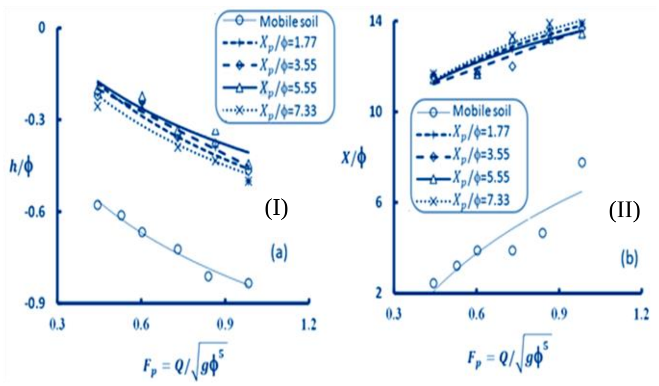

Figure 3: Relationships between h/ϕ & X/ϕ versus F_p for studied X_p/ϕ [I] h/ϕ [II] X/ϕ

Selected longitudinal profiles of bed deformations are existing for cases of F_p=0.98, see figure (4). The location of the extreme eroded point is not affected by varying the comparative pool length.

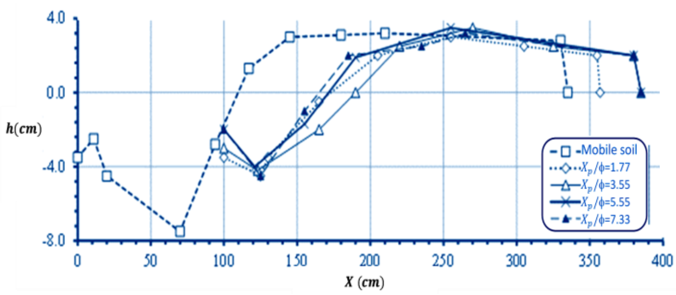

Figure 4: Longitudinal scour profiles for studied X_p/ϕ and F_p=0.98

A part of the jet moves directly to the mobile bed, see Figure (5a). As a result, the erosion depth growths more than its value for $X_p/\phi = 5.55$. For $X_p/\phi = 5.55$, the main flow jet is contained in the pool. As a result, the erosion depth was decreased to the minimal value, see figure (5b). In contrast, as the pool length growths more than $X_p/\phi = 5.55$, the turbulence formed in the pool becomes nearer to the mobile bed and the erosion increased, see figure (5c).

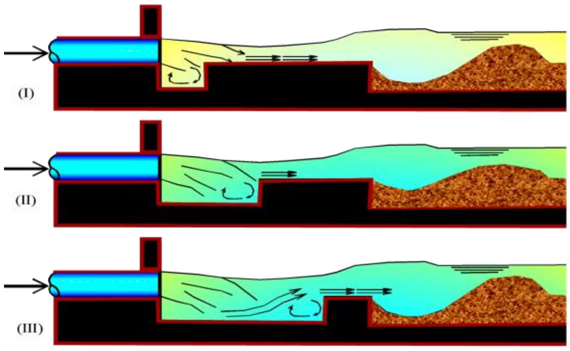

Figure 5: Flow directions sketches for studied pool lengths [I] short pool length [II] ideal pool length [III] longer pool length

6. Pool Depth Influence

The correlation between h/ϕ and X/ϕ versus F_p for $h_p/\phi = 0.29$, 0.41, 0.58 and 0.89 are demonstrated in figures (6a and 6b). The variation of the pool depth has a significant effect on h/ϕ and X/ϕ. The pool depth of $h_p/\phi = 0.29$ gives minimal h/ϕ and X/ϕ. The decrease of h/ϕ is 70% related to mobile bed case. Longitudinal profiles of bed deformations for F_p=0.98 are presented in figure (7). The scour cavity becomes smaller as the comparative pool depth decreased. The pool case of $h_p/\phi = 0.29$ decreased the scour cavity to minimal bounds.

