# STRUCTURAL FLOOD VULNERABILITY AND THE AUSTRALIANISATION OF BLACK'S CURVES

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## ABSTRACT

The Risk Research Group at Geoscience Australia (GA) in Canberra is a multidisciplinary team engaged in the development of risk models for a range of natural hazards that are applicable to Australian urban areas. The Group includes hazard experts, numerical modellers, engineers, economists, and a specialist researching social vulnerability. The risk posed by riverine flooding to residential buildings is an important component of the work undertaken by the Group and is the focus of this paper.

In 1975 researcher Richard Black published a report titled *Flood Proofing Rural Residences* as part of a multidisciplinary investigation of flood risk management in the USA. Black's research produced a number of curves describing combinations of water depth and velocity theoretically required to move a flooded house from its foundations. These so-called "Black's Curves" have been referenced by numerous researchers worldwide since their publication. The houses used in Black's study are small by modern standards, and construction materials used in Australia can differ from those used in Black's research.

In the research being undertaken by GA, a similar method to that developed by Black is used to assess the damage to residential buildings, but is applied to typical Australian structures. The representative structures were selected after assessing survey data collected in 2003 as part of a multi-hazard risk assessment of Perth. The key building types addressed in this study include timber clad, fibre cement and brick veneer structures.

Curves for each structure type are created by assessing gravity, buoyancy, and dynamic forces (due to flowing water) for various combinations of inundation depth and water velocity. The development of these curves incorporating the impact of flow momentum adds rigour to flood damage assessment in Australia, which has traditionally focused on stage damage curves.

## INTRODUCTION

The Risk Research Group at GA is a multidisciplinary team engaged in the development of risk models for a range of natural hazards that are applicable to Australian urban areas. The risk posed by riverine flooding to residential buildings is one component of the work undertaken by the Group and is the focus of this paper. Above-floor water levels in conjunction with stage-damage curves have traditionally been used to determine the impact of flooding on structures. Stage-damage curves make no allowance for the effect of flowing water on a structure. This paper presents curves that provide a means for assessing a structure's stability when inundated by flowing water. The incorporation of these curves into flood damage assessments will increase the rigour of the assessments.

The research presented in this paper is based upon a study undertaken in the United States in 1975 by Richard Black [1]. Black's curves provide a means for assessing the overall stability of a number of basic houses when water depth and velocity are known. The houses studied by Black are not considered typical Australian structures, in terms of both size and material. For this reason the current research to develop curves applicable to Australian construction has been undertaken.

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## RISK FROM RIVERINE FLOODING

Floods were found to be Australia's most costly natural disaster type between 1967 and 1999 [2]. There are a number of ways riverine flooding may pose a threat to a residential structure and its contents. Three of these are described in the following sub-sections: inundation, local damage, and overall instability.

### Inundation

Inundation involves the wetting of a structure and (potentially) its contents. Risk due to inundation is usually described by stage-damage curves. These curves generally relate overfloor depth of water to a damage state. There are a number of factors that may effect the accuracy of risk predicted using this method. Factors such as warning time and prior flood experience potentially allow householders to move vulnerable contents to higher locations. Stage-damage curves have been the subject of much research and various curves have been published as a result [3, 4, 5, 6]. Assessing damage to structures using stage-damage curves does not allow for the effect of water flow, which can cause local damage or overall instability.

### Local Damage

Local damage is typically associated with fast flowing water and results in some structural components failing (ie doors, windows, some walls). The initiation of local damage can lead to further structural damage as water ingress rapidly increases following the failure of one (or more) structural components. This type of damage is difficult to predict and is something that Geoscience Australia plans to eventually address as part of its work on structural vulnerability to flooding.

### Overall Instability

Overall instability refers to a situation when the integrity of the entire structure is compromised by being dislodged from its foundations. This can be thought of as the structure moving as a unit off its foundations as a result of the buoyancy due to inundation and the horizontal pressure created by the flowing floodwater. Overall instability is the focus of this paper and is discussed in more detail in the following section.

