

Experimental Assessment of Vegetation Density and Orientation Effects on Flood-Induced Pressure Forces and Structural Accelerations

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Abstract: The frequency and intensity of devastating floods in Pakistan have been on the rise, attributed to the effects of climate change and unsustainable environmental conditions. To mitigate the risks associated with flooding, the implementation of flood protection structures is crucial. However, these structures may fail if subjected to flow conditions exceeding their design limits. This research focuses on investigating the impact of vegetation orientations on hydrostatic pressure and acceleration acting on a building model positioned downstream of different vegetation arrangements. A series of experiments was conducted in which the vegetation array was positioned at various angles (90°, 60°, 45°, 30°) relative to the flow direction. The objective was to analyze the dissipation of fluid pressure forces, acceleration of the modelled test structure, and the arrival time of floodwater at a specific location. The acceleration of the building model was measured using an X2-2 accelerometer attached to the test structure at the downstream side of the vegetation. Two vegetation densities, namely intermediate ($G/d = 1.09$) and sparse ($G/d = 2.13$), where G is the spacing of each cylinder in the cross-stream direction and d is the diameter of the cylinder, were considered under different flow conditions, with several Froude numbers tested for each case. The findings revealed that a vegetation orientation of 90° relative to the main flow direction resulted in the most significant reduction in acceleration and hydrostatic pressure for both sparse and intermediate vegetation density scenarios. Furthermore, the arrival time of floodwater was observed to be higher for the 90° vegetation orientation. The analysis of standard deviation, mean, and range of energy dissipation demonstrated notable variations, indicating the influence of vegetation orientation on the dissipation process. In conclusion, this study underscores the importance of vegetation orientation in mitigating the effects of flooding. The results provide valuable insights for designing effective and sustainable flood management strategies, highlighting the significance of considering vegetation arrangements in enhancing resilience to the impact of Climate change.

Keywords: Climate Change, Flood mitigation, Vegetation array, Flow-induced pressure, Acceleration, Floodwater arrival time

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1. Introduction

Natural disasters, such as tsunamis, floods, and storm surges, have a significant impact on coastal regions [1]. Among these disasters, floods and tsunamis pose severe threats to infrastructure and residential buildings. Recent studies highlight the persistent threat faced by coastal communities, with annual floods claiming the lives of approximately 20,000 individuals and impacting the livelihoods of 20 million worldwide [2]. Over the past few decades, Asian and European countries have experienced catastrophic floods and tsunamis, resulting in extensive damage to buildings and loss of human life [3]. The immense losses incurred by these calamities have spurred scientific research into both structural and non-structural defences against flood and tsunami devastation [4]. Previous studies primarily focused on risk assessment through flood mapping of riverbeds and flood-prone areas. Over the past decade, researchers have investigated energy dissipation and flow behaviours across embankments using prototypes, numerical models, and analytical techniques. A multitude of studies have explored combined defence systems, such as sea embankments and riparian vegetation, double embankment configurations, and the integrated defence approach of moat dikes with vegetation. This acknowledges the prohibitive cost and time requirements associated with artificial solutions, such as dams and canals, particularly for developing nations [5].

However, the integrity of ecosystems has emerged as a critical factor in water management challenges. Given the substantial capital investments required for hard structures and their susceptibility to failure under extreme conditions, researchers have focused on the synergy between hard and soft defences, particularly the interplay between building structures or hydraulic defences (such as concrete walls) and vegetation. Recent devastating floods in various regions have been characterized by the rapid inundation of entire floodplains following embankment failures [6, 7]. Vegetation acts as a natural barrier, absorbing a portion of the flood force and stabilizing the banks. Therefore, evaluating uncertainty in such phenomena is essential, as they challenge existing risk assessment paradigms rooted in historical and deterministic approaches [7-8].

Riparian vegetation, as indicated by post-flood surveys, plays a crucial role in mitigating flood energy and capturing debris, thereby reducing the destructive impacts of flooding. Analytical and experimental findings have underscored the significance of vegetation density and geometry in diminishing flood energy [9]. Downstream of vegetation, a marked reduction in water level and velocity has been observed. Additionally, the orientation of vegetation relative to the main flow direction has a profound influence on flow parameters, including energy dissipation, approach time, and flow patterns [10-11]. To quantify energy dissipation through various vegetation densities, a series of experiments was conducted under diverse flow conditions [4]. The collision of water with plants weakens its force, resulting in a gentler impact on structures [12-13]. However, recent studies have highlighted that structural damage is significantly influenced by dynamic and impact loads induced by debris [2, 14, 15].

Therefore, there is an urgent need to mitigate structural strain caused by flooding and assess the vulnerability of civil structures to dynamic loading [3-4]. Recent efforts have aimed at mitigating dynamic loads on structures by employing both natural (soft) and artificial (hard) solutions [7,16]. While several studies have explored combinations of defence systems, including sea embankments, riparian vegetation, double embankments, moat dikes with vegetation, and moats with or without vegetation, the high costs and protracted timelines associated with artificial solutions have deterred their adoption, especially in developing nations [5, 17]. The safety of structures in floodplains constitutes a global challenge [18-19]. Persistent exposure to natural hazards, such as flooding, seismic activity, and weathering, poses the most significant threat to structural integrity [20-21]. Due to the importance of structures in human life, it is crucial to ensure ongoing

monitoring of their safety and performance [22–23]. An accelerometer model, X2-2, equipped with a high-sensitivity, rotating acceleration sensor, offers the capacity to collect crucial vibration data for calculating a structure's acceleration [24–26]. Using a USB accelerometer, one can record a building's acceleration history, with the accelerometer functioning as both a sensor and data collector [27–29].

While previous research has addressed the combined effects of vegetation and model structures on flood energy mitigation, the specific impact of vegetation arrangements on the acceleration of physical models remains unexplored. This study's principal contribution lies in its investigation of the response of the physical structure downstream of a vegetation array of different arrangements and densities, specifically in terms of its acceleration and the hydraulic pressure exerted on it. Additionally, the arrival times from the inlet to the model test area are also studied.

2. Materials and Methods

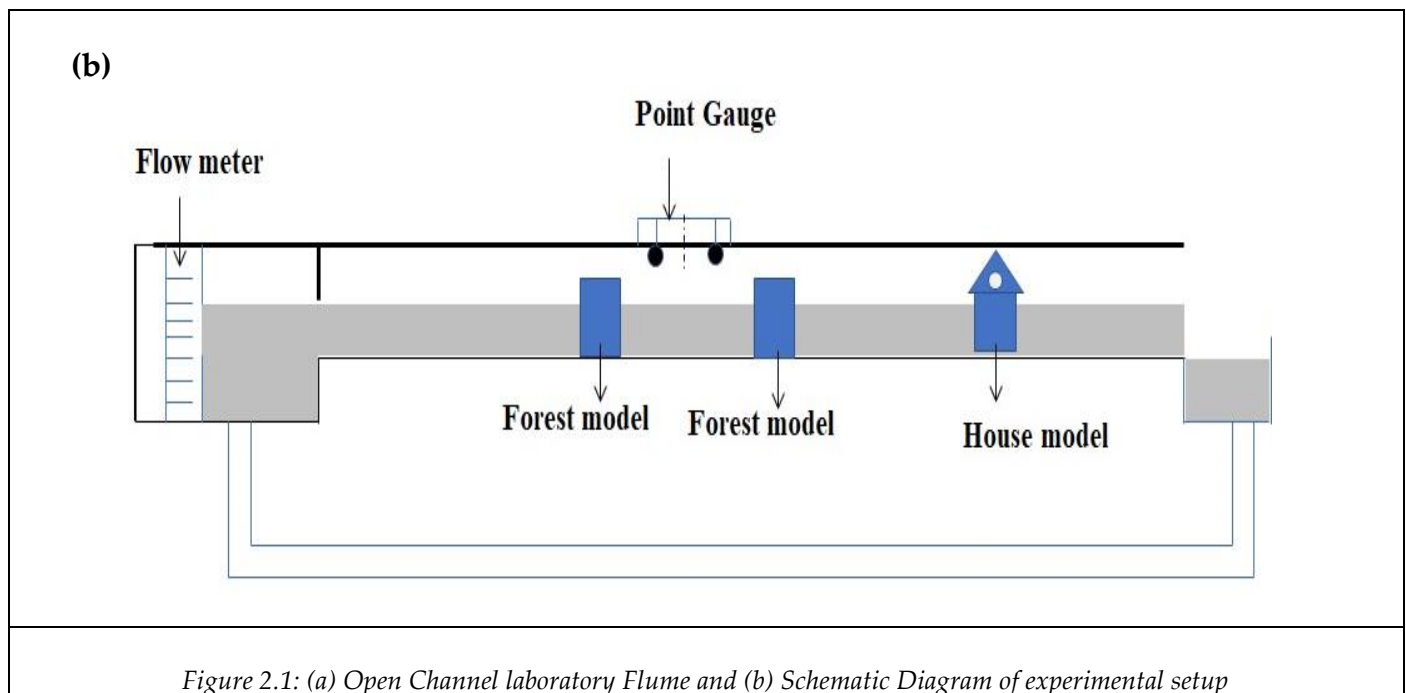
2.1 Experimental setup

First, a physical model of the building was constructed using wooden tiles, while the vegetation array consisted of steel cylinders. After preparing the model, it was placed in the channel for experiments, and the depth in front of the model structure was measured. To investigate the various forces (impact and hydrostatic forces) acting on the model structure and its acceleration under different vegetation configurations and densities, as well as in the absence of vegetation, the following methodology was employed.

Laboratory experiments were conducted in the glass-sided computerized channel at the Water Resources Laboratory of the Civil Engineering Department, University of Engineering and Technology, Taxila. The channel has specific dimensions: it is 0.31 meters wide, 0.5 meters deep, and 10 meters in length, as illustrated in Figures 2.1(a) and (b). The channel's discharge was measured using a flow meter installed on the upstream side of the channel, as depicted in the diagram. The flow velocity was controlled by a pump speed controller located at the upstream end of the channel. Water depth was measured using a point gauge integrated within the channel. These experiments were designed to represent general ground and flood conditions and were not tied to any specific geographical location.



