Optimization Wind-Induced Interference on Mono-Slope Roof: Insights from CFD Modeling and Machine Learning Validation

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**Abstract.** Mono-slope roofs have gained popularity due to their aesthetic appeal and practical advantages in construction. However, the design of these roofs must consider the impact of wind forces to ensure structural integrity and safety. Present research focuses on analyzing the wind effects on mono-slope roofs in an isolated and interfering condition with T formation with variable spacing (0, 0.5B, B, 1.5B and 2B) using Computational Fluid Dynamics to provide a comprehensive understanding of how wind interacts with mono-slope roof structures, leading to a comparative study that evaluates different design considerations and their effectiveness in mitigating wind-induced stresses. Further, with Machine application tools, parameters that crucially influence IF, ID and Cpe are determined. The findings highlight significant variations in wind pressures and flow patterns due to interference effects, emphasizing the importance of considering such factors in the design and construction of mono-slope roofs. The sensitivity analysis using ML tools suggested that the spacing and angle of wind incidence have the main influence on IF, ID and Cpe. This research is crucial for architects, engineers, and construction professionals to optimize the design and construction of mono-slope roofs for enhanced performance and resilience against wind loads.

**Keywords:** Computational Fluid Dynamics (CFD); Interference Factor (IF); Interference Difference (ID); Mono-Slope Roof; Pressure Coefficient (Cpe).

# Introduction

Although there has been considerable advancement in studying wind loads on low-rise buildings over recent years, several important questions continue to arise. These include issues related to the correct methods for testing and interpreting results, such as the impact of scaling, the choice and length of pressure peak measurements, and the uncertainty surrounding how various codes and standards apply to different building types and shapes. Specifically, the wind load guidelines for low-rise buildings found in the 1980 Supplement to the National Building Code of Canada [1], based on extensive research conducted at the University of Western Ontario, are suitable for buildings with flat or gabled roofs that are more than twice as wide as their height and where the average roof height does not exceed 20 meters. The Supplement also indicates that these guidelines can be applied to buildings outside these parameters as long as the height-to-width ratio (H/W) does not exceed 2. However, the Supplement does not provide guidance on the applicability of these specifications for different building designs. Recently, some of the researches have been conducted focused on this matter. A wind load impact assessment was done on the saw-tooth roof by Holmes and found that the suction on the saw-tooth roof was quite different from the flat and gable roofs and higher than that of the values provided in the Australian code [2][3]. A boundary layer wind tunnel investigation was conducted on the simple mono-slope roof by Rietdyk and Burgers and concluded an underestimation of the wind loading on the ridge and associated corner regions of the mono-slope roof by Canadian code [4] [5].

It is well understood that the boundary layer wind tunnel is not available everywhere, and the wind tunnel investigation is a time-consuming as well as laborious process. Therefore, researchers are moving toward the CFD simulation to find out the wind effects on the structures. Wind effects assessment on low-rise buildings with different roof forms using CFD simulation was conducted by Sharma et. al. [6]. A CFD investigation on multi-span low-rise buildings with different roof forms was conducted and highlighted the effects of shieling on middle and leeward roofs due to the presence of upstream roofs [7]. The effects of interference on the cylindrical roof of low-rise buildings arranged in rectangular formation with variable spacing using CFD simulation was conducted and concluded that the spacing varied from 0 to 2B (B is the width of the building) is beneficial in reducing the wind loads on the roofs [8] [9].

Most of the wind effects studies have been conducted using boundary layer wind tunnels either on flat or gable roofs. There are some other forms of roofs, e.g., cylindrical roofs, dome roofs, hip roofs, mono-slope roofs, etc. that got less attention from researchers and can perform better than that of flat or gable. Also, the CFD is a very good and reliable source in place of boundary layer wind tunnels for the assessment of wind loads on the structures. Therefore, in the present research, an attempt has been made to assess the wind loads on mono-slope roofs arranged in a T-pattern with variable spacing subjected to different angles of wind attack ranging between 0° to 180° at 15° wind intervals.

