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Building damage analysis in Rangiroa
following a 1 in 50 year storm surge event

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Building Damage Analysis in Rangiroa

following a 1 in 50 year storm surge event

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SECRETARIAT OF THE PACIFIC COMMUNITY
BUILDING DAMAGE ANALYSIS IN RANGIROA
FOLLOWING A 1 IN 50 YEAR STORM SURGE EVENT

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PROJECT 301015-03242 - BUILDING DAMAGE ANALYSIS IN RANGIROA

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1 INTRODUCTION

The geographic and tectonic settings and features of the Tuamotu Archipelago of French Polynesia, combined with their relatively small size and low lying land puts them at high risk of storm surge inundation during cyclone events.

Under its European Development Fund 9, C Envelope, the EU has commissioned SOPAC/SPC, to work with the Government of French Polynesia to improve risk reduction along the coastal environment, in particular, to develop solutions for coastal inundation along the coast of Rangiroa atoll in the Tuamotu group.

As part of the project, staff from SOPAC/SPC will develop scientific models to enable improved understanding of storm surge inundation from severe tropical cyclone events. The findings will be augmented by a preliminary economic analysis to assess the appropriateness of possible responses.

Rangiroa is the largest atoll in the Tuamotu group, French Polynesia. The atoll consists of about 415 small islands and sandbars, separated by around one hundred small passages. The atoll is approximately 75 km long and 25 km wide, with a maximum land elevation of only a few metres above sea level. Rangiroa has a population of around 2400 residents, who live mostly on two main islands at the northern end of the atoll. Housing is located along both the ocean and lagoon coasts of the atoll.

Three types of housing exist at Rangiroa, which will each have varying resistance to storm surge damage. The types of housing considered in this report include:

A) Concrete block, single storey housing with floor levels not elevated above ground level (as per Figure 1)

B) Concrete block, single storey housing with floor levels elevated by 1 m above ground level (similar to that shown in Figure 1, but elevated by 1 m above ground level), and

C) Single storey MTR house (or 'kit' house), built to withstand wind speeds of 204 km/h, (similar to Figure 2), with a floor elevation of 1.5 m above ground level

The Applied Geoscience and Technology Division of SPC (SOPAC) has developed a model to project the form of inundation that could occur during a tropical cyclone with an Annual Recurrence Interval (ARI) of 1 in 50 years. This modelling showed that much of the land area of the atoll would be inundated in such an event, with the inundation hazard defined into four categories based on the combination of depth of inundation and flow velocity.

The inundation categories defined by the Government of French Polynesia are illustrated in Table 1, below.

Table 1 – Storm surge hazard categories defined by the Government of French Polynesia

Force category	Description	
	Inundation depth (m)	Speed (m/second)
1	Depth<0.5	speed<0.5
2a	Depth<0.5	0.5<=speed
2b	0.5< depth<= 1.0	Speed<0.5
3a	0.5< depth<= 1.0	0.5<=speed
3b	1.0<depth	Speed<0.5
4	1.0<depth	0.5<=speed

Figure 1 – Building type A – single storey concrete block housing with floor level at ground level

Figure 2 – Building type C – MTR housing with floor level elevated by 1.5 m above ground level

Four types of adaptation options are being considered for Rangiroa:

- Staged retreat from the beach;
- Elevation of existing concrete housing to 1 metre above existing ground level;
- Establishment of a seawall between the ocean and the island (similar to the type of seawall used in Tahiti)
- Replacement of concrete buildings with MTR homes (rated for cyclonic winds), elevated to 1.5 metres above existing ground level.

SOPAC has engaged WorleyParsons to review available techniques to assess damage to the three types of buildings on the island under the various storm surge categories. In addition, the effect of construction of a seawall that could reduce the force of the waves by 25%, 50% or 75% on the damage to the buildings is to be estimated.

This report reviews available literature on techniques that can be used to produce a damage estimate, presents an overview of these techniques and applies the techniques to provide an indicative damage estimate. The sensitivity of the estimate is then tested by selection of an alternative assessment technique.

2 REVIEW OF DAMAGE ASSESSMENT TECHNIQUES

2.1 Introduction

Hazard due to flooding and storm surge is often described using depth-velocity relationships. Hazard assessment incorporates stability of pedestrians, vehicles and structures. The Government of French Polynesia has set hazard categories based on the combination of velocity and depth to describe storm surge hazard.

To estimate the direct economic cost of inundation from storm surge, damage to structures can be described in terms of water level stage-damage relationships, or stage-velocity-damage relationships,.

There are three ways that flooding due to storm surge (or riverine flooding) could cause damage to a structure and its contents (Dale *et al.*, 1994):

- Inundation – damage due to wetting of a structure and its contents, which are described by stage-damage relationships, relating over-floor depth to a damage state;
- Local damage – damage due to fast flowing water resulting in damage to some components of a building, namely doors, windows and walls (this type of damage is difficult to predict); and
- Overall instability – where the integrity of the entire structure is compromised by being dislodged from its foundations.

The techniques described in this report to assess building damage relate to both inundation damage and overall instability.

Various literature describing this topic has been reviewed and relevant discussion is provided below.

2.2 US Army Corps of Engineers literature

The US Army Corps of Engineers (1996) has released a technical manual, ”Engineering and Design – Risk Based analysis for Flood Damage Reduction Studies” which discusses the factors necessary to develop a stage-damage relationship. Factors other than depth and velocity are identified as critical to developing a structure-depth damage function, including the duration of the inundation, sediment load, internal construction, condition of the homes and flood warning. These factors are described in Table 2.

Depth-damage relationships are based on the assumption that water height, and its relationship to structure height, is the most important variable in determining the expected value of damage to buildings (USACE, 1988).

Depth-damage relationships can be computed separately for the structures and the home contents. For this study, the depth-damage relationships for the structures themselves are examined.

Post-flood damage surveys are the most accurate method to determine the susceptibility of the various housing types to damage from inundation (USACE, 1988). These surveys involve identifying a sample of representative properties, and then determining post-flood damage to these properties, either by questionnaire or by personal inspection by a trained valuer. However, in the absence of such surveys, generalised relationships need to be applied.

Table 2 – Factors other than depth that influence damage (USACE, 1988)

Table 6-6
Factors, Other than Depth, That Influence Damage (USACE 1988)

Factor	Effect
Velocity	Major factor aggravating structure and content damage. Limits time for emergency floodproofing and evacuation. Additional force creates greater danger of foundation collapse and forceful destruction of contents.
Duration	May be the most significant factor in the destruction of building fabric. Continued saturation will cause wood to warp and rot, tile to buckle, and metal objects and mechanical equipment to rust.
Sediment	Can be particularly damaging to the workings of mechanical equipment and can create cleanup problems.
Frequency	Repeated saturation can have a cumulative effect on the deterioration of building fabric and the working of mechanical equipment.
Building material	Steel frame and brick buildings tend to be more durable in withstanding inundation and less susceptible to collapse than other material.
Inside construction	Styrofoam and similar types of insulation are less susceptible to damage than fiberglass and wool fiber insulation. Most drywall and any plaster will crumble under prolonged inundation. Waterproof drywall will hold up for long periods of inundation. Paneling may be salvageable when other wall coverings are not.
Condition	Even the best building materials can collapse under stress if the construction is poor or is in deteriorated condition.
Age	May serve as an indicator of condition and building material.
Content location	Important factor, as small variations in interior location of contents can result in wide variation in damage.
Flood warning	Major reduction in both content and structural loss can be made through flood fighting and evacuation activities when there is adequate warning.

Physical damage can begin when inundation reaches the lowest levels of a building, even if the flood waters are below the ground level (USACE, 1988). Concrete foundations are less susceptible to infiltration than cinder blocks. Walls and foundations can be subject to cracking or collapse due to water pressure.