(a)



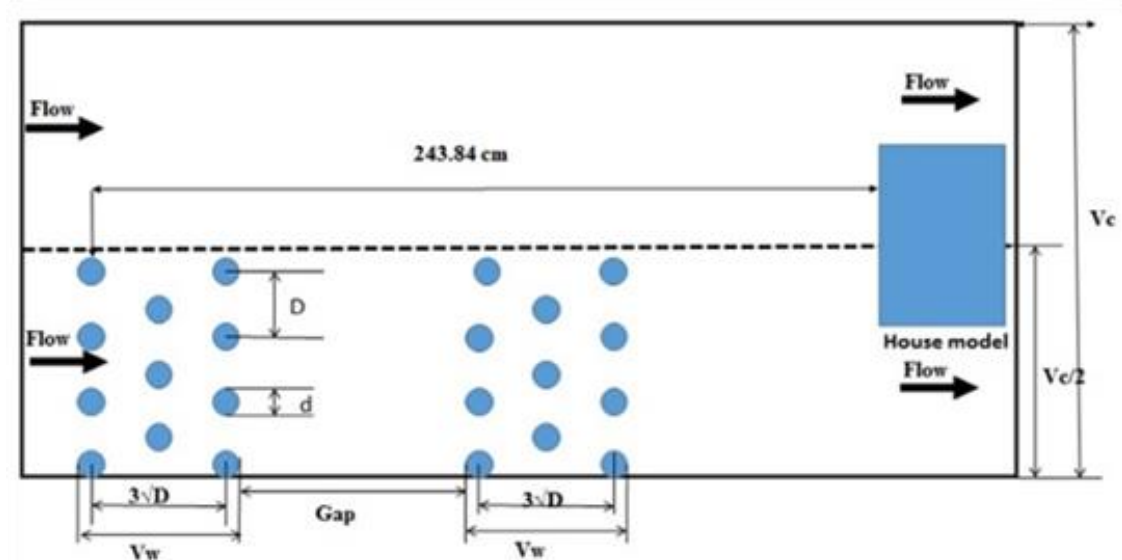
2.2. Vegetation configurations

Eucalyptus tree species were selected for the vegetation array, with an average tree length and trunk diameter ranging from 7.6 to 14.6 meters and 0.1 to 0.33 centimetres, respectively. Seven Froude numbers within the range of 0.18–0.25 were chosen for the experiments. Flow properties were observed using vegetation elements in the form of 0.3 cm diameter steel cylinders. These cylinders were arranged in two patches at different vegetation orientations (90°, 60°, 45°, 30°) relative to the direction of the flow, covering half the width of the flume, as depicted in Figure 2.2(a). Researchers have employed plastic dowels or metal rods for modelling vegetation [6, 7], but, to avoid potential issues with using wooden rods of such small diameter, which might shatter or bend significantly during the experiment, steel cylinders are used. In this experimental study, the 3 cm diameter metal rods are used to represent model trees at a 1:100 scale [7]. Various orientations of the vegetation were examined, as shown in Figures 2.2(b, c). Initially, both vegetation and building models were placed perpendicular to the flow, and experiments were conducted under these conditions. Subsequently, the vegetation angle was adjusted to 90°, 60°, 45°, and 30° for each orientation, and experiments were conducted across all scenarios [7]. The acceleration of the building model, installed on the downstream, was measured by attaching an X2-2 accelerometer to the physical model structure, as shown in Figure 2.2(d). The test building was rectangular, simulating a scaled-down physical model of a house at a scale of approximately 1:45, resulting in dimensions of 16.5 cm in length, 15.5 cm in width, and 23 cm in height. This corresponds to a genuine building with dimensions of 742 cm in length, 698 cm in width, and 1035 cm in height.

In all experimental cases, cylindrical vegetation dowels were used in a staggered pattern. The staggered arrangement was chosen for its higher flow resistance characteristics compared to a linear arrangement. Two vegetation densities were considered along with the third case of no vegetation: a sparse arrangement (denoted by "S") and an intermediate arrangement (denoted by "I"), depending on the G/d ratio within the vegetation array, where "d" is the diameter of the model tree (herein represented by a cylindrical dowel of 0.3 cm in diameter) and "G" denoted the spacing between neighbouring cylinders. Thus, the G/d ratio of 1.09 indicates the intermediate density layout, while a G/d ratio of 2.13 signifies the sparse density arrangement. Different numbers of vegetation dowels (here

denoted by "dn") are also used, resulting in two distinct thicknesses for the vegetation patch: one with $dn = 180$ and another with $dn = 380$. The following combinations are tested: two vegetation patch densities (S and I), two vegetation patch thicknesses (with 180 and 380 number of vegetation elements), and four distinct orientations of the vegetation patch relative to the main flow direction, resulting in 16 combinations of vegetation densities, which are compared to the bare (no vegetation) case, for seven flow conditions with distinct Froude numbers, resulting in a total of $(16+1)*7 = 119$ experimental combinations.

An X2-2 accelerometer, featuring a rotating sensor with high sensitivity, is depicted in Figure 2.2(e). This accelerometer type is instrumental in gauging the dynamic forces acting on the model structure when it is subjected to sudden hydrodynamic loading. To capture the building's motion over time, a USB accelerometer can be employed [20]. The accelerometer serves as both a monitoring tool and a data collection device. Depending on the gain settings, it can record accelerations within the range of 1.25g to 2g. Additionally, the data recorder is operational within a temperature range spanning from -5°F to 130°F (-20°C to 55°C). It has been specifically designed for tracking structural vibrations and seismic activity. With a 15-bit resolution, users have the flexibility to select sample rates of 8, 16, 32, 64, 128, 256, or 512 Hz [9,18].



a

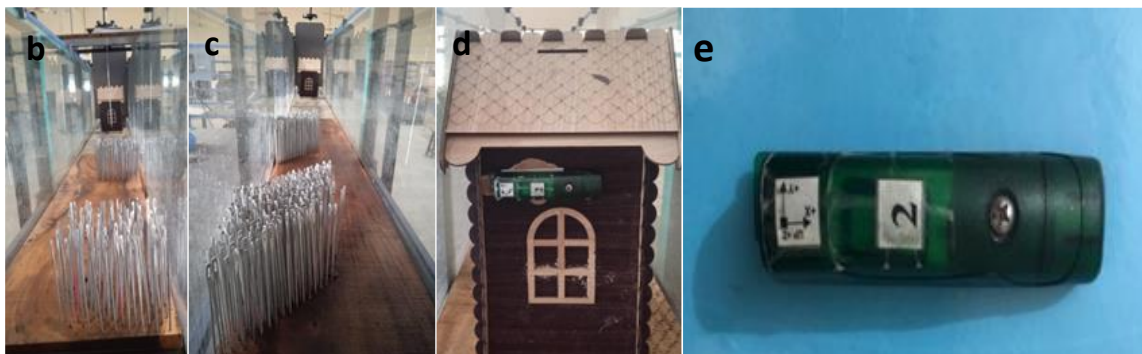


Figure 2.2: (a) Detail arrangement of vegetation provided in a staggered arrangement (b, c) Angle vegetation in front of household in a flume. (d) Accelerometer installation on house model and (e) Accelerometer

3. Results

3.1. Flow-Induced Pressure

The results illustrate the fluid pressure forces acting on the upstream face of the building model, both before and after the insertion of the vegetation array, under various flow conditions. Initially, flow parameters ranged from $Fr_o = 0.18$ to $Fr_o = 0.25$ in the absence of any vegetation within the channel. It was observed that the pressure force increased nearly linearly with the Froude number. The trees, however, demonstrated their ability to offer resistance to the incoming floodwaters, thereby reducing their hydraulic force. The effectiveness of the model depends on the vegetation's ability to mitigate these fluid forces. Consequently, this study aimed to diminish fluid forces by modifying vegetation orientations under different vegetation conditions.

3.1.1. Effects of Vegetation Patch Density and Thickness

Figures 3.1(a, b, c, d) and 3.2(a, b, c, d) illustrate the relationship between hydraulic pressure and Fr_o for the four distinct vegetation patch orientations (90° , 60° , 45° , 30°), both with and without vegetation. In these Figures, the notation for each case is represented by the first letter, e.g., "I", which indicates intermediate vegetation density, or "S" for sparse density. The 2nd number, e.g., 90 (60 , 45 or 30), represents the orientation of the patch relative to the flow direction (in degrees), and the 3rd number, e.g., 180 or 380, represents the vegetation patch thickness (i.e., the value of dn), respectively. It is worth noting that, in addition to the Froude number, the arrangement of vegetation, including its density, has a significant influence on hydraulic pressure. When the density of the vegetation patch is increased from the case of $dn = 180$ to $dn = 380$, there is a corresponding increase in the hydraulic pressure dissipation. Consequently, for a given Froude number and vegetation patch density, the fluid pressure force is lower under an intermediate vegetation arrangement compared to a sparse vegetation arrangement, resulting in reduced hydrostatic pressure. This decrease in hydrostatic pressure can be attributed to the increased flow resistance associated with intermediate vegetation. However, it is important to note that the vegetation angle plays a role in reducing the fluid force and increasing the water depth.