With the growth in domain of machine learning and its versatile adoption globally has resulted in its application in file of wing engineering also. ML techniques have recently been integrated into wind engineering to enhance the accuracy and efficiency of CFD simulations. ML models, trained on large datasets of CFD results or experimental data, can predict wind loads and optimize structural designs more rapidly than traditional methods. Studies have used ML models to validate CFD results, ensuring the reliability of simulations. These models can also identify patterns in wind-induced interference effects, guiding the optimization process. Combining CFD with ML has shown promise in reducing computational costs while maintaining high accuracy [15]. For instance, Literature demonstrated a hybrid approach where ML models were trained to predict wind loads based on a limited set of CFD simulations, achieving similar accuracy with reduced computational resources [16].

The integration of CFD and ML has been applied to various case studies involving mono-slope roofs. Many works explored the wind-induced interference effects on mono-slope roofs in urban environments, using CFD to simulate wind flows and ML for validation and optimization. Their findings emphasized the potential of these combined approaches in improving the wind resilience of buildings [17].

Parametric studies, where various geometric and environmental parameters are systematically varied, have been instrumental in understanding the complex interplay of factors influencing wind loads on mono-slope roofs. These studies have provided valuable data for training ML models [18].

The optimization of wind-induced interference on mono-slope roofs through CFD modeling and ML validation is a rapidly evolving field. While significant progress has been made, particularly in combining these approaches to enhance accuracy and reduce computational costs.

In the present work the machine learning techniques namely M5P, Random Forest and linear progression have been applied to determine the most efficient method. Moreover, the sensitivity analysis is carried out to determine the most significant parameter for determining the value of Cp, IF, ID.

# Methodology

In the present research, the wind effects are assessed on the mono-slope roof of low-rise buildings arranged in a T-pattern with variable spacing i.e., 0, 0.5B, B, 1.5 and 2B where B is the width of the building subjected to the different angles of wind attack ranging between 0° to 180° at 15° wind intervals each using CFD simulation. Further the optimization is carried out using ML techniques namely M5P, Random Forest and Linear progression with degree of angle, roof spacing Cp, ID and IF of flange and web portion for T section. The most reliable input factor is determined using sensitivity analysis.

## CFD Simulation

The process of CFD simulations includes the creation of geometry, meshing of the geometry, and setup of boundary conditions.During the geometry creation, the low-rise building with the mono-slope roof is created by reducing of 1:50. The dimensions of the isolated building model are 200 mm x 400 mm, the angle of the roof slope is 30°, and the eave height is 150 mm. The six isolated models of low-rise buildings with mono-slope roofs are arranged in a T-pattern with variable spacing, i.e., 0, 0.5B, B, 1.5B, and 2B as shown in Fig. 1.A computational domain is created surrounding the building model by considering the dimensions as recommended by various CFD researches i.e., the height of the computational domain is 5H, the distance of the inlet from the windward wall of the building is 5H, the outlet distance is at 15H and the sides faces of the domain are at 5H, where H is the height of the building model as shown in Fig. 2 [10] [11] [12]. After the creation of geometry and computational domain, the meshing is generated. Before finalizing the size of the best-suited mesh, grid sensitivity should be performed. In the present research, the grid sensitivity is performed and explained in detail in previous research by Sharma et al. [8] [9]. The size of meshing finalized after grid sensitivity is fine mesh in which the face mesh is 0.0125 m, 0.0125 m is edge mesh, and 0.05 m is ground mesh as shown in Fig. 3. After the meshing of the building model and computational domain, boundary conditions are applied. The ground and computational domain walls are assigned as s free-slip walls and building faces are assigned as a no-slip wall. The velocity of wind applied following the power-law as shown in Eqn. 1 where, Uref is the reference velocity, i.e., 10 m/s, Yref is reference height, i.e., 1 m, U is the velocity to be found out at distance Y, and α is the power-law coefficient depending upon the terrain condition, i.e., 0.15.

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| Isolated Mono-slope Roof | Zero Spacing | 0.5B Spacing |
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| B Spacing | 1.5B Spacing | 2B Spacing |
| **Fig. 1.** Mono-Slope Roofs arranged in T-pattern | | |

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| **Fig. 2.** Dimensions of the Computational Domain | **Fig. 3.** Meshing |

# Machine learning techniques

# *2.2.1. M5P model tree*

# The M5P model tree is a binary decision tree that predicts continuous numerical values using linear regression at the leaf nodes. It generates the tree by splitting based on the standard deviation of class values, aiming to reduce error and increase node purity. To prevent overfitting, the tree is pruned by replacing overgrown subtrees with linear regression functions. The M5P algorithm optimizes by selecting splits that maximize error reduction, using standard deviation as a key metric. Formula for standard reduction formula is given below:

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# Where N depicts a set of examples that arrive at the node. Ni depicts ith outcome of subset of examples of potential set and sd is standard deviation [19].