Structural measures can be used to reduce flood damage to buildings involve flood-proofing the buildings, typically by:

- Designing buildings to withstand water immersions, debris and flotation forces (i.e. double brick construction rather than the use of plasterboard or chip-board for internal wall linings);
- Raising habitable floors to a defined floor level;
- House raising (only generally suitable in low flood hazard areas and for timber-framed or houses clad with non-masonry materials).

2.3 Australian Government Literature

CSIRO (2000) describes the effect of flood severity on flood hazard and hazard to buildings. At velocities greater than 2 m/s, the stability of foundations and poles can be affected by scour. At depths greater than 2 m, lightly framed buildings can be damaged by water pressure, flotation and debris, even at low velocities.

CSIRO (2000) reports on the structural damage that occurred to 23 houses in a flood at Nyngan, NSW, Australia in 1990. It was found that over 90% of the damage to these houses was attributed to damage to the internal wall linings and built-ins, where these were constructed of particle-board or plaster-board.

The Queensland Government (2002) released a “Guidance on the Assessment of Tangible Flood Damages” document. This document provides stage-damage curves for three different categories of houses:

- Small houses (<80 m^2 and/or 1-2 bedrooms)
- Medium houses (80 – 140 m^2 and/or 3 bedrooms)
- Large houses (140 m^2 and/or 3+ bedrooms).

The stage/damage relationships are illustrated in Table 3 (Queensland Government, 2002).

Table 3 – Stage-damage relationship (Queensland Government, 2002).

		Small house ($)	Medium house ($)	Large house ($)
Depth over floor level	0 m	905	2 557	5 873
	0.1 m	1 881	5 115	11 743
	0.6 m	7 370	13 979	25 351
	1.5 m	17 379	18 585	32 276
	1.8 m	17 643	18 868	32 768

BMT Quantity Surveyors (2013) have an on-line calculator which can estimate residential housing construction costs for different size housing in Australia, back-dated to 2002. Using estimates of construction cost for houses of the size used in Table 3, the damage can be converted back to a percentage of the construction cost of the house. Construction cost estimated for small, medium and large houses is given below:

- Small House (3 bedroom full brick house, 80 m^2) = $80,000
- Medium House (3 bedroom full brick house, 120 m^2) = $120,000
- Large House (4 bedroom full brick house, 140 m^2) = $190,000

Using the figures determined above and with reference to Table 3, the percentage damage to the house caused by different over-floor depths can be estimated, as per Figure 3, below.

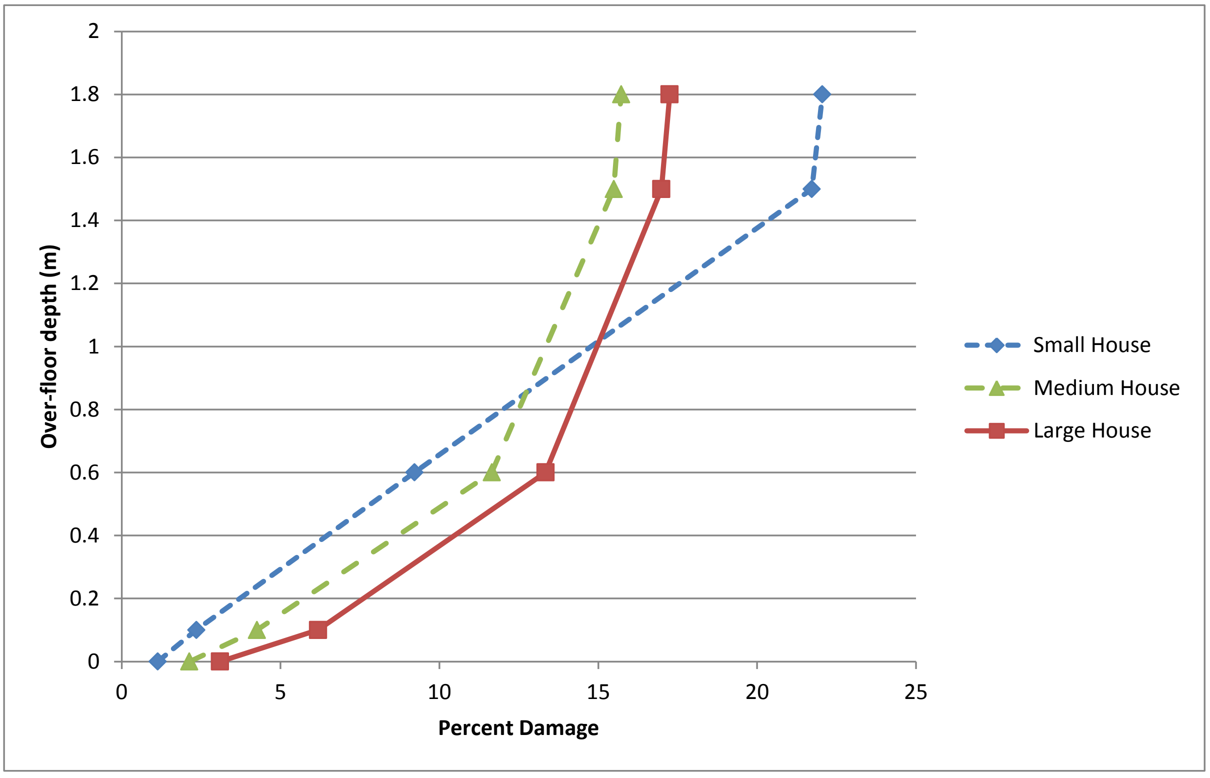
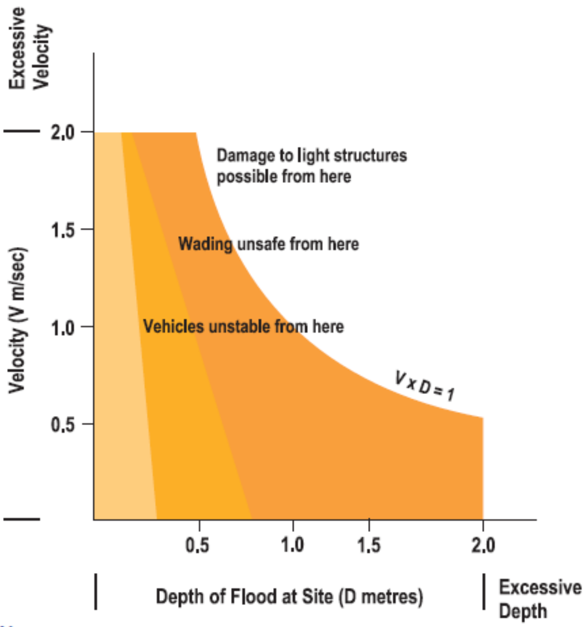


Figure 3 – Percent damage to small, medium and large houses based on estimated construction costs and Table 3

From NSW Government (2005), damage to light structures is possible when the velocity multiplied by the depth exceeds 1 (refer Figure 4). Dale *et al.* (2004) developed more specific curves that denote damage thresholds that take into account velocity, depth and style of construction. These curves are based on a study undertaken by Black (1975), who produced a number of curves describing combinations of velocity and depth that, theoretically, are required to move a house from its foundations. Curves for different types of structures were created by assessing gravity, buoyancy and dynamic forces (due to flowing water) for various combinations of depth and velocity. The basis behind Black's curves (1975) is that a house in water is subject to buoyancy, hydrostatic pressure and dynamic pressure. Black (1975) calculated buoyant forces on a basic house (about 7 m wide and 10 m long) at different depths. He then assessed the horizontal force on the houses due to the flow of the 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.



Notes

1. At velocities in excess of 2.0 m/s, the stability of foundations and poles can be affected by scour. Also, grass and earth surfaces begin to scour and can become rough and unstable
2. The velocity of floodwaters passing between buildings can produce a hazard, which may not be apparent if only the average velocity is considered. For instance, the velocity of floodwaters in a model test has risen from an average of 1 m/sec to 3 m/sec between houses.
3. Vehicle instability is initially by buoyancy.
4. At floodwater depths in excess of 2.0 meters and even at low velocities, there can be damage to light-framed buildings from water pressure, flotation and debris impact.