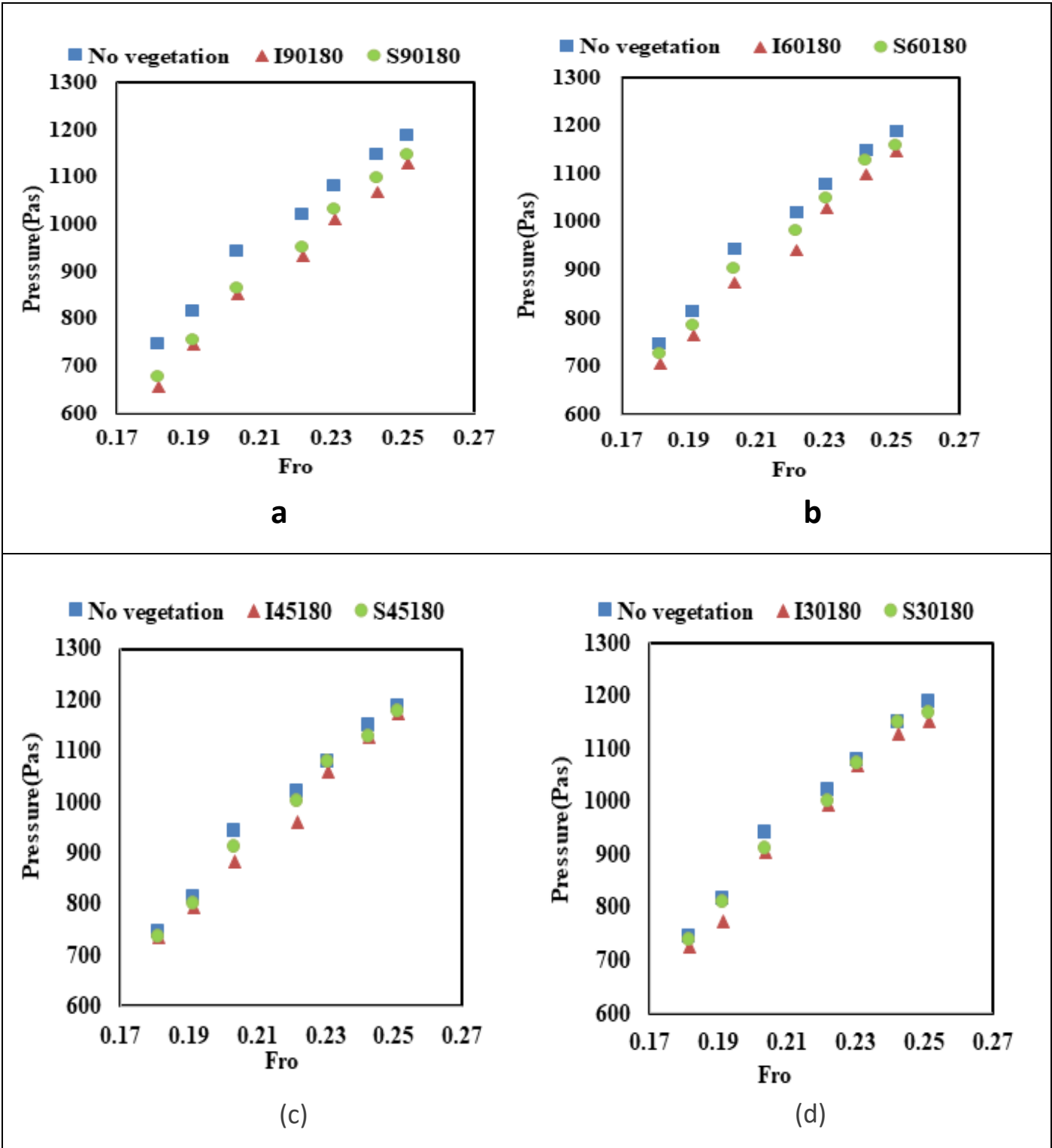


Figure 3.1 (a, b, c, d). Shows the Effect of G/d, Pressure Force in dn=180 Vegetation 90, 60, 45 & 30 angles

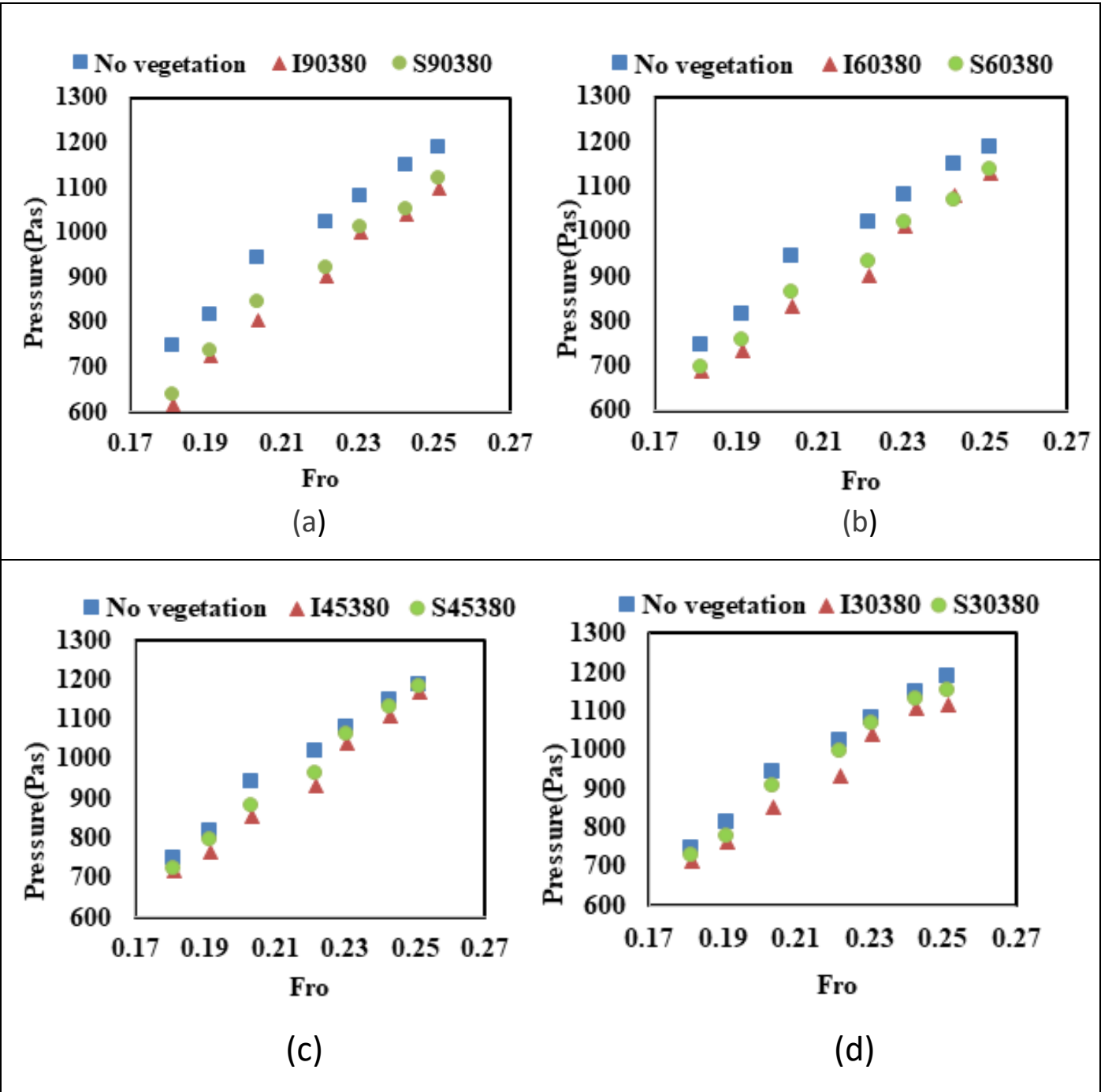


Figure 3.2 (a, b, c, d). Shows the Effect of G/d, Pressure Force in dn=380 Vegetation 90, 60, 45 & 30 angles

3.1.2. Effect of Angles and staggered arrangement

Experiments were conducted to determine the effect of different angles of staggered. Figure 3.3(a, b, c, d) depicts the hydraulic pressure force versus Fro for four various vegetation orientations (90°, 60°, 45°, 30°) and in the absence of vegetation. It demonstrates that decreasing the vegetation angle raises the hydraulic pressure upstream. The hydraulic pressure was found to be greatest in the absence of vegetation and lowest in an arrangement with vegetation at a 90° orientation. By increasing the orientation of the vegetation patch relative to the flow, more obstruction is provided by the vegetation. Perpendicular vegetation offers increased resistance to water flow, thereby reducing the water depth on the upstream face of the building model. Consequently, the fluid pressure force decreases. Maximum hydraulic pressure force reduction observed for I90380 (with

vegetation in intermediate arrangement), and minimum pressure force reduction observed for the case without vegetation.

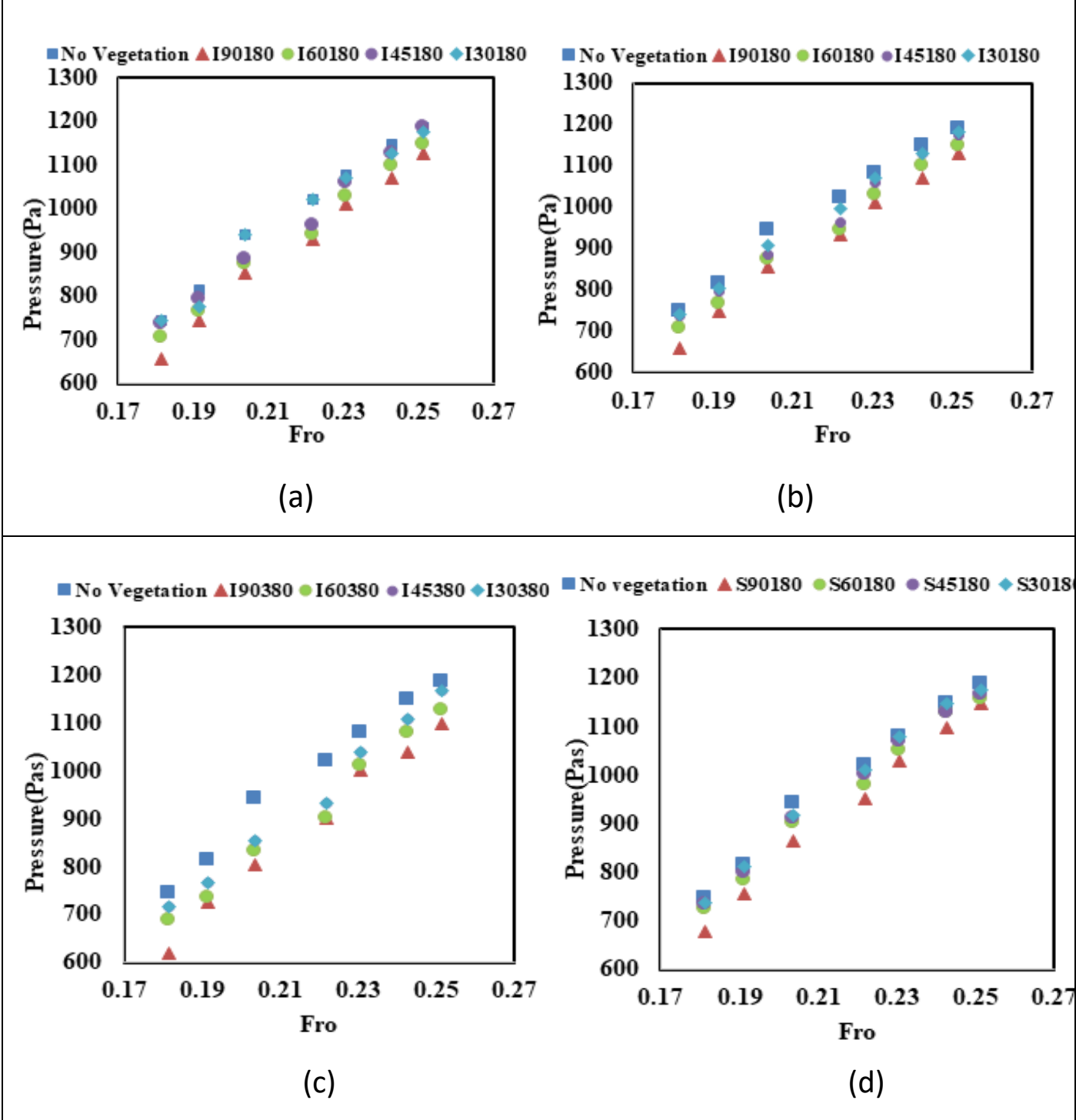


Figure 3.3 (a, b, c, d). Shows the Effect of Angle, Pressure Force in Sparse & Intermediate Vegetation $dn=180$ & $dn=380$