# *2.2.2. Random Forest*

# The Random Forest (RF) regression approach combines multiple decision trees, each generated from a randomly sampled subset of the input data. Bagging is used to create training sets by randomly drawing samples with replacement, resulting in each tree being trained on about 67% of the original data, with the remaining 33% serving as out-of-bag samples for validation. Trees are built using a randomly selected subset of variables at each node, with the Gini Index guiding the best split. The method requires specifying the number of input variables per node (m) and the total number of trees (k) in the forest [20].

# *2.2.3. Linear Progression*

# Linear regression in machine learning predicts a continuous target variable by modeling it as a linear combination of input features. The goal is to find the best-fit line (or hyperplane) by minimizing the difference between predicted and actual values, typically using Ordinary Least Squares (OLS). It includes simple linear regression (one feature) and multiple linear regression (multiple features). Linear regression is popular for its simplicity and interpretability in tasks like trend analysis and forecasting [21].

# *2.2.4. Dataset*

# The dataset is based on the numerical simulation carried out using the Ansys software. The dataset is distributed into two sections of T section as flange and web. The input parameters are spacing, angle, Cp, ID and IF for the flange and web. The machine learning techniques used are M5P, Random Forest and Linear Progression. The preciseness of the estimated values by the both models was quantified by the correlation coefficient (R), root mean square error (RMSE) and maximum absolute error (MAE). The value of correlation coefficient varies from -1 to 1, whereas the values of root mean square error and maximum absolute error vary from 0 to infinity. If the value of correlation coefficient is approaching to 1 and the values of root mean square error and maximum absolute error are approaching to 0 the model is most accurate. The output is considered for Cp, ID and IF of flange and web and with the most prominent method the most efficient parameter impacting CP, IF and ID are calculated. 70% dataset is used for training and 30% dataset for testing is utilized.

# Results and Discussion

# In the present research, wind-induced interference is being investigated on mono-slope roofs arranged in a T-pattern with variable spacing i.e., 0 to 2B and subjecting it to different angles of wind incidences at 15° intervals by application of CFD simulation. The parameters studied are pressure contours, pressure coefficient (Cpe), interference factor (IF) and interference difference (ID). The results obtained from the investigation are discussed below.

# Validation

In the present research, a low-rise building model with a mono-slope roof of 30° roof slope and a plan dimension of 200 mm X 400 mm is validated with some wind standards and previous experimental research as shown in Table 1. Stathopoulos & Mohammadian conducted a wind study on mono-slope roof to find out the local and area average wind pressure acting on the roof of low-rise building with mono-slope shape using BLWT having the roof slope of 1:12 using 1:200 model scale. The values of area average Cp obtained for different wind incidence angles i.e., 0°, 30°, 45°, 60°, 90°, 120°, 150° and 180° respectively, were compared with present study. Kumar & Stathopoulos have conducted an experimental study on mono-slope roof to find out the wind effects using stochastic perspective. The building models were subjected to 0° and 45° wind incidence angles and exposed to an open and sub-urban terrain condition. The compared values of area average Cp from the study conducted by Stathopoulos & Mohammadian, 1991 and Kumar & Statholpoulos, 2000 [13] [14] are mentioned below in Table 1.

**Table 1.** Validation of Cpe for Low-Rise Building with Mono-Slope Roof

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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wind Incidence Angles | 0° | 30° | 45° | 60° | 90° | 120° | 150° | 180° |
| Stathopoulus & Mohammadian | -0.39 | -0.59 | -0.89 | -0.87 | -1.07 | -2.37 | -4.03 | -1.06 |
| Kumar and Statholpoulos | -1.11 | - | -5.31 | - | - | - | - | - |
| Present CFD Study | -0.19 | -0.17 | -0.22 | -0.28 | -0.46 | -0.56 | -0.66 | -0.47 |

## Pressure Contours

## The wind-induced pressure distribution on mono-slope roofs arranged in a T-pattern is presented in the form of pressure contours shown in Fig. 4. The edges of roofs A, B and C, which are in the flange region of the T-pattern, are subjected to the higher suction as compared to roofs D, E and F in web region of the T-pattern. The central portions of roofs A, B, and C are uniformly distributed with wind-induced pressure that is less magnitude than the edges of the roofs. The effect of shielding plays a vital role in reducing the wind-induced negative pressure on roofs D, E and F. The spacing 0 to 2B is quite beneficial in reducing the wind pressure on mono-slope roofs.

