Flood-Induced Behavior of Reinforced Concrete Buildings: A Review of Loading Effects and Soil-Structure Interaction

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***Abstract*—Flooding is a major natural hazard that can impose significant lateral actions on buildings and their foundations. Unlike conventional structural assessments that primarily consider gravity, wind and earthquake effects, flood assessment requires attention to the interaction between water and the exposed structure. The principal flood actions include hydrostatic pressure caused by water depth, hydrodynamic forces associated with flowing water, and impact forces generated by floating debris. The response of a building may also be influenced by the flexibility of the supporting soil and foundation system. This review examines published research on flood and tsunami loading, experimental investigations of flow and debris impact, observed building damage, and soil–structure interaction. The reviewed studies are organized to explain the physical mechanisms of flood loading and the importance of considering foundation flexibility when evaluating structural response. Particular attention is given to reinforced concrete buildings, lateral displacement, inter-storey drift and the distinction between fixed base and flexible base idealizations. The review identifies limitations in existing approaches and highlights the need for integrated assessment of flood actions and foundation behavior in buildings located in flood prone regions.**

***Index Terms*—Flood loading, Hydrostatic pressure, Hydrodynamic force, Debris impact, Reinforced concrete building, Soil-structure interaction, Fixed base, Flexible base.**

I. INTRODUCTION

Flooding is one of the most widespread natural hazards and can cause extensive damage to buildings, transportation systems and other infrastructure. In India, major flood events in urban and riverine regions have demonstrated the vulnerability of the built environment to inundation. Rapid urbanization, changes in land use, obstruction of natural drainage paths and development in low lying areas can increase the exposure of buildings to flood hazards. Although reinforced concrete (RC) buildings are generally designed for gravity loads and, where applicable, wind and earthquake actions, the effects of floodwater are not always explicitly considered during structural design.

The actions generated by floodwater are different from conventional lateral loads. Hydrostatic pressure develops when water is present at rest and varies with the depth of submergence. Hydrodynamic force develops when water flows against a structural surface and is influenced by flow velocity, water depth, exposed area and the geometry of the obstruction. Floating objects carried by floodwater may collide with columns, walls or other structural components and generate short duration impact forces. Depending on the site conditions, additional mechanisms such as buoyancy, waves, local scour, erosion and water accumulation may also influence building performance.

The structural response to flood loading is not governed only by the superstructure. The foundation and supporting soil influence the transfer of lateral actions to the ground. In a conventional fixed base model, the base of the building is assumed to be perfectly restrained. This assumption simplifies structural analysis but does not represent foundation translation or rotation. A flexible base model considers the deformation of the soil foundation

system, commonly through equivalent springs or a more detailed soil-structure interaction model. The difference between these idealizations may be important when assessing lateral displacement and inter storey drift under flood actions.

Published research on flood and tsunami loading has addressed the classification of flood actions, hydrodynamic force estimation, debris impact and damage to buildings. Separate research has investigated soil–structure interaction and its influence on the dynamic behavior of buildings. However, these areas are often studied independently. A review connecting flood actions with foundation flexibility is therefore useful for understanding the current state of knowledge and identifying areas requiring further investigation.

This paper reviews literature related to the behavior of reinforced concrete buildings subjected to hydrostatic, hydrodynamic and debris impact actions, with additional consideration of fixed base and flexible base modelling. The discussion is organized into flood and tsunami loading studies, experimental and debris impact investigations, field observations of building damage, and soil structure interaction studies. The principal response measures considered in the reviewed literature include structural displacement, inter storey drift and the influence of soil and foundation flexibility.

II. REVIEW OF LITERATURE

An overview of flood actions on buildings is presented by Kelman and Spence (2004). A broad classification of the direct actions that floodwater can impose on buildings. The authors explained that flood damage cannot be assessed only by considering the gradual rise of water level, because several physical mechanisms may act on a building during an inundation event. These include differential hydrostatic pressure; pressure associated with flowing water, buoyancy, waves, turbulence, erosion and debris related effects. The paper discusses the relative relevance and predictability of these actions and provides a framework for understanding how they may contribute to building damage or failure. This review is fundamental to the present topic because it establishes the need to identify hydrostatic, hydrodynamic and debris impact actions as distinct mechanisms. It also emphasizes that the load path and physical basis of each action should be understood before the actions are represented in a structural model.