3.2. Acceleration of the Physical Model

3.2.1. Effect of vegetation density and thickness

The dissipation of the acceleration of the upstream wall of the model building, due to the presence of the vegetation array, was assessed using the aforementioned accelerometer. Figure 3.4(a, b, c, d) illustrates that reducing the spacing within the vegetation leads

to decreased acceleration. However, the angle of vegetation also plays a significant role in acceleration dissipation.

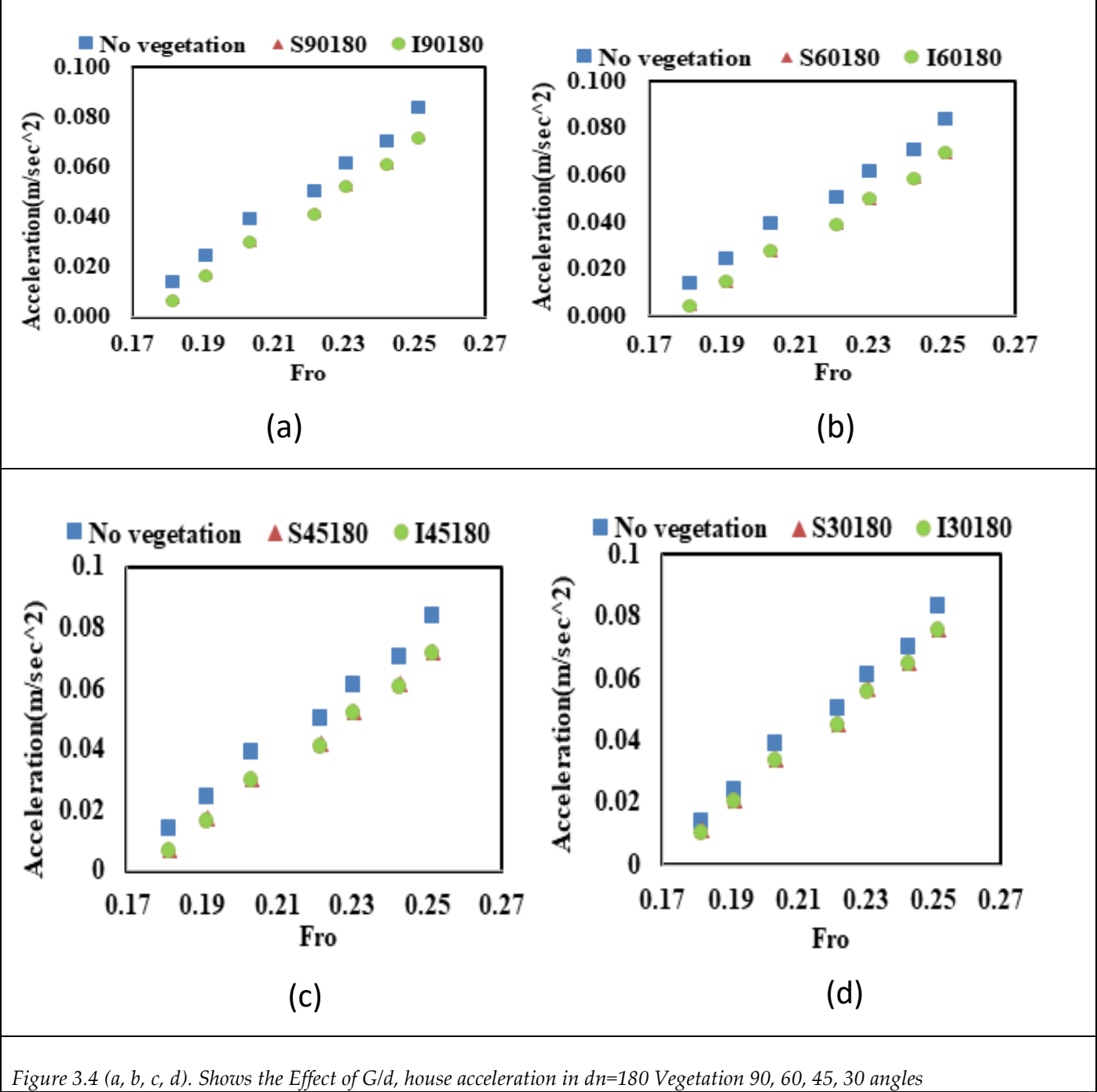


Figure 3.4 (a, b, c, d). Shows the Effect of G/d, house acceleration in dn=180 Vegetation 90, 60, 45, 30 angles

The highest percentage reduction in acceleration was observed for intermediate vegetation at a 90° orientation. The results once again underscore the significance and impact of vegetation orientations and patch density parameters. Additionally, the results indicate that the dissipation of the acceleration of the physical model structure increases with the vegetation orientation increasing from 30° to 90°. In all the studied cases, the maximum acceleration dissipation was associated with a 90° angle (I90, I60, I45, I30) and an intermediate vegetation patch (e.g., forest) arrangement with dn=380, as depicted in Figure 3.5(a, b, c, d).

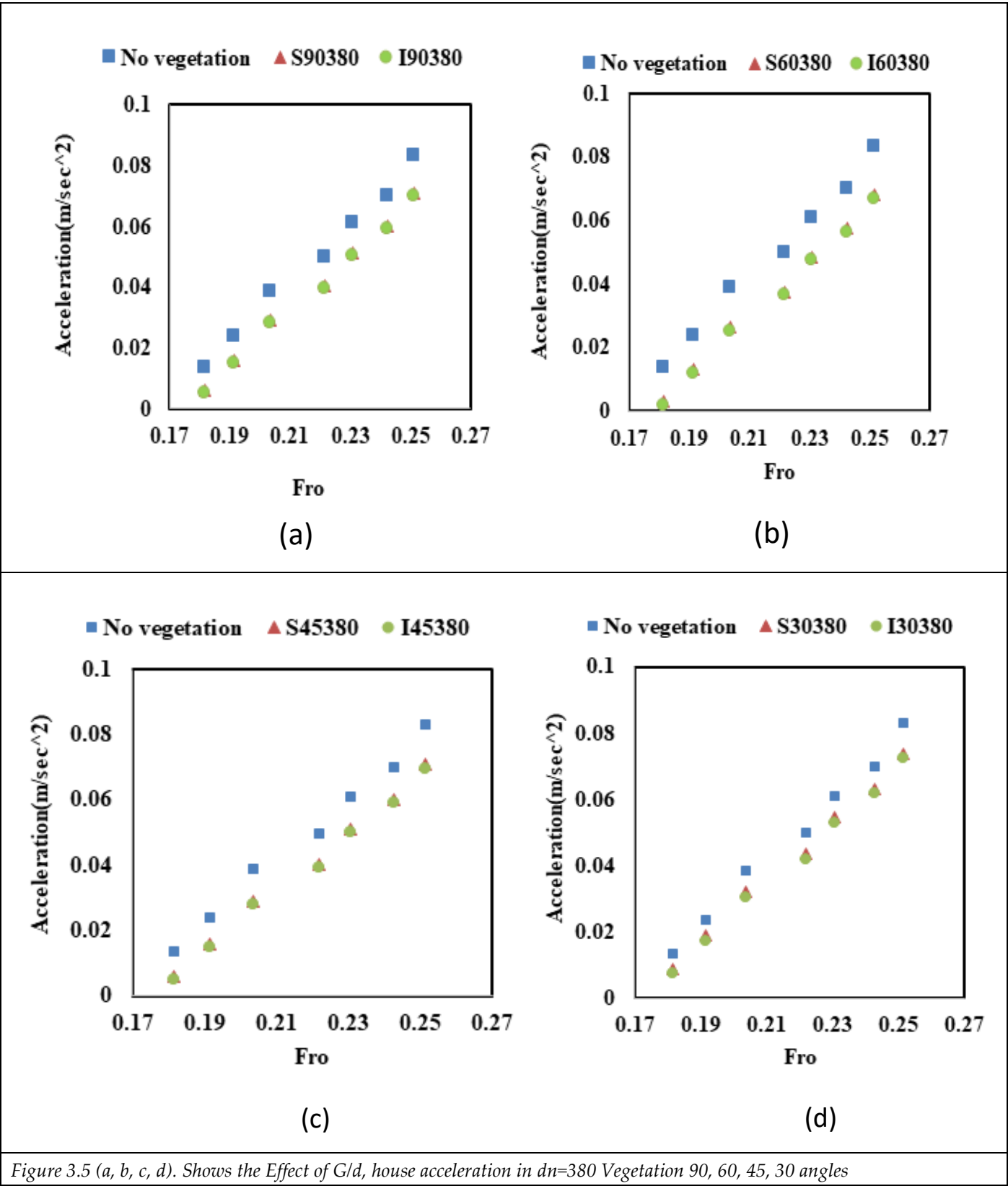


Figure 3.5 (a, b, c, d). Shows the Effect of G/d, house acceleration in dn=380 Vegetation 90, 60, 45, 30 angles

Comparatively, in the non-vegetated scenario, model-building acceleration dissipation decreases as the spacing within the vegetation array increases. Furthermore, reducing the vegetation patch density from dn = 380 to dn = 180 also reduces the model building's acceleration dissipation due to the shorter span of the vegetation patch. This emphasizes the crucial role of vegetation patches of intermediate density, which effectively obstruct the flow approaching the inland region. The increased resistance provided by the