Derived from laboratory testing and flood conditions which caused damage.

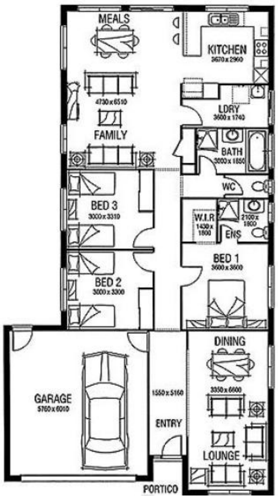
Figure 4 – Velocity and Depth relationships (from NSW Government, 2005).

In Dale *et al.* (2004), the horizontal force used to produce the stage-velocity-damage curves is calculated using the following equation:

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

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 water above the foundation. The vertical force is represented by the weight of the structure on its foundations, multiplied by the coefficient of friction.

The curves for damage threshold from Dale *et al.* (2004) are illustrated in Figure 5.



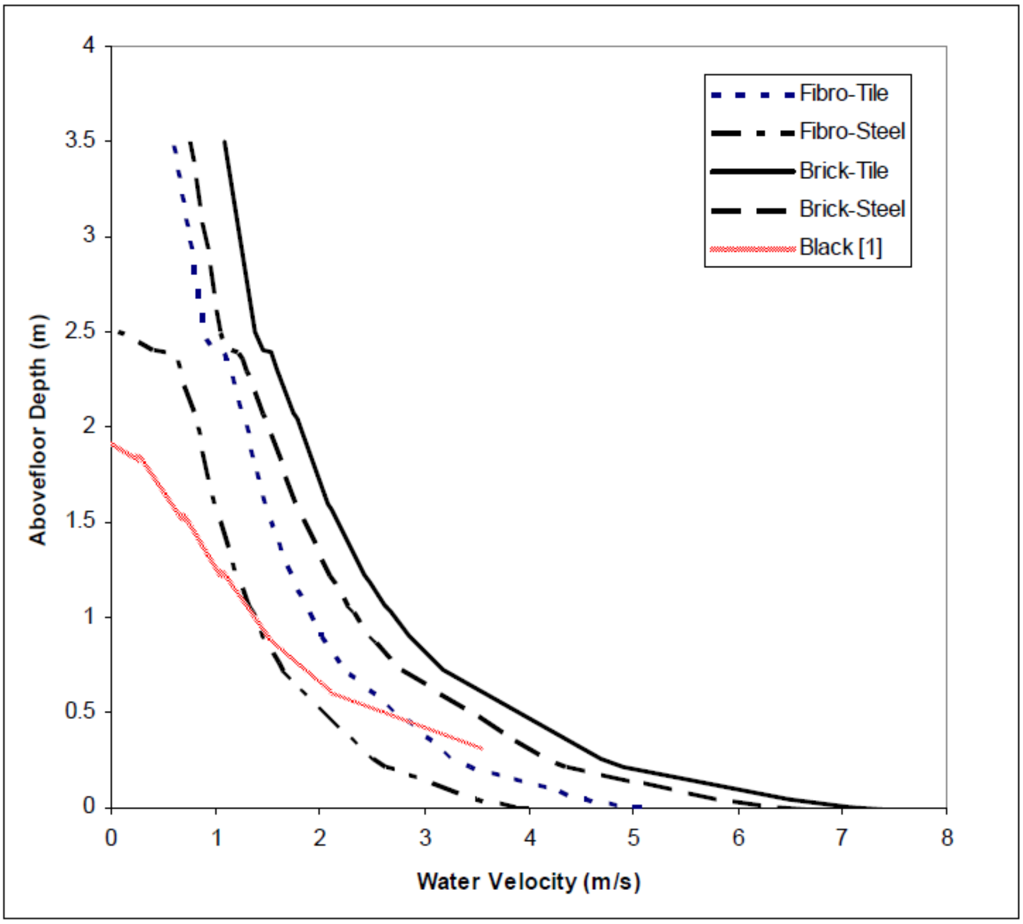


Figure 5 – Top: House plan used by Dale to calculate damage curves; Bottom: Curves representing damage thresholds for different construction types (Dale *et al* 2004)

Betts (2011) states that structurally, buildings are not generally designed to withstand floods. However, recently they have been designed to withstand wind forces. Betts (2011) undertakes a simple calculation, whereby a unit length of a 3 m high wall subject to cyclonic wind speeds equates to a 4.5 kN/m wind load, and compares this to the static force from a one metre water depth of 4.9 kN/m (however, this ignores the approach velocity of the flow). This calculation suggests that houses built to withstand cyclonic winds are also more likely to withstand horizontal forces due to flood flows.

2.4 Analysis of building damage after Hurricane Katrina

Pistrika and Jonkman (2009) analysed the direct damage to residential buildings caused by the flooding of New Orleans after Hurricane Katrina in 2005. The analysis was based on a public dataset of 95,000 residential buildings in the flooded area. It was found that the highest damage percentages occurred in the areas subject to the highest flood velocities, and they proposed a general approach to distinguish damage zones based on water depth and velocity. Figure 6 illustrates actual observations of surveyed damage vs. depth following Hurricane Katrina. It also illustrates damage-depth-velocity criteria proposed by Clausen (1989), and relates depth times velocity vs. percentage damage with actual observations from Hurricane Katrina.

2.5 Roos 2003

Roos (2003) undertook a research study to examine the effect of floods on damage to buildings. Roos (2003) considered that the most relevant failure mechanisms were scour of the foundations and failure of walls. Roos (2003) considered that scour of the foundations will occur if the top layer of the soil washes away and the affected building is built on a shallow foundation. This is a relevant factor for buildings constructed on sandy soils at Rangiroa. This failure mechanism would not be relevant if the building foundations are piled to depth and the piles are designed for the level of scour that would be expected in a storm surge event.

The mechanism for wall failure depends on the loads applied to the buildings and the strength of the buildings. The four load cases examined by Roos (2003) were:

- Hydrostatic pressure due to water level difference inside and outside the building;
- Velocity of the incoming water
- Wave action
- Pounding debris.

In addition to the direct effect of forces from storm surge flows, reinforced concrete that has been subjected to saltwater can be affected by chloride-induced corrosion (Roos, 2003). The study found that, for reinforced concrete structures, debris impact is the limiting factor that causes wall failure. Figure 7 shows the point at which failure is initiated for various construction types. This figure shows that cast and pre-fabricated concrete buildings have a greater resistance to failure and that for over-floor depths greater than 0.6 m, velocities greater than 1 m/s would initiate failure. This corresponds to the conditions experienced under the Government of French Polynesia's storm surge categories 3a and 4.