Kreibich et al. (2009) identified whether the flow velocity a significant parameter in flood damage modelling? Kreibich examined the role of flow velocity in flood-damage modelling and considered whether velocity provides additional information alongside flood depth and other indicators. The study used observed flood-damage information to investigate the relationship between flood characteristics and damage to exposed assets. The authors showed that the contribution of flow velocity is not uniform across all damage categories and that its significance depends on the type of exposed structure or infrastructure and the damage measure being considered. This work is important because flood depth and flow velocity represent different physical characteristics of an inundation event. Depth is associated with the extent of submergence and hydrostatic pressure, whereas velocity contributes to the dynamic action of moving water. The study supports treating these parameters separately when defining flood scenarios and highlights the need to state the assumptions used to relate flow velocity to water depth.

Further, Yeh et al. (2007) discussed the physical basis and estimation of tsunami forces acting on onshore structures. The paper considers the hydrodynamic action generated by inundating water and explains the importance of flow and inundation conditions in estimating the forces imposed on buildings. It provides a rational basis for relating the characteristics of the flow to the forces acting on structures of finite breadth. The study is useful for understanding that the lateral action of moving water depends not only on the water level but also on the velocity and the geometry of the exposed surface. It therefore provides methodological background for the hydrodynamic component of flood load assessment. The paper also reinforces the need to check the applicability of the selected equations, coefficients and assumptions against the particular flood scenario and the design guidance adopted for a structural investigation.

Palermo et al. (2009) presented an overview of tsunami loading on near shoreline structures and brought together important physical mechanisms and available experimental and analytical evidence. The

study discusses hydrostatic and hydrodynamic actions, debris impact and other effects associated with inundation. It explains that the loading on a structure may change during the passage of a tsunami and that the resulting forces depend on inundation conditions, flow characteristics and structural geometry. The authors also considered experimental observations and compared them with available design formulations, providing context for the use and limitations of simplified equations. This work is relevant to the present topic because it supports the separate identification of the principal flood load components and the consideration of their possible combinations. It also highlights the importance of documenting whether the different actions are evaluated independently or represented together in a justified load case.

Another author Eames and Johnson (2014) investigated the force acting on a square cylinder placed in a free surface channel flow. Their experimental and analytical study examined the flow around a fixed obstacle and considered the relationship between flow conditions and the force acting on the obstacle. The presence of a free surface is important because the water level and flow field around an obstruction can change as the water interacts with the structural element. The study demonstrates that hydrodynamic force depends on flow characteristics and the geometry of the exposed object rather than on water depth alone. Although the square cylinder represents a simplified obstruction rather than a complete multi storey building, the research provides useful evidence on the interaction between moving water and a vertical structural element. It supports consideration of flow velocity and projected area when assessing hydrodynamic actions on buildings.

Arnason, Petroff and Yeh (2009) conducted laboratory investigations of a tsunami bore striking a vertical column. The study examined the interaction between a rapidly advancing water front and a structural element, with attention to the force generated during initial impingement and the flow behavior that follows. The research is useful because the initial impact of a bore may produce a transient action that differs from the force associated with the later flow around the column. This distinction is important when interpreting simplified structural models. A static equivalent load can be used for a comparative parametric investigation, but it does not reproduce the complete time history of a rapidly changing bore or the detailed flow field around the structure. The study therefore provides experimental context for hydrodynamic loading and highlights the need to explain the limitations of static load idealization.

A review done by Nistor, Goseberg and Stolle (2017) for movement of debris carried by tsunami flows and the loads generated when such debris interacts with structures. The review explains how floating objects may become entrained in moving water, travel with the inundation flow, collide with structural elements or accumulate against a building. It identifies debris characteristics and flow conditions as important factors governing the resulting actions. The authors also discuss uncertainties associated with debris entrainment, motion, momentum transfer and impact force prediction, and identify the need for further experimental validation and improved assessment methods. This work is directly relevant to flood resistant building assessment because debris impact represents a separate loading mechanism from hydrostatic pressure and hydrodynamic drag. It also indicates that debris mass, velocity, impact location and contact duration should be considered when estimating impact actions.