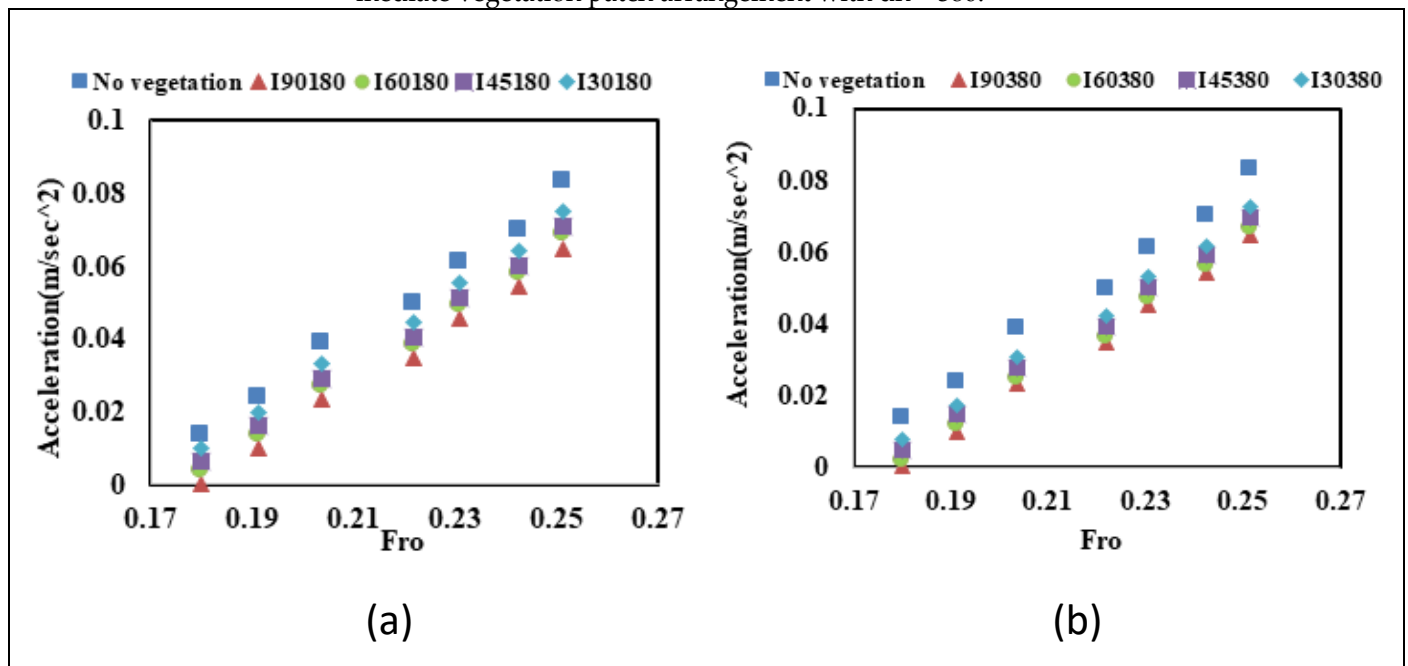
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intermediate vegetation arrangement resulted in the highest total relative energy reduction. In contrast, the least reduction was observed for sparse vegetation ($G/d = 2.13$) while maintaining constant vegetation patch thickness.

These findings demonstrate that closely spaced vegetation can serve as a more effective strategy against approaching inland floods. Therefore, the intermediate vegetation arrangement with a vegetation patch thickness of $dn=380$ and perpendicular vegetation is preferable to the sparse arrangement with a patch thickness of $dn=180$. On average, the model building acceleration dissipation for the four angles (90° , 60° , 45° , and 30°) in the intermediate arrangement was 22.1%. Similarly, in the sparse vegetation configuration, the average percentage reduction in the physical model structure acceleration due to the presence of the vegetation array was 21.8%. The maximum percentage loss of physical model structure acceleration was observed for the intermediate arrangement with I90380, as perpendicular vegetation provides greater hydraulic resistance than I60380, I45380, and I30380. The $dn=380$ vegetation patch model with an intermediate arrangement proves to be more resilient against these conditions.

3.2.2. Significance of vegetation orientations in physical model structure acceleration

Figure 3.6(a, b, c, d) illustrates the relationship between acceleration and F_{ro} for four different vegetation orientations (90° , 60° , 45° , and 30°) to emphasise the importance of angle selection. The results demonstrate the significant role of vegetation in reducing the structural impacts on the physical model structure. In the case of $dn = 180$, positioning the vegetation patch at a different orientation results in an approximate 11.0% increase in the attenuation of the model building's acceleration. In contrast, for $dn = 380$, the loss of physical model structure acceleration is approximately 18.0%. The highest percentage of acceleration loss was observed for intermediate vegetation with a 90° orientation. The acceleration results exhibit a similar trend to vegetation density, highlighting that the maximum acceleration dissipation is associated with an angle of 90° (I90, I60, I45, I30) and an intermediate vegetation patch arrangement with $dn = 380$.



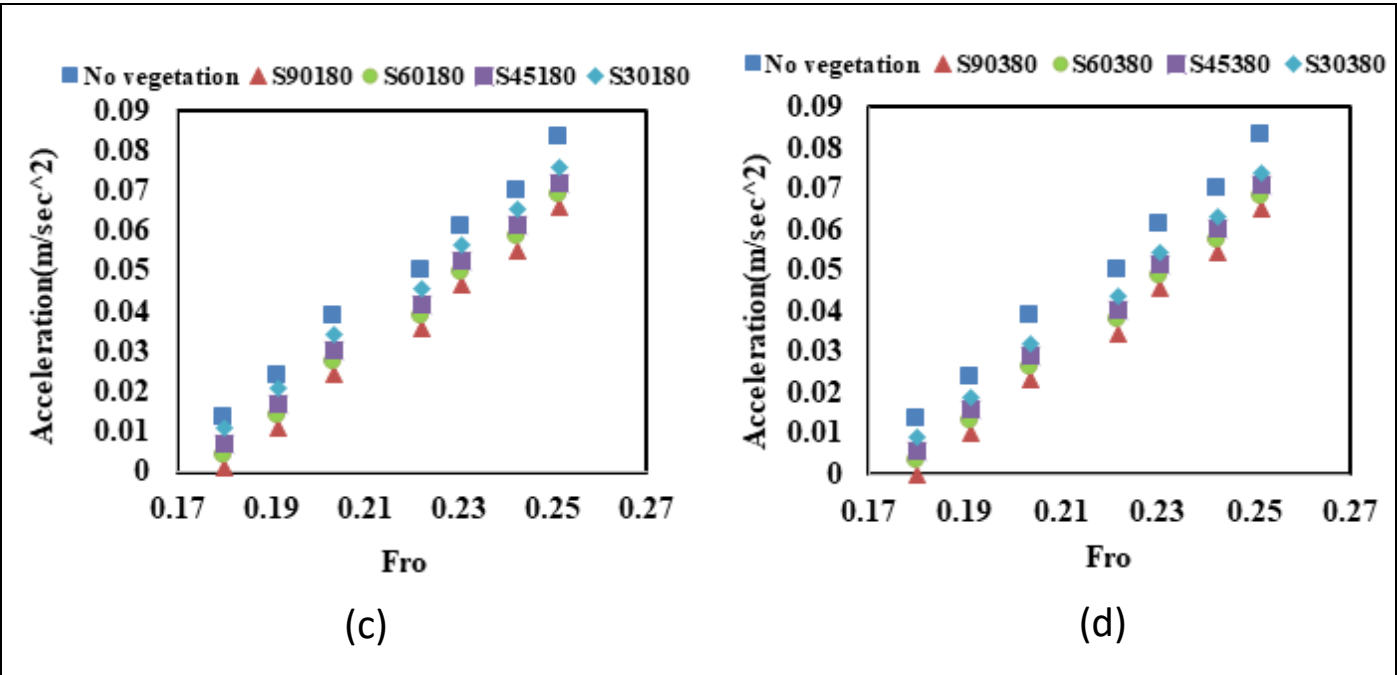
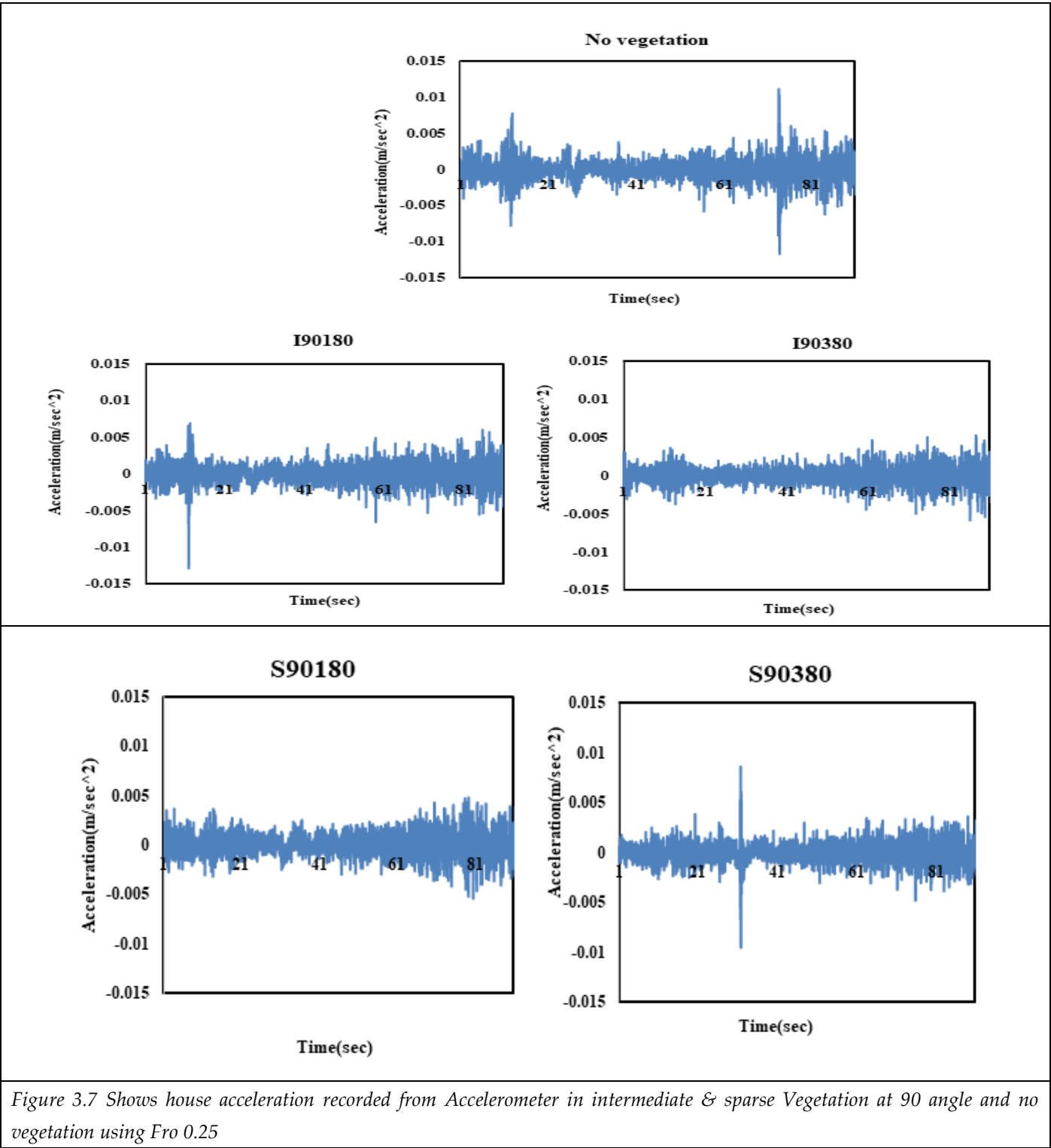