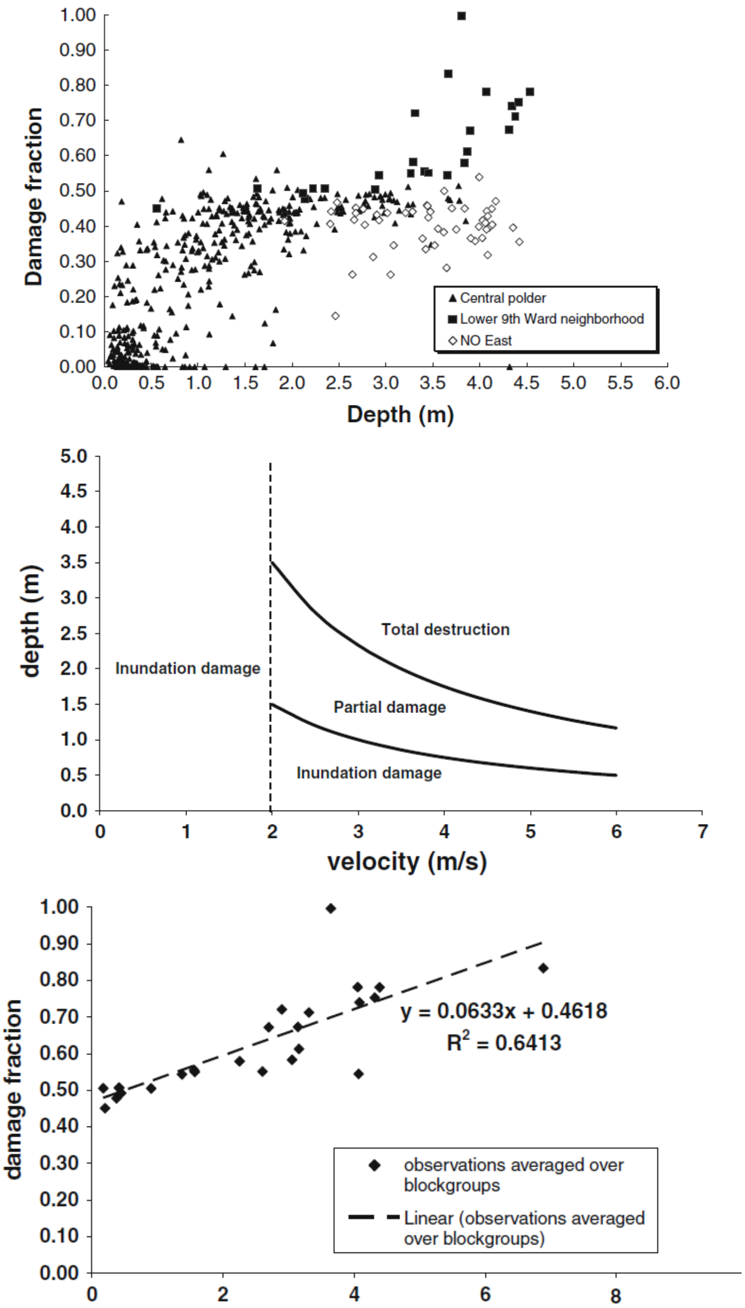


Figure 6 – Top – Observed percentage damage to housing vs. depth after Hurricane Katrina (Pistrika and Jonkman, 2009); Centre – Clausen criteria for structural damage to brick and masonry buildings (Clausen 1989); Bottom: Proposed damage vs. velocity x depth function with observations from Hurricane Katrina (Pistrika and Jonkman, 2009).

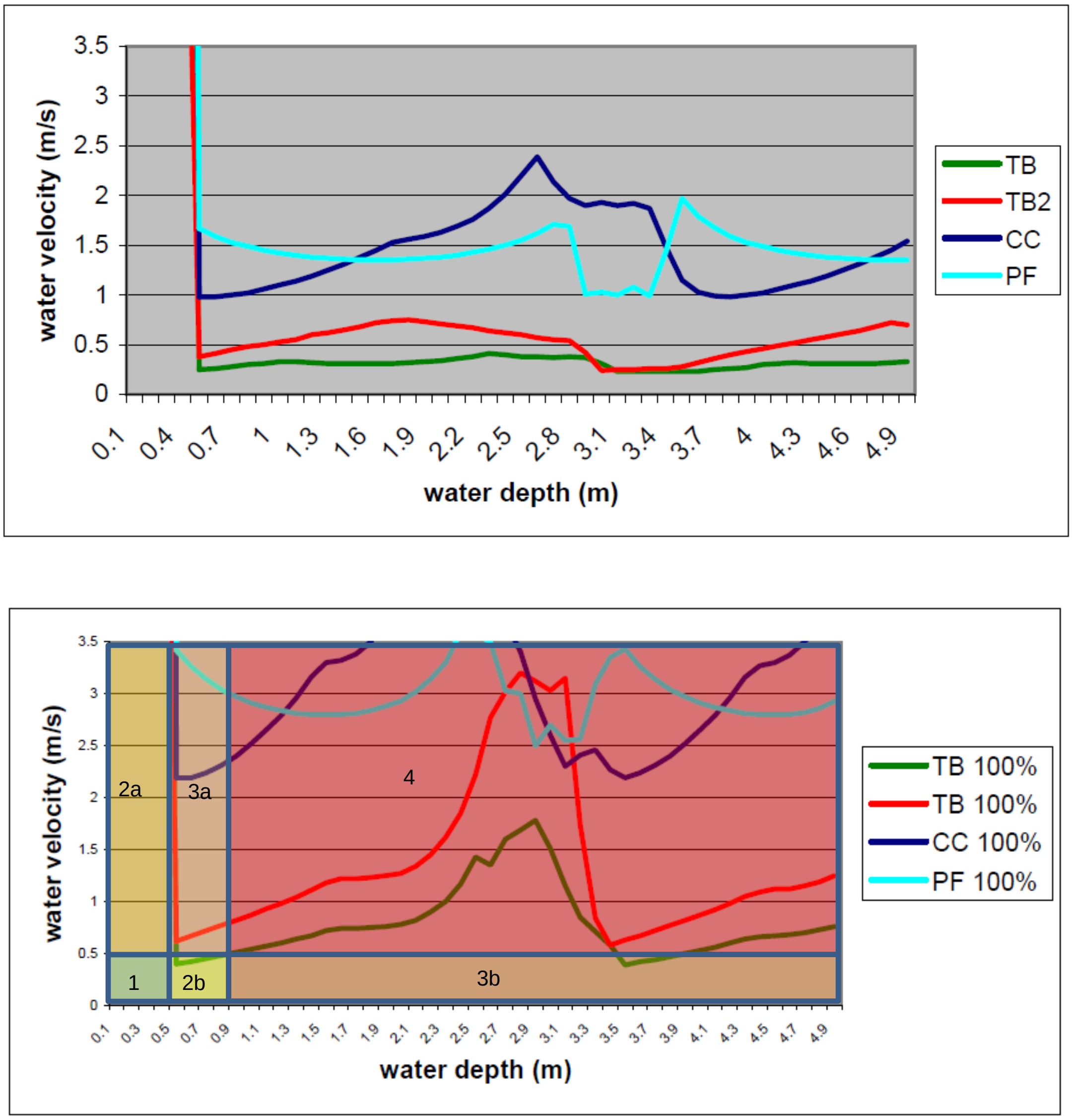


Figure 7 – Damage curves presented by Roos (2003). TB, TB2 = traditional brick structures, CC = cast concrete buildings, PF = pre-fabricated concrete buildings. Top: Start of wall failure; Bottom: Complete wall failure, superimposed with Government of French Polynesia storm surge categories.

3 APPLICATION OF TECHNIQUES TO RANGIROA

3.1 Introduction

Several of the above techniques presented in the literature can be applied to answer the questions required by the objectives of the damage analysis. These questions include:

1. Using the Government of French Polynesia's level rating system for storm surges, how much structural damage (as a percentage of the cost of the building) might be anticipated if the houses were inundated?
2. How much damage – as a percentage of the value of the building – might be expected to be caused to housing type A, B and C if a Tahiti-style seawall were in place on Rangiroa and was able to reduce the force of the waves by 25%, 50%, 75%?
3. Bearing in mind the modelled depth and speed of inundation for Rangiroa in a 1 in 50 year event, how much might houses realistically need to be elevated (on stilts or otherwise) to minimise inundation? Is such elevation reasonable/realistic?
4. How much might elevating a house (on stilts or otherwise) to the level actually reduce structural damage (% damage reduced from no elevation damage)?
5. Bearing in mind that smaller storm surges would occur in the area periodically and that this would imply occasional inundation between cyclones, what might be the resilience of the foundations of the three house types (A, B, C) over time?

These questions are discussed below.

3.2 Structural damage to building types A, B, C

The Government of French Polynesia's level rating system for storm surges is described in Table 1. To explore the expected structural damage to building types A, B and C (described in Section 1 of this report), the various rating categories can be plotted on the stage-velocity-damage curves presented in the literature.