Haehnel and Daly (2002) investigated the impact of floating woody debris on structures located in floodplains. Their engineering report describes experimental collision investigations and examines the forces generated when moving debris strikes a structural target. The work considers impact mechanics and the factors that influence the maximum force transferred during a collision. It demonstrates that debris impact is different in nature from the sustained pressure exerted by surrounding water, because the collision involves a transfer of momentum over a relatively short period. The report is relevant to flood resistant structural assessment because it provides an experimental basis for considering debris impact as an independent action. It also indicates that debris properties, motion and collision characteristics should be documented when an equivalent impact force is adopted in a structural analysis. The experimental arrangements and debris properties, however, need to be checked before they are applied to a building model with different characteristics.

A method proposed by Matsutomi (2009) for estimating the collision force produced by driftwood carried through tsunami inundation flow. The paper examines the interaction between moving debris and a structure and discusses parameters that influence the estimated impact, including flow velocity, acceleration distance, impact duration and force rise time. It also considers the occurrence of collision forces in the context of debris transported by inundating water. The study is relevant to flood load assessment because it shows that debris impact cannot be described by debris weight alone. The motion of the debris and the duration of contact also influence the force transferred to the structure. The work supports the need to document the assumed debris properties and collision conditions when impact forces are estimated for different flood scenarios. It also provides a basis for discussing the limitations of simplified impulse-based force estimates when they are represented as equivalent loads in building analysis.

Shafiei et al. (2016) experimentally investigated the impact force generated when tsunami borne debris strikes a structure. The experiments used instrumented debris and force measurement arrangements to examine the impulse–momentum relationship and the factors influencing impact force. The study considered the influence of debris characteristics and collision conditions, including debris mass, impact velocity and contact duration. The findings indicate that the magnitude and time variation of the impact action are closely related to the momentum transferred during collision. This work is directly relevant to the debris impact component of flood load assessment because it provides experimental support for treating debris impact separately from hydrostatic and hydrodynamic actions. It also demonstrates why the assumptions adopted for debris properties and impact duration should be clearly identified rather than treated as universal values.

Building damage in Thailand in the 2004 Indian Ocean tsunami and clues for tsunami resistant design conducted by Lukkunaprasit and Ruangrassamee (2008) examined building damage and discussed the implications for tsunami resistant design. The paper uses field observations to relate damage patterns to inundation and building characteristics. It provides practical evidence that the effects of inundation depend on the interaction between water and the building, including the arrangement of structural and nonstructural components. The observations are useful for understanding the vulnerability of building elements and the importance of openings and flow paths during inundation. Field observations do not isolate every load component or provide a direct numerical prediction for a particular building configuration; therefore, they are most appropriately used as contextual evidence. The study nevertheless demonstrates the importance of considering inundation effects in the planning and structural design of buildings in exposed areas.

Petrone et al. (2017) compared different analytical approaches for assessing structures subjected to tsunami loading. Their work considered a reinforced concrete tsunami evacuation building and examined nonlinear static procedures in relation to time history analysis. The study discussed the influence of the adopted tsunami force distribution and analysis procedure on the assessment of structural response. It also drew attention to the limited guidance available for representing complex tsunami actions in conventional structural analysis. The research is relevant to flood load assessment because the assumed distribution of lateral pressure over the inundated height can influence the response predicted by a building model. It also demonstrates the limitations of simplified static representations when the actual loading is transient and changes with the passage of the flow. For comparative structural studies, the adopted load distribution and analysis assumptions should therefore be clearly explained.

Alam et al. (2018) developed a physics-based framework for evaluating the vulnerability of structures subjected to tsunami loading. The study considered structural member failure and uncertainty in material and structural properties through numerical simulation and fragility assessment. Rather than relying exclusively on a global response parameter, the framework connects the intensity of tsunami loading with the likelihood of reaching different structural damage states. This approach is important because the behavior of a building under severe inundation may involve local damage to individual members as well as changes in the overall structural response. The paper provides a wider perspective on the assessment of buildings under increasing flood or tsunami intensity. Although a

comparative study based on displacement and inter storey drift has a more limited scope than a probabilistic fragility assessment, the work highlights the importance of interpreting global response in relation to possible member level damage and structural performance.