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| Zero Spacing | 0.5B Spacing | | B Spacing |
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| 1.5B Spacing | | 2B Spacing | |
| Fig. 4. Pressure Contours on Mono-Slope Roofs arranged in T-Pattern | | | |

## Pressure Coefficient (Cpe)

The variation of pressure coefficient (Cpe) on mono-slope roofs arranged in a T- pattern with variable spacing is shown in Fig. 5. The pressure coefficient (Cpe) is measured using the Eqn. 2, in which the value of average pressure on roof is taken form CFD simulation, ρ is density of air (1.225 kgm-3) and v is the reference wind velocity (10 ms-1) The nomenclature of mono-slope arranged in T-pattern is being done as roof A, roof B, roof C, roof D, roof E and roof F in which roofs A, B and C are arranged in Flage part and roofs D, E and F are arranged in web part of T-pattern respectively. The spacing and angle of wind attack play a vital role in changing the behaviour of wind on mono-slope roofs. The overall impact of wind on mono-slope roofs is suction in nature. When the spacing between the roof is zero, the Cpe is increased on interfering mono-slope roofs as compared to an isolated mono-slope roof. However, it is reduced when the spacing is changed from 0 to 2B due to interference from the surrounding building. The effect of interference is mostly visible on roofs D, E and F when the angle of wind incidence is 0°, 15° and 30° and 180° respectively.

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| Fig. 5. Pressure Coefficient (Cpe) on Mono-Slope Roof arranged in T-Pattern | |

## Interference Factor (IF)

## Interference Factor (IF) is defined as the ratio of the pressure coefficient during interference conditions to the pressure coefficient during an isolated condition as presented in Eqn. 3. The effect of interference on the roof can be exactly measured using IF which gives the idea of how much the wind-induced pressure is increased or decreased on the roof. When the magnitude of IF is more than 1, it indicates increased suction on the roof due to interference or vice versa. Fig. 6 represents the variation of IF on mono-slope roofs arranged in a T-pattern subjected to the different angles of wind incidence. The value of IF is reduced by changing the spacing from 0 to 2B which proves to be beneficial in reducing the wind pressure on the roofs.

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| Fig. 6. Interference Factor (IF) on Mono-Slope Roof arranged in T-Pattern | |

## Interference Difference (ID)

## The difference between the pressure coefficient obtained during interfering conditions and the pressure coefficient obtained during isolated conditions is known as interference difference (ID), shown in Eqn. 4. When the value of ID comes out to be positive, it indicates that the magnitude of suction is decreased on the roof and nature of wind getting converted from suction to positive pressure or vice-versa. Fig. 7 shows the variation of ID on mono-slope roofs arranged in a T-pattern with variable spacing subjected to the different angles of wind incidence ranging between 0° to 180° at 15° wind intervals each. It can be predicted from Fig. 7 that negative pressure on the roof is reduced due to the interference of surrounding buildings.

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| Fig. 7. Interference Difference (ID) on Mono-Slope Roof arranged in T-Pattern | |

* 1. **Machine learning output**

# *3.6.1. M5P*

## The M5P model tree (with parameter ‘m’) was implemented using WEKA software. The value of ‘m’ was finding out by error and trial method which suggests that ‘4’ was the optimum value for ‘m’. The optimization is carried out for CP, IF and ID for web.