3.2.1 Queensland Government (2002) stage-damage curves

The Government of French Polynesia's level ratings (Table 1) for storm surges have been plotted on the stage-damage relationship presented by Queensland Government (2002), in Figure 8. As this relationship does not include velocity, only the depth is considered.

Based on this method, Building type A (which is at ground level) could expect damage of 2 – 12% of the cost of the building under force categories 1 and 2a, 7 – 15% under force categories 2b and 3a, and 13 – 22% for force categories 3b and 4. The shortcomings of this method are that:

- Velocity is not considered; and
- Varying building construction type is not considered (although variations in house size are considered).

From the photographs provided by SOPAC (Figure 1 and Figure 2), the houses would be classified as “small” in Figure 8, below. If the house is to be raised by 1 m or 1.5 m (as per Building types B and C), then over-floor flooding would be eliminated for all storm surge categories except for Categories 3b and 4, and damage would be reduced proportionately according to Figure 8 below. Under this scenario, the elimination of over-floor flooding would reduce damage to around 2% of the value of the building, presumably due to damage to under-floor structures or scour around the building foundations.

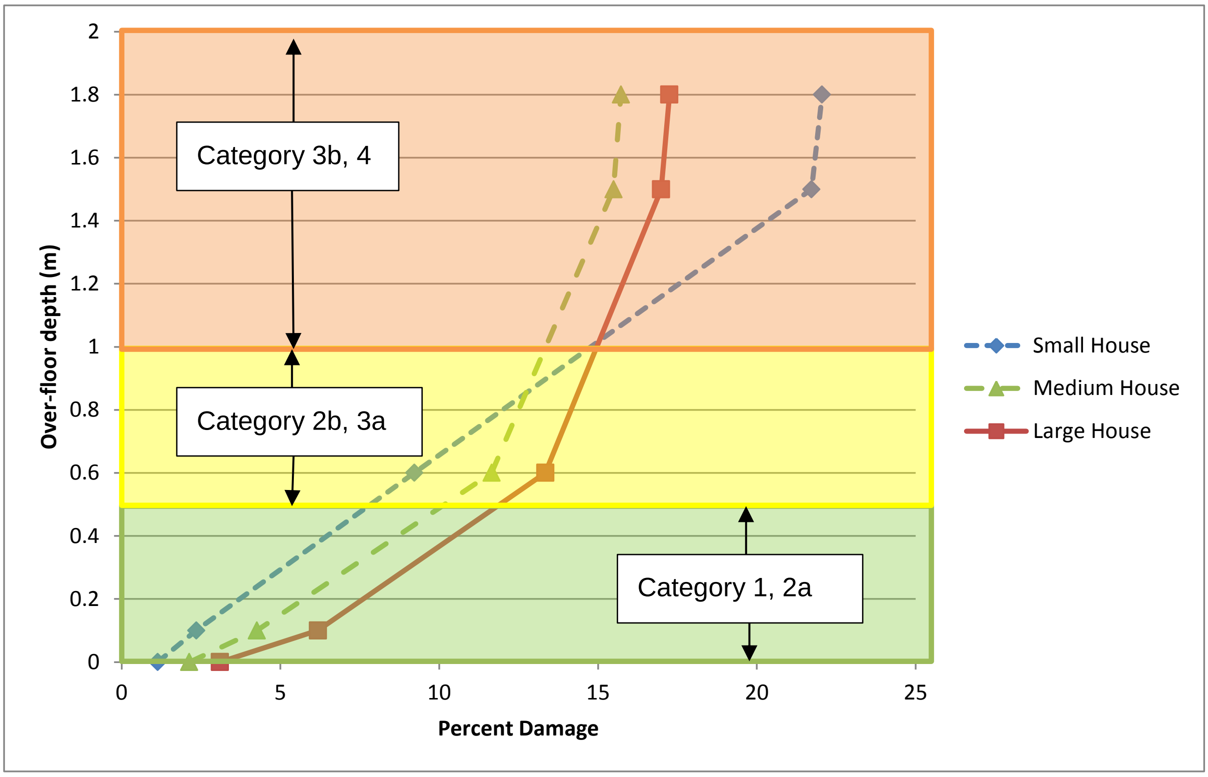


Figure 8 – Percent damage to buildings due to varying over-floor depth (Queensland Government 2002).

As velocity is not considered in the above, the reduction in damage as a result of reduced wave forces from construction of a seawall cannot be assessed using this method.

3.2.2 Dale *et al.* (2004)

Dale *et al.* (2004) derived damage curves based on depth and velocity that describe thresholds for damage which, if exceeded, the house is deemed to have ‘failed’ because the dynamic force on the house is deemed to have exceeded the frictional force required to keep the house on its foundations.

The damage curves superimposed with the Government of French Polynesia’s force categories determined by Dale *et al.* (2004) are shown in Figure 9. It can be seen that:

- The damage threshold is not reached for the storm surge categories 1 and 2b;

- The damage threshold is exceeded under Category 2a for velocities above 2 – 4 m/s, depending on the type of construction of the house;
- The damage threshold is exceeded under Category 3a for velocities above 1.5 m/s – 3 m/s, depending on the type of construction of the house;
- The damage threshold is exceeded under Category 3b for overfloor depth above 2 – 2.5 m, for lightweight houses but is not exceeded for housing of brick construction;
- The damage threshold is exceeded under Category 4 for the conditions indicated in Figure 9.

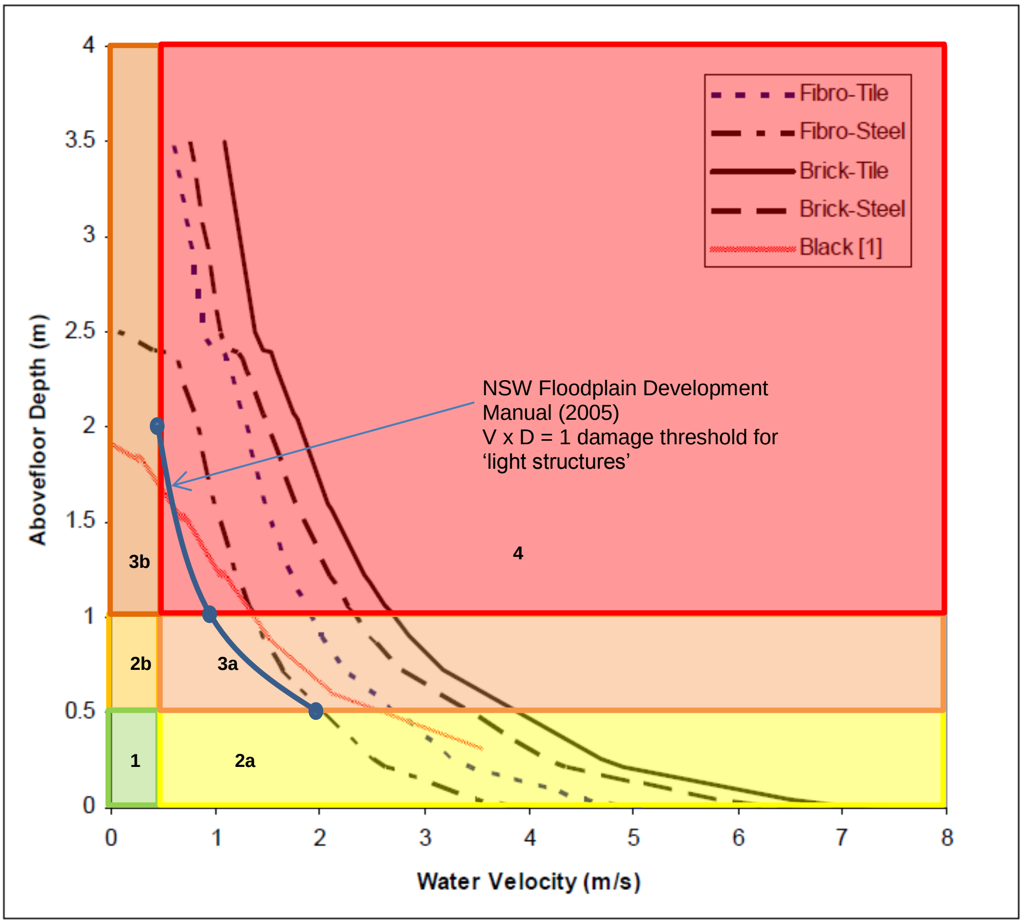


Figure 9 – Government of French Polynesia storm surge hazard categories superimposed with damage curves from Dale *et al* (2004)

Should the houses be raised by 1 m or 1.5 m (as per Building Type B and Type C), the curves in Figure 9 would raise to reflect this (i.e. only Category 4 would present a risk of total or catastrophic structural failure).