Vivek and Raychowdhury (2017) investigated the influence of soil structure interaction on the period and damping of buildings supported on shallow foundations resting on cohesionless soil. Their study considered building frames supported on different soil conditions and used experimental and analytical approaches to examine the effect of soil flexibility. The research indicates that the dynamic characteristics of a building are influenced by the supporting soil and that the extent of this influence depends on building characteristics and soil condition. This is important when comparing a fixed base model, in which foundation movement is restrained, with a flexible base model that permits soil and foundation deformation. Although the study focuses on seismic dynamic characteristics rather than direct flood loading, it provides a technical basis for including foundation flexibility in structural comparisons and emphasizes the need to define the soil and foundation properties used in a spring supported model.

Tabatabaiefar and Fatahi (2014) examined the idealization of the soil-structure system for determining the inelastic seismic response of midrise building frames. The study used numerical modelling to represent the interaction between the building and the supporting soil and investigated the influence of soil conditions on structural response. The work highlights that the flexibility of the soil foundation system can affect deformation demands, including inter storey drift and overall structural performance. It is relevant to the earthquake component of comparative building assessment and provides a basis for examining the difference between fixed base and flexible base idealizations. The study also indicates that soil modelling should be based on defined geotechnical properties and a transparent representation of the soil foundation system. For flood related building assessment, it offers supporting evidence on the importance of foundation flexibility, while its direct findings should be interpreted within the seismic loading conditions considered by the authors.

III. SUMMARY

The reviewed literature demonstrates that flood loading on buildings involves several distinct physical actions, including hydrostatic pressure, hydrodynamic force and impact from floating debris. These actions are governed by different parameters and should be identified separately when developing a flood load assessment. Hydrostatic pressure is associated with water depth, while hydrodynamic action depends on the characteristics of the moving flow and the geometry of the exposed structure. Debris impact is governed by the momentum transfer and collision characteristics of the moving object. Experimental and field studies also show that the loading process may be transient and that simplified static representations have limitations when describing rapidly changing flow conditions.

The literature on soil-structure interaction establishes that the supporting soil and foundation system can influence the dynamic characteristics and deformation response of a building. A fixed base idealization does not represent foundation translation or rotation, whereas a flexible base model can account for soil and foundation deformation through an appropriate representation of stiffness. The reviewed SSI studies mainly address seismic response, and their findings provide supporting knowledge for understanding foundation flexibility rather than direct evidence of flood induced response.

Overall, the literature indicates a need for integrated studies that consider flood actions and foundation flexibility together. Further investigation is required to understand how hydrostatic; hydrodynamic and debris impact loads influence reinforced concrete buildings when the foundation is represented by fixed and flexible support conditions. Comparative evaluation of lateral displacement and inter storey drift, with clearly defined flood, flow, debris and soil parameters, can contribute to a more complete understanding of building behavior in flood prone regions.

IV. CONCLUSION

Based on the reviewed literature, the following conclusions can be drawn:

- Flood loading involves multiple physical actions, including hydrostatic pressure, hydrodynamic forces

and debris impact, which need to be considered separately during structural assessment.

- The structural response of buildings under flood loading depends on the magnitude and nature of flood actions, flow characteristics and building geometry.
- Soil-Structure Interaction plays an important role in determining the overall structural response, as foundation flexibility can influence lateral displacement and inter storey drift.
- Fixed base and flexible base modelling approaches may produce different structural responses due to variations in foundation stiffness and soil deformation.
- Existing research predominantly investigates flood loading and Soil–Structure Interaction independently, indicating a lack of integrated studies considering both effects simultaneously.
- Further investigation is required to evaluate the behaviour of Reinforced Concrete (RC) buildings subjected to hydrostatic, hydrodynamic and debris impact loads under fixed base and flexible base conditions.
- A comparative study focusing on lateral displacement and inter storey drift, considering appropriate flood, flow, debris and soil parameters, can provide better insight into the structural performance of buildings in flood prone regions.

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