## The values of square R, RMSE and MAE is presented in table 2.

Table 2 The performance parameters output for M5P

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Cp for Flange | ID for Flange | IF for Flange | Cp for web | IFfor web | ID for web |
| R2 | 0.8326 | 0.9761 | 0.4659 | 0.9797 | 0.861 | 0.9835 |
| RMSE | 0.1693 | 0.0304 | 0.7959 | 0.0582 | 0.033 | 0.5004 |
| MAE | 0.1343 | 0.0241 | 0.6481 | 0.0468 | 0.033 | 0.3632 |

*3.6.2. Random Forest*

The random forest regression (with parameter k, m and I) was also implemented using WEKA software. The values of k, m and I also found out by error and trial method which suggests that optimum values of k, m and I were 0, 1 and 500 respectively. Similarly, M5P model tree, the values of the performance evaluation parameters (R, RMSE, and MAE) were listed in Table 3.

Table 3 The performance parameters output for Random Forest

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| --- | --- | --- | --- | --- | --- | --- |
|  | Cp for Flange | ID for Flange | IF for Flange | Cp for web | IF for web | ID for web |
| R2 | 0.9897 | 0.978 | 0.7986 | 0.9776 | 0.9612 | 0.8942 |
| RMSE | 0.0296 | 0.0296 | 0.338 | 0.0577 | 0.3718 | 0.0487 |
| MAE | 0.0267 | 0.0193 | 0.1734 | 0.0392 | 0.1642 | 0.0301 |

*3.6.3. Linear Progression*

The values of R, RMSE and MAE for the linear progression are specified in Table 4.

Table 4 The performance parameters output for Linear Progression

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|  | Cp for Flange | ID for Flange | IF for Flange | Cp for web | IF for web | ID for web |
| R2 | 0.9047 | 0.8971 | 0.4871 | 0.9217 | 0.8971 | 0.7611 |
| RMSE | 0.4794 | 0.5214 | 0.5144 | 0.3142 | 0.3218 | 0.1487 |
| MAE | 0.2705 | 0.0193 | 0.1724 | 0.1394 | 0.1822 | 0.3021 |

From the above results it can be inferred that Random Forest method is the most suitable method to determine the Cp, ID and IF value for flange and web of T section. Therefore, Figure 8 demonstrates the scatters details of the experimentally estimated and predicted values of Cp, ID and IF value for flange and web of T section using the Random Forest model with the testing dataset and the variation of the experimentally estimated and predicted values with column have almost the same height with experimentally estimated values column. Moreover, the above value is calculated shows that Id for web is the most important parameter as by eliminating this parameter the worst results have been obtained for Random Forest method.

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| **Fig. 8.** The scatters details of the experimentally estimated and predicted values of Cp, ID and IF value for flange and web of T section using the Random Forest model with the testing dataset and the variation of the experimentally estimated and predicted values | |

# Conclusions

# The study uses CFD simulation to determine the wind effects on low-rise buildings with mono-slope roofs. Six models of low-rise buildings with mono-slope roofs are arranged in a T-pattern with variable spacing and subjected to various angles of wind incidences. The important conclusions drawn from the present investigations are as follows.

# The overall impact of wind on the mono-slope roofs of the low-rise buildings is suction in nature.

# The angle of wind incidence and spacing between buildings plays a crucial role in modifying the wind effects on mono-slope roofs.

# The edges of mono-slope roofs are subjected to higher suction as compared to the central portion of the roof.

# The spacing between 0 to 2B proves to be beneficial, which helps in reducing the suction on mono-slope roofs arranged in a T-pattern.

# The results indicated that the effects of interference in mostly dominated on roofs B, D, E and F especially when the angles of wind incidence are 0°, 15° and 30°, since these roofs are lying just behind each other.

# The Random Forest method as the machine learning technique can be implemented to optimize the Cp, IF and ID of T section.

# The sensitivity analysis shows that ID for the web is the most important parameter for optimizing the T section.

# This study offers important insights into how wind pressure is distributed on mono-slope roof low-rise structures, which can aid in designing more efficient and sustainable mono-slope roof systems in the future.

# The findings are particularly useful for structural designers, as they propose wind pressure coefficients for both single, multi-span and variable spacing of mono-slope roofs. These coefficients could potentially be incorporated into wind codes and standards following further testing and validation.

**Acknowledgements**

The authors express sincere gratitude for the encouragement from the faculty and research scholars in the Department of Civil Engineering at Delhi Technological University (DTU), Delhi. The authors would like to thank Delhi Technological University (DTU), Delhi for the financial assistance received as a part of fellowship to the first and second author for carrying out the present work.

**Conflict of Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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