3.2.3 Pistrika and Jonkman (2009)

The Government of French Polynesia's storm surge hazard categories are superimposed upon the stage-velocity-damage curves presented in Pistrika and Jonkman (2009), which attempts to correlate the degree of damage (as recorded following Hurricane Katrina) with the stage and velocity. Figure 10 plots the recorded damage following Hurricane Katrina vs. overfloor depth (Pistrika and Jonkman, 2009). It shows that, for overfloor flooding up to 1 m, up to 50% damage can occur, with 80% damage having occurred in some areas where depths were above 3 m. However, this diagram does not take velocity into account.

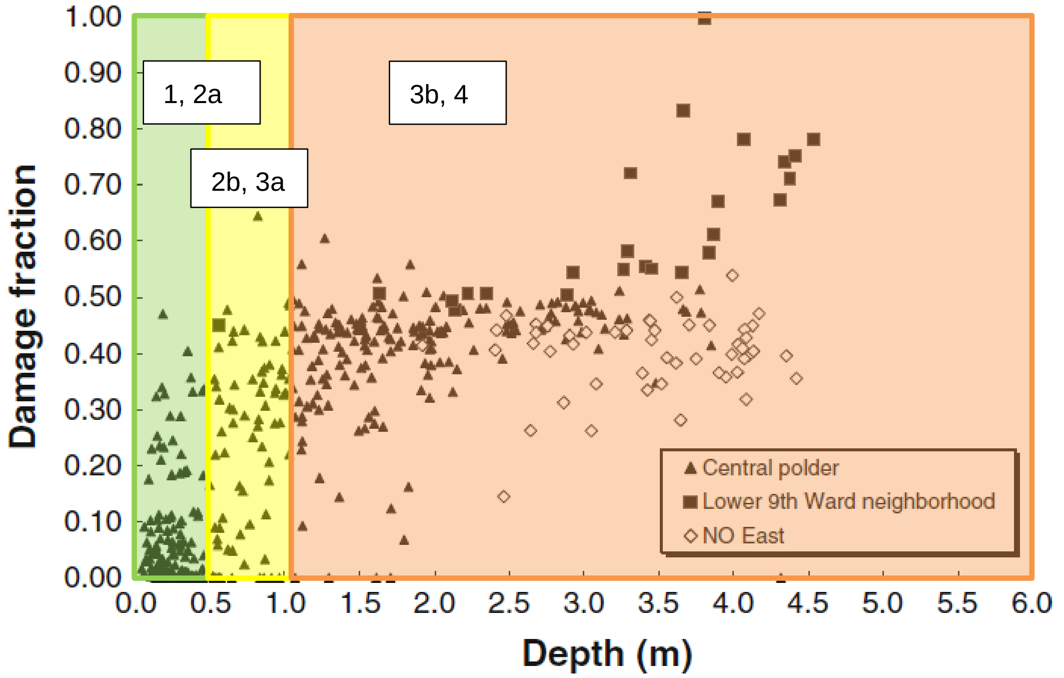


Figure 10 – Recorded damage percentage vs. overfloor depth, Hurricane Katrina, superimposed with Government of French Polynesia storm surge categories (Pistrika and Jonkman, 2009)

Clausen (1989) proposed damage curves based on velocity and depth. Superimposing the Government of French Polynesia's storm surge categories on this graph, inundation damage only (not structural damage to the building) occurs for storm surge hazard categories 1, 2a, 2b and 3b. Partial structural damage (but not total destruction of a residential building) can occur in hazard category 3a, with total destruction only possible in hazard category 4 (Figure 11).

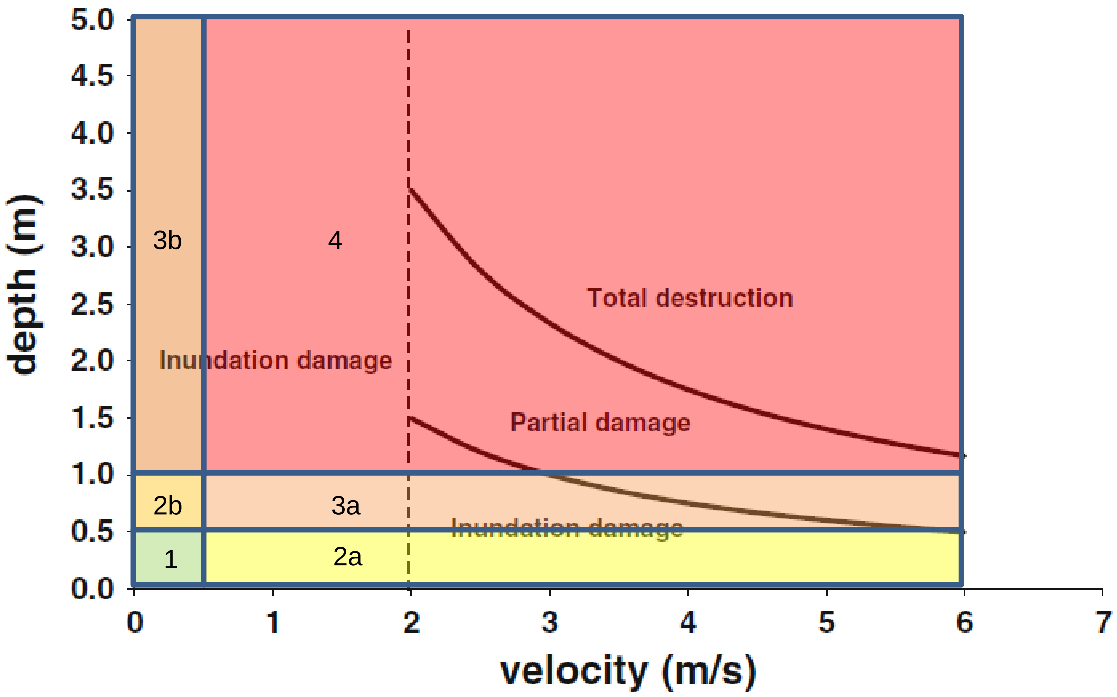


Figure 11 – Clausen (1989) criteria superimposed with Government of French Polynesia storm surge classes

In Figure 12, the proposed Pistrika and Jonkman (2009) linear relationship between velocity x depth and percentage damage is shown against the French Polynesia Government's storm surge categories. It can be seen here that, using this relationship, 50% damage occurs even when velocity x depth is very low (i.e. for storm surge categories 1 and 2b), whereas damage ranging from 50% up to total destruction is predicted for Category 4.