Figure 3.6 (a, b, c, d). Shows the Effect of angles, house acceleration in dn=380 & 180

Figure 3.7 depicts the acceleration of the model building during the period from 1 to 90 seconds under both non-vegetated and vegetation conditions. These graphs were generated using accelerometer data and underwent base correction using seismosignal. These graphs illustrate the acceleration patterns for intermediate and dense vegetation densities at Fro = 0.25. Figures 3.7 show the acceleration of the model building during the first 90 seconds for both non-vegetated and vegetated conditions. These graphs are obtained with the help of an accelerometer and base correction using seismosignal. These graphs show the pattern of acceleration for intermediate and dense vegetation densities using Fro = 0.25.



3.3. Time of Approach

The presence of the vegetation array introduces an increase to the flow approach time due to the resistance the flow experiences. Initially, the approach time before positioning the model in the channel was recorded, followed by the time after placement. The time difference between these two recordings represents the increase in approach time, termed herein as "time delay".

The approach time values range from 35 to 47 seconds in the absence of the vegetation array. However, after situating the model under different Froude numbers, the

approach time varied. For the case of the $dn=180$ vegetation arrangement (Figure 3.8(a, b, c, d)), the approach time ranged from 37 to 52 seconds for I90180, 36 to 50 seconds for I60180, 37 to 48 seconds for I45180, and 36 to 45 seconds for I30180.

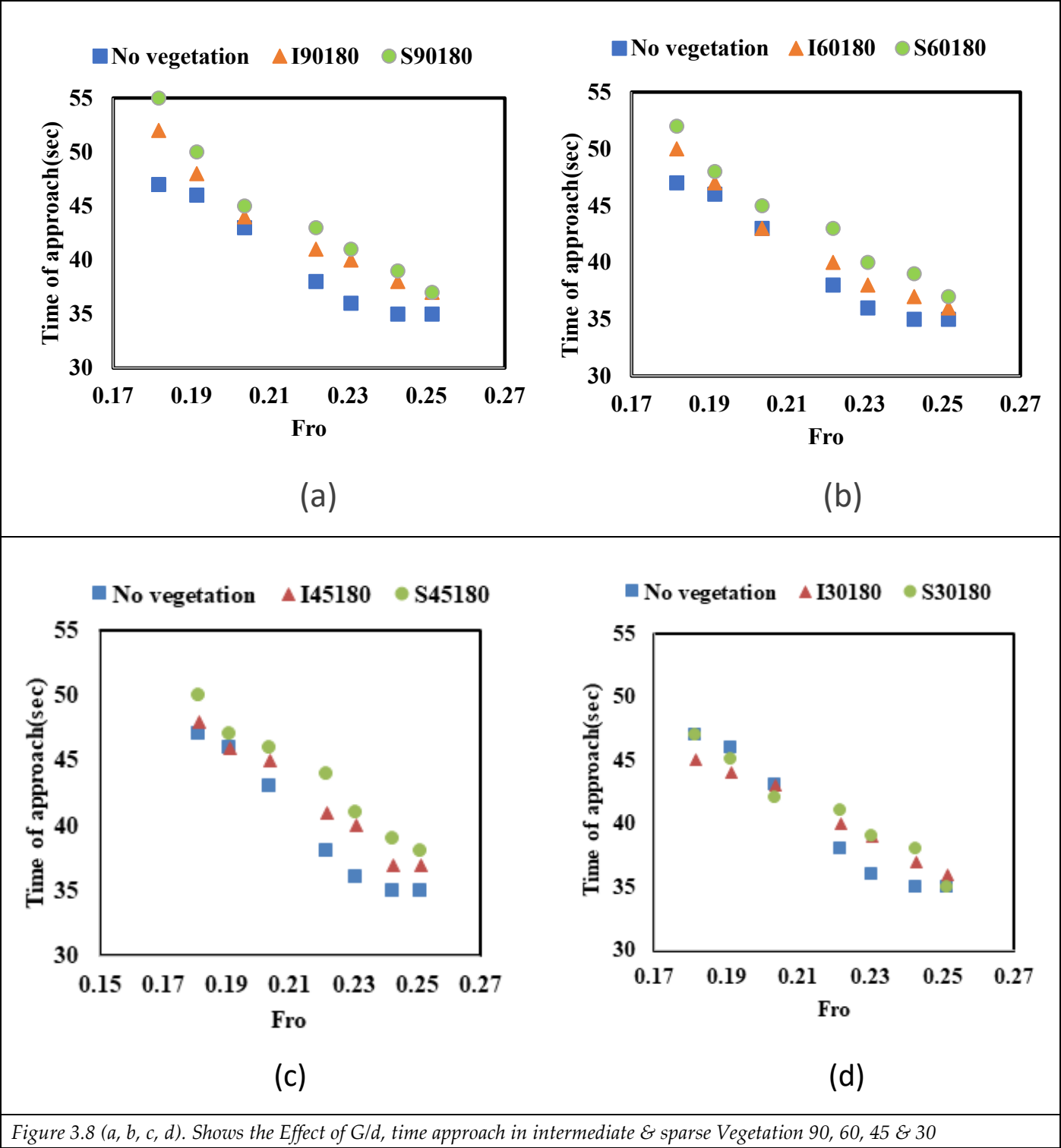


Figure 3.8 (a, b, c, d). Shows the Effect of G/d , time approach in intermediate & sparse Vegetation 90, 60, 45 & 30

In the case of a vegetation patch thickness of $dn=180$ in a sparse arrangement, the approach time varied from 37 to 55 seconds for S90180, 37 to 52 seconds for S60180, 38 to 52 seconds for S45180, and 35 to 47 seconds for S30180. Notably, the maximum time delay was observed for I90180, reaching 60 seconds, indicating a 21.7% increase compared to F_{ro} 0.18.

The results indicate that as the angle of the vegetation increases, the approach time also increases. Effective management of inland forests may have a significant impact on the time delay, as the findings suggest that thicker and denser vegetation contributes to increased time delays, as it hinders the propagation of the flow.

3.4. Statistical Analysis

Vegetation proves to be a highly effective method for mitigating flood damage and reducing hydraulic pressure. In a rectangular channel, we conducted investigations into the impact of vegetation at various angles relative to the flow direction [2,4]. The resistance offered by tree structures to the passage of flow influences flow hydraulics, including the water surface profile within the forest, which directly affects the structural accelerations beyond the forest [1]. Our findings demonstrated a linear increase in acceleration as the Fr value increased in all cases examined. In our statistical analysis, we considered parameters such as standard deviation, range, and mean value. In the absence of obstructions in the water's path, water flows effortlessly. However, when obstructions are present in the water's path, water movement is impeded due to friction. As the angle of the plants in front of the water flow increases, so does the resistance to flow. While maintaining all other parameters constant, we observed that as the Froude number increases, the depth on the upstream face of the model building also increases. This increase in depth is reflected in statistical parameters, such as standard deviation, mean value, and range, as illustrated in Figures 3.9(a), (b), (c), and (d).

The results indicate that the highest water depth corresponds to the highest Froude number, which is 0.25. Consequently, in the absence of vegetation, statistical parameters are optimized at $Fro = 0.25$.

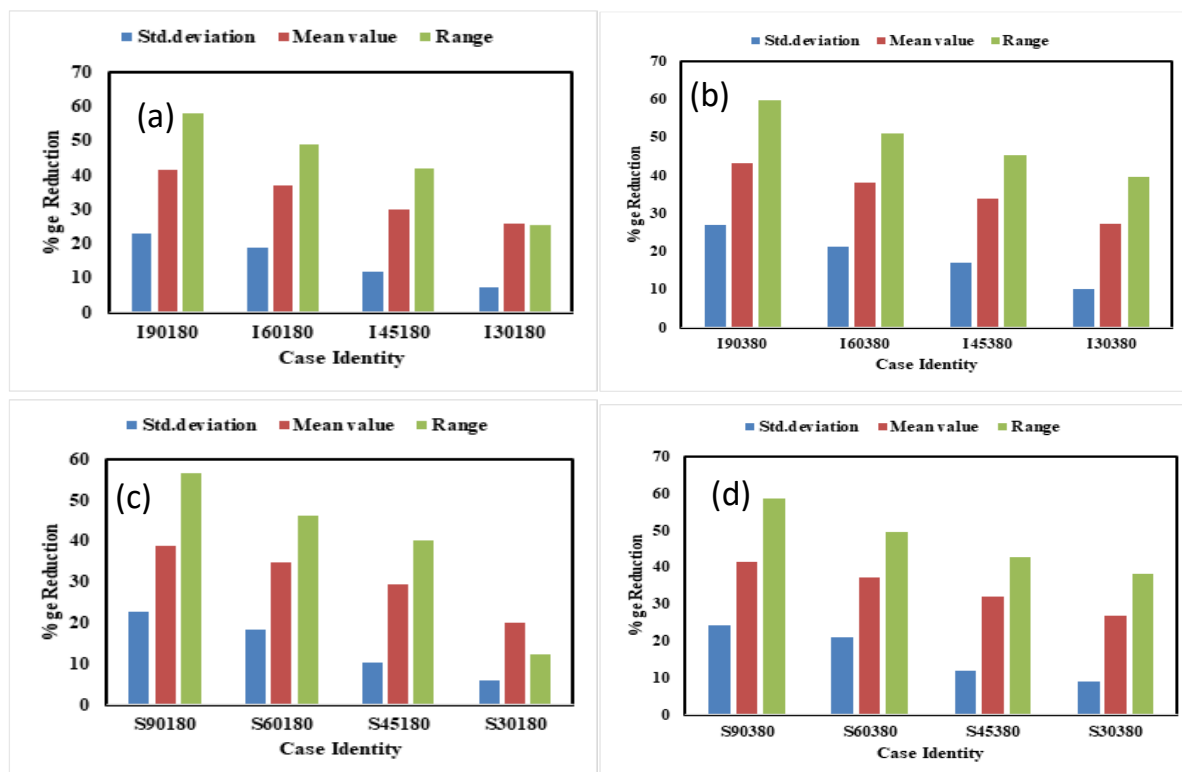


Figure 3.9 (a, b, c, d). Shows the %ge reduction of Statistical Analysis in intermediate & sparse Vegetation 90, 60, 45 & 30 angles.