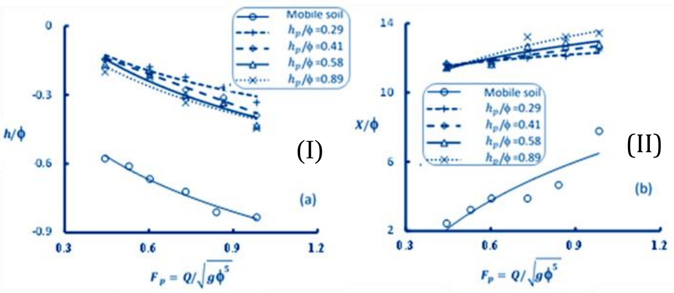

Figure 6: Relationships between h/ϕ & X/ϕ versus F_p for studied h_p/ϕ [I] h/ϕ [II] X/ϕ

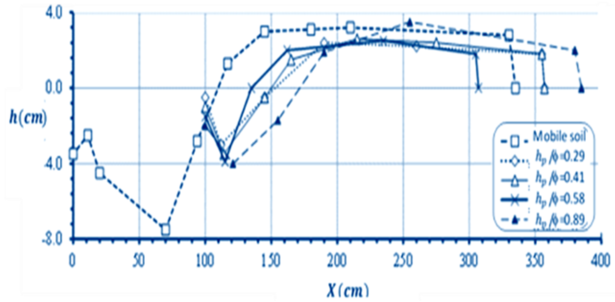

Figure 7: Longitudinal scour profiles for studied h_p/ϕ and F_p =0.98

Flow behaviors are sketched for two pool depths, see Figure (8). For $h_p/\phi = 0.29$, the jet losses the energy by turbulences formed in the pool. As a result, the erosion decreased to the least value, see Figure (8a). As h_p/ϕ becomes > 0.29, turbulences become adjacent to the dead zone formed in the pool, see Figure (8b). The energy loss becomes smaller than $h_p/\phi = 0.29$

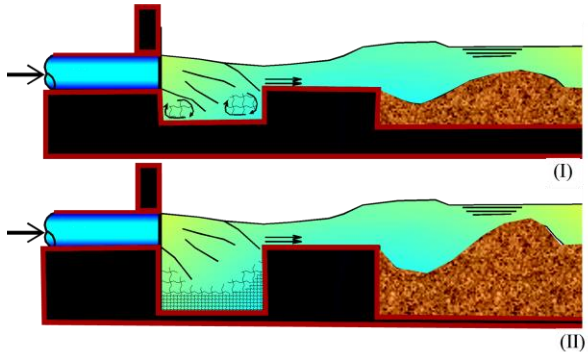

Figure 8: Flow directions sketches for studied pool depths [I] ideal pool [II] deeper pool

7. Multiple Linear Regressions (MLR)

The items governing erosion at the exit of the culvert are correlated under the basis of Multiple Linear Regression (MLR). The equation predicting each of h/ϕ; and X/ϕ is proposed for the pool case, see Eq. (2).

$$h/\phi \;\&\; X/\phi = a + b \times \frac{h_p}{\phi} + c \times \frac{X_p}{\phi} - d \times \frac{h_{out}}{\phi} + e \times F_p - f \times \frac{h_{up}}{\phi} \tag{2}$$

Eq. (2) is proposed depending on 85% of experiments. The rest data is utilized to approve Eq. (2). Figures (9a and 9b) demonstrates the assessment of Eq. 2 versus records of h/ϕ and X/ϕ, respectively. There is a good acceptance between Eq. (2) and records, see table no. (1).

Table 1: MLR equations features

	Trained data		Validation data		Equation coefficients					
	R^2	Corr. Factor	R^2	Corr. Factor	**a**	**b**	**c**	**d**	**e**	**f**
h/ϕ	**0.862**	**0.928**	0.844	0.918	0.0069	0.0741	0.0509	0.7540	0.4040	0.2067
X/ϕ	**0.914**	**0.956**	**0.841**	**0.917**	9.0635	4.2692	0.6597	10.9696	2.7863	1.7026

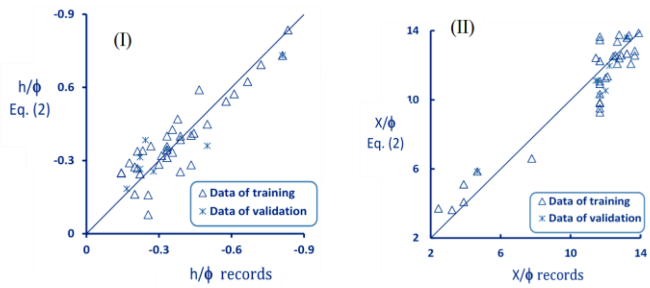

Figure 9: [I] The calculated h/ϕ using Eq. 2 vs. the measured ones [II] The calculated X/ϕ using Eq. 2 vs. the measured ones