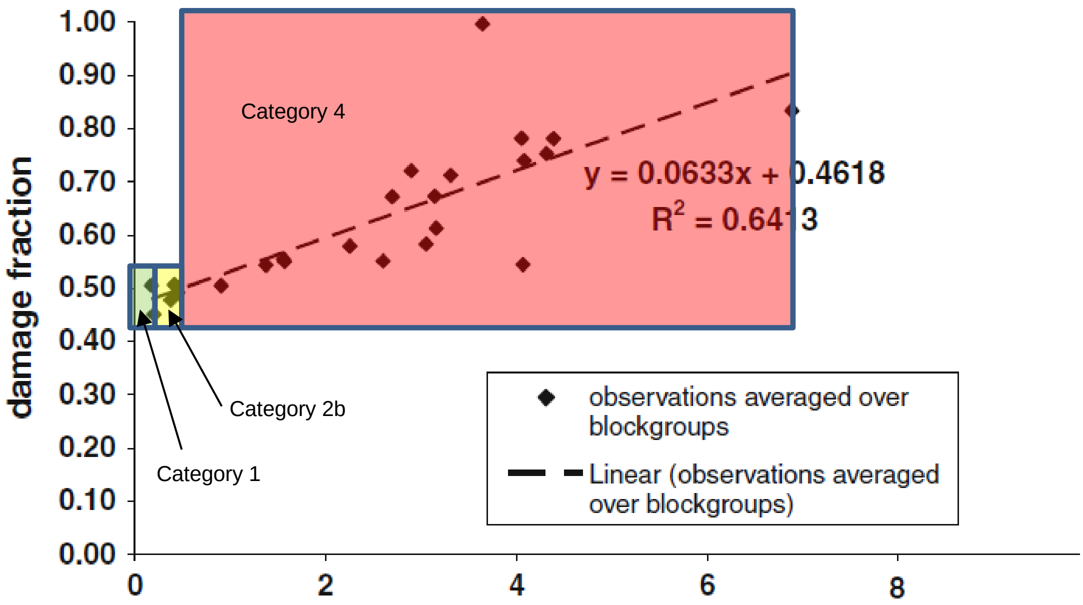


Figure 12 – Pistrika and Jonkman (2009) linear relationship between velocity x depth and percentage damage, Hurricane Katrina, superimposed with Government of French Polynesia storm surge hazard categories

3.2.4 Summary

Several techniques to explore damage to residential buildings with flood stage and velocity have been examined. These techniques have been used to answer the following question posed by the Government of French Polynesia:

> *Using the Government of French Polynesia's level rating system for storm surges, how much structural damage (as a percentage of the cost of the building) might be anticipated if the houses were inundated?*

Using the Queensland Government (2002) criteria to assess percentage damage relative to overflow or depth, combined with curves from Dale *et al.* (2004) and Roos (2003) to estimate the thresholds for complete failure, the percentage damage that can be expected is illustrated in Table 4. The table below assumes that the building foundations are not damaged due to excessive scour.

Table 4 – Estimated % structural damage to Building Types A, B and C for Government of French Polynesia storm surge categories

Force category	Description		Damage as a percentage of value of building		
	Inundation depth (m)	Speed (m/second)	Building A	Building B	Building C
1	depth<0.5	Speed<0.5	2 – 7%	2%	2%
2a	depth<0.5	0.5<=speed	2 – 7%[A]	2%	2%
2b	0.5< depth<= 1.0	Speed<0.5	7 - 15%	2%	2%
3a	0.5< depth<= 1.0	0.5<=speed	7 – 15%[B]	2%	2%
3b	1.0<depth	Speed<0.5	15 - 22%	2 - 22%	2 - 22%
4	1.0<depth	0.5<=speed	15 - 100%[C]	2 - 100%[C]	2 - 100%[C]

Notes:

A – For velocity below 3 m/s. Above 3 m/s complete building failure is possible

B – For velocity below 2 m/s. Above 2 m/s complete building failure is possible.

C – If velocity exceeds 2 m/s complete building failure is possible. As there is no upper limit to depth and velocity the upper damage range is 100%

The estimates in Table 4 above include an allowance for debris impact, as this is included in the curves of Roos (2003).

3.3 Structural damage to building types A, B, C with seawall

Should a seawall in the style of that built at Tahiti be considered for Rangiroa (i.e. a mass gravity structure designed as a wave return wall), the horizontal force[1] of the waves could be reduced. The question posed by the Government of French Polynesia is:

> *How much damage – as a percentage of the value of the building – might be expected to be caused to housing type A, B and C if a Tahiti-style seawall were in place on Rangiroa and was able to reduce the force of the waves by 25%, 50%, 75%?*

To answer this question, it is assumed that the seawall would not reduce the depth of flow at the location of the houses, and that only the horizontal force acting on the buildings would be reduced by 25%, 50% and 75%.

The horizontal force acting on the building is calculated using the method of Dale *et al.* (2004), using the equation below:

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

[1] Horizontal force refers to the dynamic force acting on the walls of a building as a result of the waves running up onto the shore. The force depends on the depth and velocity of flow and width of the building exposed to the flow.

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 water above the foundation.

To estimate the percentage damage to each building type with a reduction in force of 25%, 50% and 75%, an equivalent velocity is calculated for each storm surge category by solving the horizontal force equation above for *v*, and keeping the other variables constant (including depth, drag coefficient and width of the house). In this way, the storm surge categories can be re-defined with equivalent velocity bounds depending on the force reduction applied. Once these are re-defined, the damage curves presented in the literature can be used to estimate the damage to each housing type.

Table 5 below shows the reduction in velocity for each storm surge category, if the horizontal force is reduced by 25%, 50% and 75%.

Table 5 – Force reduction factor vs. equivalent velocity reduction factor

Force Reduction factor	Velocity Reduction factor
25%	13%
50%	29%
75%	50%

Using the above logic, assuming the depth remains the same for each case, there would be a reduction in velocity as a result of construction of a seawall. While the percentage damage to the houses appear from the literature to be dependent mainly on depth, the reduction in velocity will reduce the probability that complete failure will occur (as well as reduce the probability of damage to the foundations caused by scour). The damage percentage ranges in Table 4 as a result of the various storm surge categories would therefore not change. However, the probability of complete or catastrophic failure of the house would be reduced if the velocity is reduced by the presence of the seawall. This is because the seawall would reduce the velocity of flow and therefore change the hazard category that the houses would be subjected to.

Table 6 provides new “equivalent” category limits that would apply to the existing housing at Rangiroa if the seawall were to reduce wave force by 25%, 50% and 75%. For example, if a seawall is constructed that would reduce the wave force by 75%, then a house which is currently in Hazard Category 2a (i.e. subject to flow velocities of 0.5 m/s – 1 m/s and depth less than 0.5 m) would be reclassified as being in Hazard Category 1.

Figure 13 shows the reduction in predicted damage as a result of reduced horizontal force, applying the Pistrika and Jonkman (2009) predictive equation for damage as a result of depth and velocity. The most benefit of a seawall would be felt mainly in areas subjected to Category 4 hazard conditions.