4. Discussion

This experimental investigation revealed several critical relationships between vegetation configuration and the effectiveness of flood mitigation. Vegetation models demonstrated significant capacity to reduce hydrostatic pressure forces acting on structures, with effectiveness varying by density configuration. Sparse vegetation ($B/d = 2.13$) achieved a good pressure reduction, while intermediate vegetation ($B/d = 1.09$) provided a smaller reduction under identical flow conditions. Perpendicular vegetation arrangements demonstrated superior performance compared to oblique configurations in reducing both hydrostatic pressure and structural acceleration, with perpendicular layouts achieving a greater reduction in force. The X2-2 accelerometer measurements revealed that vegetation presence reduced building acceleration across all tested Froude numbers (0.18–0.25), with intermediate density vegetation providing optimal performance. Vegetation implementation altered subcritical flow patterns, creating energy dissipation zones that effectively reduced downstream fluid forces while maintaining stable flow conditions.

In the current paper, the perpendicular and oblique vegetation arrays are tested in relation to hydraulic pressure, acceleration of the model structure, time of approach, and flow characteristics. Many researchers defined the density of vegetation on the basis of B/d [2]. It was previously studied that the characteristics of undular jump formation were considered for three densities of vegetation: sparse vegetation ($B/d = 2.13$), intermediate vegetation ($B/d = 1.09$), and dense vegetation ($B/d = 0.25$) [12]. However, in the current paper, only sparse and intermediate vegetation types are adopted because, practically, dense vegetation ($B/d = 0.25$) is difficult to construct and is very rare. The phenomenon of energy reduction and the effect of vegetation density under subcritical flow conditions has been studied previously, and it was found that denser vegetation dissipates more energy than lower-density vegetation. In that study, the hydraulic pressure and acceleration of the model building under subcritical flow conditions are determined, based on two variables: B/d and Froude number (Fro).

In previous studies, researchers conducted laboratory experiments to investigate the effect of riverbank vegetation density on flow velocity variation in the main channel and within the vegetation [30, 31]. The effect of different riverbank vegetation densities on flow hydrodynamics across the channel is investigated experimentally [31–32]. The scour pattern around the isolated vegetation element has been investigated to study the sediment scour pattern [33]. In the current study, for S90, the acceleration of model building is drawn against the selected range of Fro (0.18–0.25). However, the results show that by decreasing the orientation of the vegetation patch from 30° to 90° , the model building acceleration dissipation increases, with the maximum acceleration reduction found to be associated with the 90° orientation, specifically for the case of intermediate density with $dn = 380$. Maximum percentage loss of model building acceleration observed for intermediate arrangement with I90380, as perpendicular vegetation provides more hurdles than I60380, I45380 and I30380. Similar results are reported in the literature [7].

Pasha & Tanaka (2017) have conducted an experimental investigation of undular hydraulic jump formation under subcritical conditions by selecting three different vegetation patch thicknesses, that is, dn values of 180, 380, and 580, and the energy reduction for sparse and intermediate vegetation are in the ranges of 26–28% and 29–32%, respectively [12]. In the current study for S90 and I90, a constant patch thickness ($dn = 180$) is used, and the average acceleration reduction against the range of Froude numbers (0.18–0.25) is in the range of 20.8% and 22.0%, respectively. Similarly, a constant patch thickness ($dn = 380$) is used, and the average acceleration reduction is in the range of 22.1% and 22.1%, respectively. When the flow expands toward the floodplain, the angle of flow toward the floodplain is usually oblique for straight [34–35] and meandering channels [36]. Previously, some authors have studied perpendicular weirs [5, 36], while others have used oblique weirs in their studies of open-channel hydraulics [37–38]. The combined effect of

vegetation and weir (placed in perpendicular direction) on energy head loss has also been studied previously [39-40]. The same results are observed in the current study of hydraulic pressure. The vegetation array causes an increase in time delays, with differences in the approach time of the flow ranging from 35 to 47 seconds, regardless of the vegetation patch orientation. After situating the model against different Froude numbers, the approach time increased by 21.7% compared to Fro 0.18.

5. Conclusion and Recommendations

5.1. Conclusion

This study clarifies the importance of vegetation orientation variation in different vegetation conditions in dissipating hydraulic pressure and structural acceleration. The primary findings of this study are as follows.

- Experimental results indicate that the reduction in hydraulic pressure increases with increasing vegetation thickness and decreasing vegetation orientation relative to the main flow, reaching a maximum at an intermediate vegetation density, with $dn = 380$. Thus, intermediate vegetation density ($B/d = 1.09$) emerges as the optimal configuration, achieving superior hydrostatic pressure and acceleration reduction compared to sparse arrangements while remaining practically implementable.
- Perpendicular vegetation alignment provides measurably superior flood force mitigation compared to oblique arrangements, supporting design recommendations for nature-based flood defences.
- The results show that vegetation plays a significant role in influencing fluid pressure forces and the dissipation of acceleration in model building. The X2-2 accelerometer methodology successfully quantified structural response under flood conditions, providing a replicable framework for evaluating vegetation
- -based mitigation strategies. The physical model's structural acceleration reduction increases with the vegetation patch orientation changing from 30° to 90° . The hydraulic pressure and maximum model building acceleration reduction for the case of sparse vegetation patch arrangement with a vegetation patch thickness of $dn = 180$ and 90° orientation were 3.3% and 20.8%, respectively.
- The hydraulic pressure and maximum model building acceleration dissipation in the intermediate arrangement, with a vegetation patch thickness of $dn = 380$ and orientation at 90° relative to the flow direction, were 7.4% and 22.1%, respectively.
- The time of approach within the vegetation depends upon the resistance offered by the vegetation. The findings demonstrated that, in all cases considered, the time of approach decreased linearly as the Fr value increased. The value of approaching time for I90 is higher than for S90. The maximum value of approaching time is seen to increase by 21.7% and 14.5% respectively.
- The results show maximum depth of water against the highest Froude number, i.e., 0.25. Therefore, the statistical parameters are at their maximum without vegetation at Fro = 0.25. The standard deviation, mean, and range values dissipated to a maximum in intermediate cases. The values of statistical analysis I90 are higher than S90. The maximum values of standard deviation, mean, and range dissipation were 26.1%, 43.5%, and 59.8%, respectively. These findings support the integration of strategically configured vegetation into flood risk management systems, offering

sustainable alternatives to traditional hard infrastructure while providing quantifiable protection benefits.

5.2. Recommendations

Based on the findings of this research, it is recommended that flood management strategies should incorporate vegetation as a key component. The results highlight the significance of vegetation angle and density in reducing hydraulic pressure and house acceleration during flooding events. To optimise flood protection, practitioners should consider implementing vegetation arrangements with a 90° angle to the flow direction and prioritise intermediate vegetation density levels. Furthermore, ongoing monitoring and research efforts should be encouraged to refine and adapt these strategies to changing environmental conditions. Collaborative initiatives involving hydrologists, ecologists, engineers, and policymakers are crucial for developing comprehensive and effective flood management policies. Community engagement is crucial for raising awareness and garnering local support for vegetation-based flood protection measures. Overall, integrating vegetation into flood management practices represents a sustainable and cost-effective approach to mitigate flood risks and enhance resilience in flood-prone regions.

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References

- [1] Lacerna, K. C., & Dalugdog, W. D. (2025). Disaster Preparedness among Selected Beach Resorts in San Juan Batangas. *International Journal of Multidisciplinary: Applied Business and Education Research*, 6(6), 3208-3230.
- [2] Smith, K. *Environmental Hazards: Assessing Risk and Reducing Disaster*; Routledge: New York, NY, USA, 2003.
- [3] Singh, R., Gupta, M., Verma, A., Vyas, M., & Buddhi, D. (2024). Japan's Nuclear Energy Crisis: Lessons for Energy Security with Sustainable Clean Energy. In *The South Asian Energy Corridor* (pp. 123-141). Apple Academic Press.
- [4] T. Zaha, N. Tanaka, and Y. Kimiwada, "Flume experiments on optimal arrangement of hybrid defence system comprising an embankment, moat, and emergent vegetation to mitigate inundating tsunami current," *Ocean Eng.*, vol. 173, pp. 45–57, 2019. [Online]. Available: <https://doi.org/10.1016/j.oceaneng.2018.12.054>
- [5] A. Ahmed and A. R. Ghumman, "Experimental investigation of flood energy dissipation by single and hybrid defence systems," *Water (Switzerland)*, vol. 11, no. 10, 2019. [Online]. Available: <https://doi.org/10.3390/w11101971>
- [6] M. Ahmad et al., "Investigating the flow hydrodynamics in a compound channel with layered vegetated floodplains," *Civil Eng. J. (Iran)*, vol. 6, no. 5, pp. 860–876, 2020. [Online]. Available: <https://doi.org/10.28991/cej-2020-03091513>