## BLACK'S CURVES

Black's curves were developed in 1975 as a part of 'Project Agnes', a multidisciplinary investigation of flood risk management produced for the US Department of Commerce [1]. The basis behind the curves is that a house in water is subjected to three additional forces due to the water: buoyancy, hydrostatic pressure and dynamic pressure. Buoyant forces were calculated by Black for four houses at rising water levels. The basic house used in the analyses was about 7m wide and 10m long. Once buoyant forces at different depths were calculated, Black assessed the horizontal force on the houses due to the flowing water. When the force due to the flow equalled the frictional force available to keep the house on its foundations the building was deemed to have failed. Threshold velocities were calculated for various depths, and plotted on a graph with a velocity axis and a water depth axis. For combinations of depth and velocity that fall "inside" the curve (ie. closer to the origin), the structure is considered stable and will remain on its foundations. Conversely, if a point described by a water depth and velocity lies "outside" the curve, the structure is considered to have failed.

Black's curves have been cited in many different studies since their development [7, 8, 9, 10]. There are a number of reasons why it was considered worthwhile to evaluate similar curves applicable to Australian houses. For example, the houses analysed by Black were very small by Australian standards and United States residential construction also differs from Australia's with regard to materials, with plywood sheathing and bituminous roofing common in the US. Furthermore, the accuracy of Black's curves was questioned by Sangrey *et al* in their report on structurally interrupted flood plain flows [9]. The issue centres on the drag coefficient ($C_D$) used to assess drag due to fluid flow. Sangrey *et al* use a value of two for $C_D$ while it appears Black applied the Bernoulli equation (incorrectly) in calculating a pressure rather than a drag force. The Bernoulli equation does not allow for a drag coefficient and the horizontal forces therefore differ by a factor of two. Given these issues, it was decided to perform a similar study using the same methodology as Black for residential stuctures considered more relevant to the work being undertaken at GA.

## CURVES FOR AUSTRALIA

### Structural Layout and Size

A house shape considered representative of Australian residential construction was selected. It is an L-shaped floor plan (Figure 1) which corresponds to the predominant plan shape surveyed by Geoscience Australia in Perth as part of the Perth Cities Project [11]. The survey involved analysing aerial photography for three suburbs (about 1900 homes) and determined that 46% of the houses were L-shaped.

Data from the Australian Bureau of Statistics (ABS) regarding floor areas of new dwellings indicates that the average floor area of houses constructed in Perth in the financial year of 1984/1985 was approximately 190m$^2$. This size was selected as an area that best represents the mean Perth housing stock. The floor plan selected (Figure 1) has a total area of 192.7m$^2$ and corresponds very well with the adopted size and shape. It is worth noting that the single storey house assessed by Black had a floor area of roughly 71m$^2$, only 37% of the adopted Australian area.

### Component Details

The houses analysed have timber frames, and three different wall types: brick veneer, fibre cement cladding, and timber cladding. Two roofing materials were considered in combination with the various wall materials. Tile roofs and sheet metal roofs were analysed. More detailed descriptions of the houses are given in the following sections.

*Floor and sub-floor*

All structural timber used in this study is assumed to be seasoned hardwood with a density of 850kg/m$^3$. The sub-floor support consists of 100x75mm bearers at 1800mm centres, with 100x38mm floor joists at 450mm centres. The sub floor is 20mm thick particle board with a density of 650kg/m$^3$.

*Wall frame*

The stud wall frames are 2400mm high with 100x38mm studs at 600mm centres, 75x38mm noggings at approximately mid-height, and the top and bottom plates are 100x38mm members. Studs are doubled adjacent to openings, and 150x50mm lintel beams are used above openings. The frames are braced by 10mm thick bracing board.

*Roof system*

The roof is assumed to be a hip roof system with 125x38mm rafters at 600mm spacings. The rafters feature 100x75mm underpurlins at about mid-span. Every second rafter features a 75x38mm collar tie with 100x75mm toms bracing it to the interior wall system. The ceiling joists are 100x38mm, the fascia is 200x38mm, and the ridgeboard and hip rafters are 175x38mm. Battens are located at 350mm centres and are 50x25mm sections.

*Cladding and roofing materials*

The fibre cement cladding sheet is assumed to be 8mm thick with a density of 1500kg/m$^3$. Timber cladding is 21mm thick and 450kg/m$^3$, while bricks are assumed to be a standard 230x110x76mm house brick with a density of 1900kg/m$^3$. Roofing materials such as tiles were assumed to have a mass of 50kg/m$^2$, and steel sheeting a mass of 6kg/m$^2$.

