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Mathematical formula to evaluate the required gap distance and impact from wind-induced pounding of tall buildings

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SUMMARY:
Extreme wind events are becoming a higher risk within dense locations involving the newer generation of tall buildings. When tall structures are constructed in proximity, pounding can arise when subjected to such extreme lateral loading due to the separation distance becoming insufficient. Damages from pounding can range from minor to total collapse of structures. A separation distance between the interactive structures must be determined to mitigate a pounding event. This study focuses on developing mathematical formulations through an optimization process to determine first the required minimum separation distance between two adjacent structures to mitigate a wind-induced pounding event and then to determine the maximum pounding force of the two structures if the separation distance cannot be achieved. Numerical Large Eddy Simulations (LES) and Finite Element Method (FEM) models are validated and then examined for two equal-height structures in proximity. A Genetic Algorithm (GA) is utilized to develop mathematical formulations for estimating required separation distances and maximum pounding forces while optimizing fitting parameters. Based on the results, taller structures are shown to be more susceptible to vital pounding forces when becoming closer in proximity. The complexity of the developed formulations depends on achieving a more accurate mapping for the trained database.

Keywords: Structural Pounding, Wind-Induced Deflection, Tall Buildings

1. INTRODUCTION

Buildings are constructed within dense metropolitan locations, ultimately in proximity to surrounding structures due to limited available land space and the increase in population. The new generation of high-rise structures is becoming more flexible due to the buildings becoming increasingly taller and slender (Elshaer et al., 2017). With the design of new, tall, and slender buildings, the term pounding has become an important objective when a structure is built within proximity. The pounding of structures is defined when two or more adjacent structures are subjected to a great lateral force, making the structures collide from exceeding the adequate separation distance (Anagnostopoulos and Spiliopoulos, 1992; Kasai and Maison, 1997). A pounding occurrence can also be produced when the structures involved are subjected to extreme wind events (Brown and Elshaer, 2022; Huang et al., 2012). Extensive literature reviews on structural pounding have been presented (Brown and Elshaer, 2022; Miari et al., 2021).

A challenge arises for pounding is when existing structures are already building within proximity and were designed before the new building codes and provisions to determine a minimum required separation distance, leading to possible pre-existing structural pounding events (Rezavandi and Moghadam, 2007). Without adequate mitigation measures, the pounding of structures can occur if adequate applied wind loads are subjected to adjacent tall structures. Moreover, an out-of-phase vibration is more likely to transpire in such wind phenomena, leading to a larger probability of collisions. Therefore, the objective of this investigation is to examine a case study of two structures in close proximity subjected to an extreme wind event. The study uses varying wind intensity through an experimentally-validated Computational Fluid Dynamic (CFD) modelling with altering, heights, and flexibility in a Finite Element Method (FEM) model to systematically estimate the required minimum Separation Gap Distance ($d_{g,min}$) for mitigating a wind-induced pounding phenomena. The study then estimates the maximum wind-induced pounding force (F_I) if the developed separation gap distance is not provided. Mathematical equations are developed using a Genetic Algorithm (GA) to estimate the required $d_{g,min}$ and the F_I.

2. GEOMETRIC DETAILS AND NUMERICAL MODELS

The structure observed has the same geometric form as the Commonwealth Advisory Aeronautical Research Council (CAARC) standard building. A 50-year return period of a mean wind velocity of 41 m/s at the top height of the examined CAARC building was considered in the CFD analysis located in an open terrain (Huang, 2017). The study first conducts three-dimensional Large Eddy Simulation (LES) models to evaluate the applied wind forces acting on the two adjacent tall structures, see Fig. 1(a) while validating the model with wind tunnel results. To conduct the LES simulation, a Consistent Discrete Random Flow Generator (CDRFG) technique is assigned as the inflow boundary condition (Aboshosha et al., 2015). Once the initial structure is properly modelled, with alterative structures heights, H, are considered (i.e., 60 m, 100 m, 140 m, and 180 m, in full-scale) with varying applied mean wind velocities, v, (i.e., 20 m/s to 50 m/s). Individual time-history wind forces in the x and y directions are captured to perform the structure's dynamic responses on the two adjacent tall structures in the FEM analysis. The wind forces are monitored individually per storey, per structure as a single summed lateral force. The applied wind force time-history will act at each structure's center diaphragm of each storey in the FEM model.