- [7] A. Ahmed, M. Valyrakis, A. R. Ghumman, G. A. Pasha, and R. Farooq, "Experimental investigation of flood energy reduction through vegetation at various angles," *River Res. Appl.*, vol. 37, no. 4, pp. 644–655, 2021. [Online]. Available: <https://doi.org/10.1002/rra.3777>
- [8] Rehman, S. U., Ahmed, A., Gilja, G., Valyrakis, M., Ghumman, A. R., Pasha, G. A., & Farooq, R. (2023). A laboratory study of the role of nature-based solutions in improving flash flooding resilience in hilly terrains. *Water*, 16(1), 124.
- [9] A. Ali, G. A. Pasha, U. Ghani, A. Ahmed, and F. M. Abbas, "Investigating Role of Vegetation in Protection of Houses during Floods," *Civil Eng. J.*, vol. 5, no. 12, pp. 2598–2613, 2019. [Online]. Available: <https://doi.org/10.28991/cej-2019-03091436>
- [10] Vundavilli, V. S. S. R. H. (2023). The interaction of buoyant river plumes with vegetation and consequences for sediment transport and deposition in coastal regions (Doctoral dissertation, The University of Waikato).
- [11] V. T. M. van Zelst et al., "Cutting the costs of coastal protection by integrating vegetation in flood defences," *Nat. Commun.*, vol. 12, no. 1, 2021. [Online]. Available: <https://doi.org/10.1038/s41467-021-26887-4>
- [12] G. A. Pasha and N. Tanaka, "Undular hydraulic jump formation and energy loss in a flow through emergent vegetation of varying thickness and density," *Ocean Eng.*, vol. 141, pp. 308–325, 2017. [Online]. Available: <https://doi.org/10.1016/j.oceaneng.2017.06.049>
- [13] Liu, X., Xiao, C., Wang, Z., Zhu, N., Du, N., Xu, J., & Li, Y. (2025). Experimental Investigation on Effect of Vegetation Distribution Pattern on Hydraulic Characteristics of Overland Flow. *Hydrological Processes*, 39(8), e70234.
- [14] N. Tanaka, "Effectiveness and limitations of coastal forest in large tsunamis," *Annu. J. Hydraul. Eng. JSCE*, vol. 56, 2012.
- [15] T. Tiggeloven et al., "The benefits of coastal adaptation through conservation of foreshore vegetation," *J. Flood Risk Manag.*, vol. 15, no. 3, 2022. [Online]. Available: <https://doi.org/10.1111/jfr3.12790>
- [16] P. Kumar Yadav, S. Thapa, X. Han, C. Richmond, and N. Zhang, "Investigation of the Effects of Wetland Vegetation on Coastal Flood Reduction Using Hydrodynamic Simulation," presented at *AJKFluids* 2015, Jul. 2015. [Online]. Available: <https://doi.org/10.1115/ajkfluids2015-3044>
- [17] K. D. C. R. Dissanayaka, N. Tanaka, and T. L. C. Vinodh, "Integration of Eco-DRR and hybrid defense system on mitigation of natural disasters (Tsunami and Coastal Flooding): a review," *Nat. Hazards*, vol. 110, no. 1, 2022. [Online]. Available: <https://doi.org/10.1007/s11069-021-04965-6>
- [18] A. Ali, T. Y. Sandhu, and M. Usman, "Ambient vibration testing of a pedestrian bridge using low-cost accelerometers for SHM applications," *Smart Cities*, vol. 2, no. 1, pp. 20–30, 2019. [Online]. Available: <https://doi.org/10.3390/smartcities2010002>
- [19] M. Varanis, A. Silva, A. Mereles, and R. Pederiva, "MEMS accelerometers for mechanical vibrations analysis: a comprehensive review with applications," *J. Braz. Soc. Mech. Sci. Eng.*, vol. 40, no. 11, 2018. [Online]. Available: <https://doi.org/10.1007/s40430-018-1445-5>
- [20] R. E. Martínez-Castro, S. Jang, and R. E. Christenson, "Rapid cable tension estimation using dynamic and mechanical properties," *Proc. SPIE* 9803, 2016. [Online]. Available: <https://doi.org/10.1117/12.2219425>
- [21] N. Tanaka, "Vegetation bioshields for tsunami mitigation: review of effectiveness, limitations, construction, and sustainable management," *Landsc. Ecol. Eng.*, vol. 5, pp. 71–79, 2009.

- [22] P. C. Jennings, "Distant motions from a building vibration test," *Bull. Seismol. Soc. Am.*, vol. 60, no. 6, 1970. 507
508
- [23] R. E. Martínez-Castro, S. Jang, and R. E. Christenson, "Rapid cable tension estimation using dynamic and mechanical properties," *Sensors and Smart Structures Technologies*, vol. 9803, 2016. 509
510
- [24] K. Hayat and S. S. Mehboob, "Mass distribution effect on the finite model updating using operational model analysis technique," unpublished. 511
512
- [25] I. A. Jamil, M. I. Abedin, D. K. Sarker, and J. Islam, "Vibration data acquisition and visualization system using MEMS accelerometer," unpublished. 513
514
- [26] H. S. Park, H. G. Sohn, I. S. Kim, and J. H. Park, "Application of GPS to monitoring of wind-induced responses of high-rise buildings," *Struct. Des. Tall Spec. Build.*, vol. 17, no. 1, pp. 117–132, 2008. [Online]. Available: <https://doi.org/10.1002/tal.335> 515
516
517
- [27] Hott, J. W. (2024). *The Design and Implementation of an Underfloor Accelerometer-Based Local Structural Dynamics Monitoring System for the Ashraf Islam Engineering Building* (Master's thesis, Tennessee Technological University). 518
519
520
- [28] N. Chitsaz and M. E. Banihabib, "Comparison of different multi-criteria decision-making models in prioritizing flood management alternatives," *Water Resour. Manag.*, vol. 29, no. 8, pp. 2503–2525, 2015. [Online]. Available: <https://doi.org/10.1007/s11269-015-0954-6> 521
522
523
- [29] A. Mita and I. Yokoi, "Fiber Bragg grating accelerometer for buildings and civil infrastructures," *Proc. SPIE* 4330, pp. 479–486, 2001. [Online]. Available: <https://doi.org/10.1117/12.434148> 524
525
- [30] M. Sanjou, T. Okamoto, and I. Nezu, "Experimental study on fluid energy reduction through a flood protection forest," *J. Flood Risk Manag.*, vol. 11, no. 4, p. e12339, 2018. 526
527
- [31] M. Valyrakis, D. Liu, U. Turker, and O. Yagci, "The role of increasing riverbank vegetation density on flow dynamics across an asymmetrical channel," *Environ. Fluid Mech.*, vol. 21, pp. 643–666, 2021. 528
529
530
- [32] C. J. Williams et al., "Vegetation, ground cover, soil, rainfall simulation, and overland-flow experiments before and after tree removal in woodland-encroached sagebrush steppe," *Earth Syst. Sci. Data*, vol. 12, no. 2, pp. 1347–1365, 2020. 531
532
533
- [33] O. Yagci et al., "Scour patterns around isolated vegetation elements," *Adv. Water Resour.*, vol. 97, pp. 251–265, 2016. 534
535
- [34] E. Keramaris, G. Pechlivanidis, D. Kasiteropoulou, N. Michalolias, and A. Liakopoulos, "Experimental and numerical study of turbulent flow in open channels with impermeable and porous bed," *Procedia Eng.*, vol. 162, pp. 381–387, 2016. [Online]. Available: <https://doi.org/10.1016/j.proeng.2016.11.078> 536
537
538
539
- [35] G. Mahtabi and H. Arvanaghi, "Experimental and numerical analysis of flow over a rectangular full-width sharp-crested weir," *Water Sci. Eng.*, vol. 11, no. 1, pp. 75–80, 2018. 540
541
- [36] W. M. Van Dijk, R. Teske, W. I. Van de Lageweg, and M. G. Kleinhans, "Effects of vegetation distribution on experimental river channel dynamics," *Water Resour. Res.*, vol. 49, no. 11, pp. 7558–7574, 2013. 542
543
544
- [37] O. G. Aichel, "Discharge ratio for oblique weirs," *Z. VDI*, vol. 95, no. 1, pp. 26–27, 1953. 545
- [38] N. B. Tuyen, "Flow over oblique weirs," M.S. thesis, Faculty of Civil Engineering and Geosciences, Delft Univ. Technol., Netherlands, 2006. 546
547

[39] S. Ali and W. S. Uijttewaai, "Flow resistance of vegetated weirlike obstacles during high water stages," *J. Hydraul. Eng.*, vol. 139, no. 3, pp. 325–330, 2013.

[40] S. Ali and W. S. J. Uijttewaai, "Flow resistance of vegetated oblique weir-like obstacles during high water stages," *Hydrol. Earth Syst. Sci.*, vol. 18, no. 1, pp. 1–14, 2014. [Online]. Available: <https://doi.org/10.5194/hess-18-1-2014>

Table 1. Where Fr_0 is the initial Froude number, d the diameter of cylinder, dn is the thickness of forest.

Case #	Angle of vegetation	Initial Froude No. (Fr_0)	d (cm)	Forest type	Tree thickness (dn)
1	No vegetation	0.18, 0.19, 0.20, 0.22, 0.23, 0.24, and 0.25	0.3		180,380
2	90	0.18, 0.19, 0.20, 0.22, 0.23, 0.24, and 0.25	0.3	Intermediate	180,380
3	90	0.18, 0.19, 0.20, 0.22, 0.23, 0.24, and 0.25	0.3	Sparse	180,380
4	60	0.18, 0.19, 0.20, 0.22, 0.23, 0.24, and 0.25	0.3	Intermediate	180,380
5	60	0.18, 0.19, 0.20, 0.22, 0.23, 0.24, and 0.25	0.3	Sparse	180,380
6	45	0.18, 0.19, 0.20, 0.22, 0.23, 0.24, and 0.25	0.3	Intermediate	180,380
7	45	0.18, 0.19, 0.20, 0.22, 0.23, 0.24, and 0.25	0.3	Sparse	180,380
8	30	0.18, 0.19, 0.20, 0.22, 0.23, 0.24, and 0.25	0.3	Intermediate	180,380
9	30	0.18, 0.19, 0.20, 0.22, 0.23, 0.24, and 0.25	0.3	Sparse	180,380