*General*

In Black's methodology, no allowance was made for mechanical systems (plumbing, heating etc) or contents (furniture, appliances, etc). Kitchen cabinets and other built-in items were included. This is also the case in the current research.

## Curves

*Buoyancy*

The weight of each of the houses can be calculated by summing the masses of its components. The houses assessed as a part of this research were much heavier than those studied by Black. For example, the lightest Australian structure analysed (timber clad, steel roofed) has a mass of about 19000kg, compared with the one storey drywall house analysed by Black which had a mass of just over 7000kg. The buoyant effect of the rising water can be assessed by calculating the weight of the water displaced by the various components of the structure. If the buoyant force is equal to the weight of the structure it will float (in theory). Buoyancy values were calculated at various water levels, representing changes in the structural system of the house. It is assumed for the current level of this research that water levels inside and outside the structure are identical. This eliminates the need to consider hydrostatic forces during the analysis.

*Horizontal force*

The horizontal force on the structure due to the flowing water is calculated using

$$F_H = \frac{C_D \rho v^2 bd}{2} \tag{1}$$

where $C_D$ is the drag coefficient, ρ is the density of water, v is the mean velocity of the water, b is the width of the house, and d is the depth of the water above the foundation. The horizontal force can be equated to the force required to overcome friction (Equation 2).

$$F_F = fN \tag{2}$$

where f is the coefficient of friction and N is the normal force (weight of the structure on its foundations). When values are assumed for $C_D$ and f, a velocity can be calculated at each of the water depths for which there is a buoyancy calculation. The normal force, N, includes a reduction due to any buoyancy present, and results in lower velocities required to cause instability as water depths (and buoyant forces) increase.

The drag coefficient is assumed for highly turbulent inviscid flows to be two in this study. The coefficient of friction used was 0.48, which is the same as that used by Black, and is within the range typically quoted for wood on wood (0.25-0.50). No allowance was made for any mechanical connection between the structure and its foundations in this study, and it is assumed that simple nailed connections will not effect the results significantly.

The structures assessed in this paper are assumed to have their widest plan dimension perpendicular to the flow. If the flow is normal to a smaller dimension the drag force will be reduced by the ratio of the lengths, and the velocity required for failure increased by the square root of the inverse ratio. If the flow direction is is non-normal to the structure the drag will also be reduced.

*Curves*

The curves have been plotted (Figure 2) and are shown along with one of Black's curves. The curves for timber clad buildings have not been shown here as they are very similar to those for fibre cement clad structures. The curve from Black's study displayed in Figure 2 represents a single storey house with drywall construction. This is much lighter than the Australian structures and is more vulnerable at lower velocities as the frictional force is much less. At higher velocities Black's structure appears more resiliant. This would be due in part to the different methods of calculating the horizontal force on the structures. There is also a scale issue due to the differences is size between the Australian and US houses where the weight of the structure is proportional to the area, while the drag is roughly proportional to the square root of the area. It should be noted that some of the velocities shown are extremely high. There is an obvious trend with the Australian curves that the heavier structures are more stable and again this is due to the normal force contributing to a larger friction force.

*Continuing/future work*

There are a number of possible areas for further study and refinement of this research. Assessments when the water levels inside and outside the structure are unequal will address the case when the flood water level is rising and the level inside the house is lagging. There is also scope to investigate different house shapes and sizes, so other regions in Australia have curves that more accurately represent the building population.

## CONCLUSIONS

A number of curves have been created that define overall structural failure due to flooding for a range of residential structure types relevant to Australia. The methodology used in creating the curves is based on that used by Richard Black in the US in 1975, and involves assessing horizontal and buoyant forces due to flood water. The use of these curves adds rigour to structural damage assessments for flood as they consider the effect of water flow, in addition to inundation.

The Australian houses addressed were much heavier than those assessed by Black, and as such display a greater stability at low velocities. As flow velocities are increased the Australian structures appear more vulnerable, in part due to the use of a different method for calculating horizontal force than that adopted by Black.