In the Finite Element Analysis, all beam and column members are made from steel (i.e., W14 and W30 sizes, respectively) on the initial CAARC structure and other structures examined as from (Brown et al., 2022; Huang, 2017), see Fig. 1(b). Structures steel columns will vary with the applied mean wind velocity. For validation purpose, the initial chosen steel member has exceeded both the maximum deflection of H/400 and inter-storey drift limit ratio of 1/400, respectively (Huang, 2017), since the structures system is initially intended for optimization purposes to evaluate its drift and deflection strains. Once the validated steel structure is in agreement with the validation model, the remaining examined structures (e.g., 140 m, 100 m, and 60 m tall buildings) are then calculated per the preliminary strength check for the AISC (2001) to accurately replicate the validated model. A total of 28 FEM models are examined in the FEM analysis when determining the $d_{g,min}$. While a total of 112 FEM models are examined for determining the maximum F_I as the initial separation gap distance, d_g, is lowered than the determined $d_{g,min}$. To capture the pounding force, F_I, a contact gap element was used at the locations that the structural pounding would arise. The compression gap element implemented in this study is a linear elastic compression model (Jankowski, 2008). The pounding location considered in this analysis is located as floor-to-floor pounding (floor diaphragms among the storey’s masses) as the examined structures have identical overall heights and storey level heights (see Fig. 1(c)).

A Genetic Algorithm (GA) is adopted to optimize the development of mathematical formulas for determining the design pounding force. GA will optimize the fitting parameters of the mathematical formulas used to correlate the input parameters to the Separation gap distance and pounding forces determined from FEM analysis. Such input parameters include building height, H, the building's dynamic properties (i.e., natural frequency, F_n), structures' dynamic responses (i.e., lateral deflection), v, and d_g between structures. The formulated equation will be generated from the GA to determine the minimum separation gap distance $d_{g,min}$ and the maximum F_I of the two adjacent tall structures in proximity when a d_g is insufficient to mitigate structural pounding from wind-induced lateral deflections of the structures.

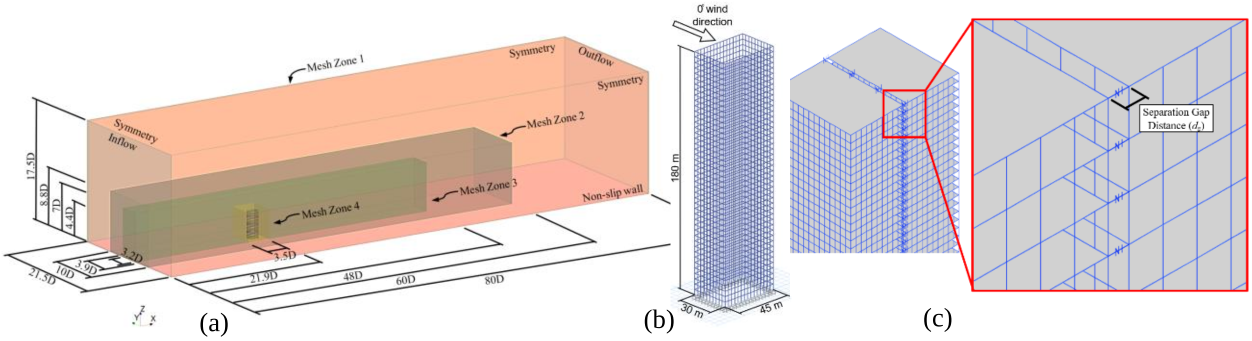

Figure 1. (a) Computational Domain of the CFD Model, (b) 45-storey CAARC structure framework, and (c) Response of gap element for pounding forces

3. RESULTS AND DISCUSSION

The GA used different combinations of geometric parameters (i.e., building height, natural frequency, and mean wind velocity) with twenty-eight samples to determine the required $d_{g,min}$. More than 2.1 x 10^{12} formulas were generated. The most applicable analytical model and their formulas for evaluating the objective function can be seen in Table 1, as its regression plot can be seen in Fig. 2(a). For the observed outcomes for the maximum F_I, a total of 112 testing samples are produced in the GA having over 2.9 x 10^{12} formulas evaluated through the GA analysis, also seen in Table 1. These formulas were chosen since the highest rank gave the highest correlation coefficient, leading to the lowest mean absolute error. The regression plot for the targeted versus the output maximum pounding force (F_I) is presented in Fig. 2(b). Fig. 2(c) and (d) sample a contour graph for a structure of 60 m tall for the required $d_{g,min}$ and maximum F_I , respectively, based on the applied v, and Natural Frequency, F_n for $d_{g,min}$, and gap distance, d_g, for F_I.