8. Multi Expression Programming (MEP)

Multi Expression Programming technique (MEP) is utilized to predicting erosion at the exit of the culvert tube. Three equations predicting h/ϕ for the pool case are presented, see Eqs. (3, 4 and 5). Two equations are proposed to anticipate X/ϕ, see Eqs. (6 and 7). Features of equations are represented in table (2).

$$\frac{h}{\phi} = \frac{\exp\frac{h_p}{\phi}\times(F_p-\frac{h_{up}}{\phi})}{\frac{X_p}{\phi}} + \exp(F_p) + \frac{(\sin\frac{h_p}{\phi}+\frac{h_p}{\phi})^2}{\exp(DI\times\frac{h_{out}}{\phi})} \tag{3}$$

$$\frac{h}{\phi} = \frac{\exp\left[\frac{h_p}{\phi}\times F_p-(\frac{X_p}{\phi}\times\frac{h_p}{\phi}+F_p)\right]-\frac{h_{up}}{\phi}}{(\frac{h_{out}}{\phi}\times F_p)^2+\frac{h_{up}}{\phi}+\frac{X_p}{\phi}} + \frac{\frac{h_p}{\phi}\times(\frac{X_p}{\phi}\times\frac{h_p}{\phi}+F_p)}{\sin(\frac{h_{up}}{\phi})+\frac{X_p}{\phi}\times\frac{h_p}{\phi}+F_p-\frac{X_p}{\phi}+\exp(\frac{X_p}{\phi}\times\frac{h_p}{\phi}+F_p)} \tag{4}$$

$$\frac{h}{\phi} = \frac{h_{up}/\phi}{\frac{h_p}{\phi}+2F_p\frac{h_{up}}{\phi}+\frac{X_p}{\phi}+1-\frac{h_p/\phi}{F_p\times\frac{h_{out}}{\phi}\times(\frac{X_p}{\phi}-\frac{h_{out}}{\phi})}} \tag{5}$$

$$\frac{X}{\phi} = \frac{X_p}{\phi} + \frac{h_p}{\phi}\left(\frac{2h_{up-h_{out}}}{\phi\, F_p} - \frac{X_p}{\phi}\right) + \left(\frac{2h_{up-h_{out}}}{\phi\, F_p}\right) + \frac{\phi\,(F_p)^3+X_{p-2h_{out}}}{h_{out}+(X_p)^3} \tag{6}$$

$$\frac{X}{\phi} = \frac{2h_{up}}{\phi} + \frac{{h_p}^3}{\phi}\exp\frac{h_{out}}{\phi} + \frac{X_p+{h_p}^2}{\phi} + \frac{X_p}{X_{p-{h_p}^2-h_{out}}} + \frac{h_p}{{h_p}^3+\phi {F_p}^3} - F_p\frac{h_p}{\phi}\left(\frac{X_p}{\phi} - \exp\frac{h_{out}}{\phi}\right) \tag{7}$$

Table 2: MEP equations features

Equation	Trained data		Validation data	
	R^2	Corr. Factor	R^2	Corr. Factor
Eq.(3)	0.880	0.938	0.909	0.953
Eq.(4)	0.932	0.956	0.928	0.963
Eq.(5)	0.901	0.949	0.886	0.941
Eq.(6)	0.968	0.984	0.973	0.986
Eq.(7)	0.951	0.975	0.948	0.974

The equations are proposed depending on 85% of the measures. The rest 15% of the measures are utilized to check MLP equations. An assessment of h/ϕ records are demonstrated in figures (10a and 10b) versus Eqs. (3, 4 and 5). Equation (3) may be refused. Figures (11a and 11b) demonstrate an assessment of X/ϕ records opposing Eqs. (6 and 7).