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**FIGURES**

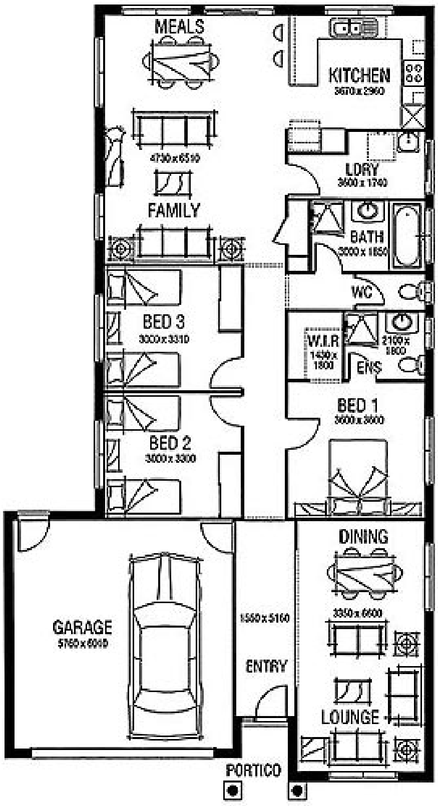


Figure 1: House Plan used in Calculating Curves

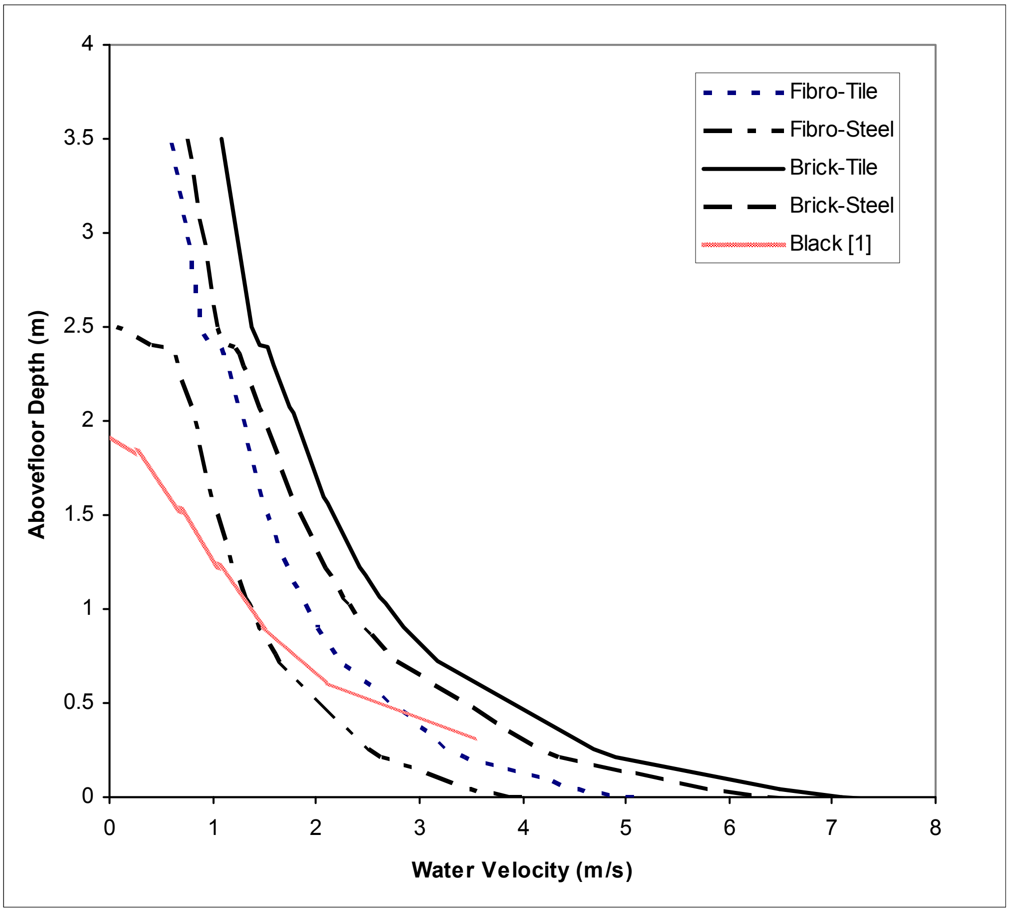


Figure 2: Curves for Australian Residential Construction