Table 1. Developed GA formula for the mathematical models

Type	Correlation Coefficient	Mathematical formula*
$d_{g,min}$	0.9987	$d_{g,min}\,(mm) = (48280 - 3378 * v)/(H - 149.49 - 393.25 * F_n) + 0.8274/\cos((48280 - 3378 * v)/(H - 149.49 - 393.25 * F_n)) + (149.49 - 2226 * F_n\text{^}2)/(149.49 * F_n + 0.1956 * H - v - \mathrm{H} * F_n) + \cos((48280 - 3378 * v)/(H - 149.49 - 393.26 * F_n))$
F_I	0.9344	$F_I(kN) = ((16.5 * v^2 + 1.21 * v * d_g * \sin(2.38 * H) + 1.21 * v^2 - d_g - 2.38 * H / \sin\,(197 * F_n)\text{^}\cos(0.304 + 21.6 * d_g)) * \cos(\cos(\mathrm{d_g}))$

*v, d_g, H, and F_n are in *m/s*, mm, *m*, and *Hz*, respectively

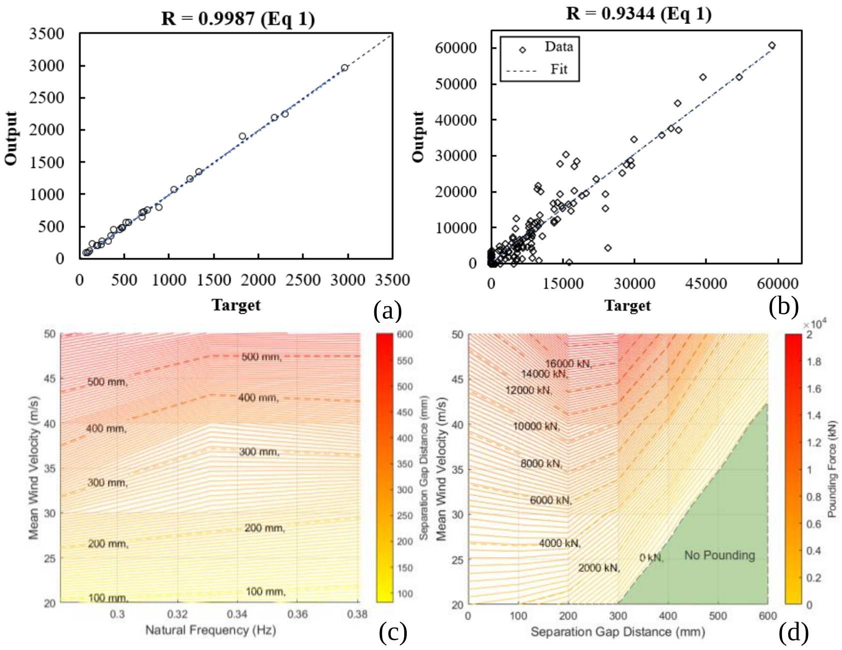

Figure 2. Regression plot of the determined Output vs. Target for (a) $d_{g,min}$, and (b) F_I, and contour plot of a 60 m tall structure for (c) $d_{g,min}$, and (d) F_I

4. CONCLUSION

This paper aims to develop mathematical formulas for determining the required minimum separation gap distance and maximum wind-induced pounding forces between two tall buildings in proximity. The complexity of the mathematical formulations can become challenging for defining a best-fit for determining the minimum gap distance and maximum pounding force for two adjacent structures. Pounding during extreme wind events significantly influences the storey levels of the pounding structures when the initial separation distance is significantly small. When the minimum gap distance is just lowered to prevent pounding, the collision mostly only occurs once, and the pounding locations arise at the highest part of the structures.

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