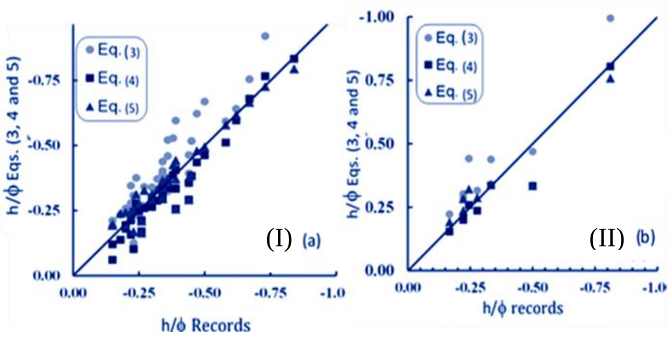

Figure 10: The calculated h/ϕ using Eqs. 3, 4 and 5 and the measured ones [a] the training data sets [b] the validated data sets

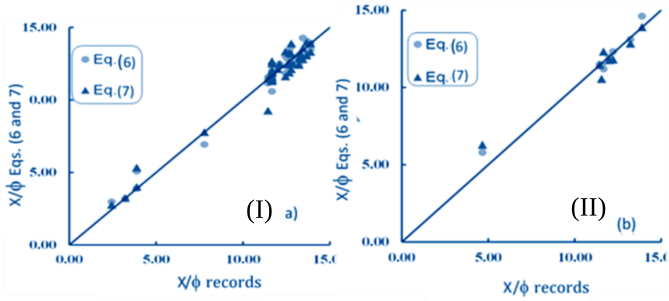

Figure 11: The calculated X/ϕ using Eqs. 6 and 7 and the measured ones [a] The training data sets [b] The validated data sets.

9. Comparison Between MLR and MEP

The accuracies of MEP equations (3, 4, 5, 6 and 7) are evaluated with respect to MLR equation (2) depending R^2 and the coefficient of correlation. Figures (12a and 13a) demonstrate an assessment between R^2 of MEP and MLR's equations. MEP are more precise than MLR. The average increasing in R^2 is 8%. Figures (13b and 13b) demonstrate an assessment of the coefficient of correlation for MEP and MLR. MEP equations are more correlated to the records than MLR. The average increasing coefficient of correlation is 4.5%. Obviously, MEP is a confident tool.

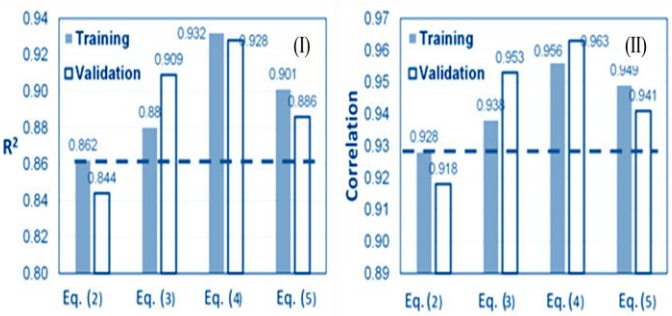

Figure 12: Comparisons between MLR and MLP models [a] R^2 for Eqs. 2, 3, 4 and 5 using different data sets [b] the correlation factor for Eqs. 2, 3, 4 and 5 using different data sets

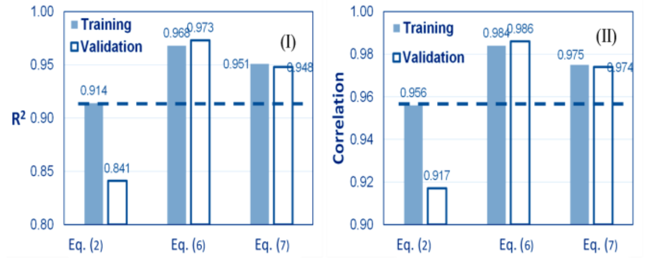

Figure 13: Comparisons between MLR and MLP models [a] R^2 for Eqs. 2, 6 and 7 using different data sets [b] the correlation factor for Eqs. 2, 6 and 7 using different data sets.

10. Conclusion

The study examines the local erosion features at the exit of tube culverts. The measurements and modeling prove that:

1. The varying of the pool's length has a small influence on the comparative erosion length, X/ϕ;
2. The pool length has a significant influence on the comparative erosion depth h/ϕ;
3. The pool of X_p/ϕ = 5.55 gives minimal h/ϕ with respect to the mobile soil case. It decreases the average h/ϕ by 50%;
4. The pool of h_p/ϕ = 0.29 gives the minimal h/ϕ and X/ϕ.
5. The pool of h_p/ϕ = 0.29 decrease of the comparative erosion depth by 70% with regard to mobile soil case.
6. Multi Expression Programming equations are more accurate than multiple linear regression equations. The average increasing in R^2 is 8%.
7. MEP equations are more correlated to records than multiple linear regression equations by 4.5%.

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