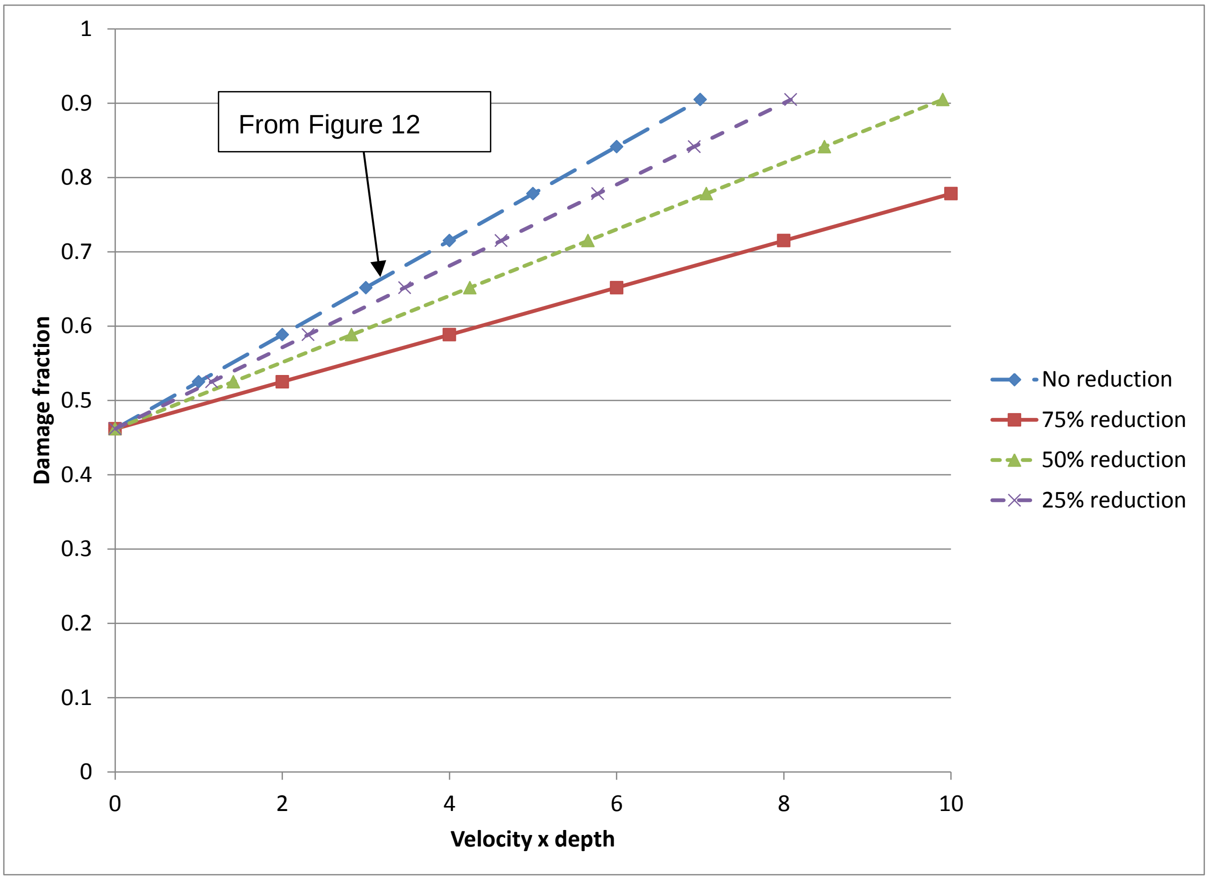


Figure 13 – Effect of reducing horizontal force on percentage building damage predicted by Pistrika and Jonkman (2009).

Table 6 – Equivalent hazard category limits for 25%, 50% and 75% reduction in wave forces

Force		Damage as a percentage of value of building		
	New equivalent category limits	Building A	Building B	Building C
25% of category 1[2]	1 (depth <0.5 m, speed <1 m/s)	2 – 7%	2%	2%
25 % of category 2a	2a (depth <0.5 m, speed >1 m/s)	2 – 7%[A]	2%	2%
25 % of category 2b	2b (0.5 <depth <= 1.0, speed < 1 m/s)	7 – 15%	2%	2%
25% of category 3a	3a (0.5 <depth <= 1.0, speed > 1m/s)	7 – 15%[B]	2%	2%
25% of category 3b	3b (1.0 <depth, speed <1 m/s)	15 – 22%	2 – 22%	2 – 22%
25% of category 4	4 (1.0 <depth, speed >= 1 m/s)	15 – 100%[C]	2 – 100%[C]	2 – 100%[c]
50% of category 1[3]	1 (depth <0.5 m, speed <0.7 m/s)	2 – 7%	2%	2%
50% of category 2a	2a (depth <0.5 m, speed >0.7 m/s)	2 – 7%[A]	2%	2%
50 % of category 2b	2b (0.5 <depth <= 1.0, speed < 0.7 m/s)	7 – 15%	2%	2%
50% of category 3a	3a (0.5 <depth <= 1.0, speed > 0.7 m/s)	7 – 15%[B]	2%	2%
50% of category 3b	3b (1.0 <depth, speed <0.7 m/s)	15 – 22%	2 – 22%	2 – 22%
50% of category 4	4 (1.0 <depth, speed >= 0.7 m/s)	15 – 100%[C]	2 – 100%[C]	2 – 100%[c]
75% of category 1[4]	1 (depth <0.5 m, speed <0.57 m/s)	2 – 7%	2%	2%
75% of category 2a	2a (depth <0.5 m, speed >0.57 m/s)	2 – 7%[A]	2%	2%
75% of category 2b	2b (0.5 <depth <= 1.0, speed < 0.57 m/s)	7 – 15%	2%	2%
75% of category 3a	3a (0.5 <depth <= 1.0, speed > 0.57 m/s)	7 – 15%[B]	2%	2%
75% of category 3b	3b (1.0 <depth, speed <0.57 m/s)	15 – 22%	2 – 22%	2 – 22%
75% of category 4	4 (1.0 <depth, speed >= 0.57 m/s)	15 – 100%[C]	2 – 100%[C]	2 – 100%[c]

Notes:

A – For velocity below 3 m/s. Above 3 m/s complete building failure is possible

B – For velocity below 2 m/s. Above 2 m/s complete building failure is possible.

C – If velocity exceeds 2 m/s complete building failure is possible. As there is no upper limit to depth and velocity the upper damage range is 100%

[2] This is equivalent to a 75% reduction in the force of the wave, or a 50% reduction in the velocity at which the wave hits the building.

[3] This is equivalent to a 50% reduction in the force of the wave, or a 29% reduction in the velocity at which the wave hits the building.

[4] This is equivalent to a 25% reduction in the force of the wave, or a 13% reduction in the velocity at which the wave hits the building.

3.3.1 Damage due to scour of foundations

The above analysis assumes that the foundations are resistant to scour (i.e. they are piled foundations).

If the flow velocity is reduced as a result of placement of a seawall and the building foundations are not piled, there would be a lower probability of scour of the foundations and subsequent failure of the building. Further, according to CSIRO (2000), the probability of damage to foundations is low if the velocity is less than 2 m/s.

The scour potential will depend on the soil type as well as the velocity and more information would be required to quantify this factor. The potential for scour could be examined using pre and post-storm survey which can be collected using standard surveying techniques, using photogrammetric analysis of aerial photographs or by comparing pre and post-storm datasets of LiDAR data.

3.3.2 Impact of Groundwater Levels on Foundations

In granular soils, should the storm surge event result in a temporary increase in the elevation of the water table, bearing capacity of residential foundations can be reduced significantly. Effective stresses in saturated sand can be up to 50% lower than in dry sand.

If the soils at Rangiroa consist of loose sands, then saturation the soil due to storm surge could reduce the bearing capacity of the footings to levels below those for which they have otherwise been designed. If the soil comprises dense sand, then the footings would be more likely to withstand the reduced bearing capacity due to saturation of the soil. The reduction in bearing capacity of the foundations can be overcome by designing larger footings, based on the results of geotechnical tests to gauge the density of the foundation conditions.

3.4 Remaining questions

The remaining questions posed by the Government of French Polynesia are:

> *Bearing in mind the modelled depth and speed of inundation for Rangiroa in a 1 in 50 year event, how much might houses realistically need to be elevated (on stilts or otherwise) to minimise inundation? Is such elevation reasonable/realistic?*
>
> *How much might elevating a house (on stilts or otherwise) to the level actually reduce structural damage (% damage reduced from no elevation damage)?*
>
> *Bearing in mind that smaller storm surges would occur in the area periodically and that this would imply occasional inundation between cyclones, what might be the resilience of the foundations of the three house types (A, B, C) over time?*

These questions are examined qualitatively based on the literature review and analyses presented above.

For the 1 in 50 year event, much of the inhabited area of Rangiroa is subject to Category 4 conditions (i.e. depth greater than 1 m and velocity greater than 0.5 m/s). It is also understood that the significant wave height is 12 m. From examination of aerial photography, the fringing reef at Tiputa is very narrow (of the order of 50 metres). Without detailed knowledge of the bathymetry of the site, it can be said that most of the storm waves would likely wash over the crest of the atoll, which is at approximately 6 m above mean sea level. The depth of wave overwash will depend on the elevation of the ground at the location of the houses, as well as proximity of the house to the ocean side of the atoll.

For a beach slope of 1 in 50 and a deepwater significant wave height of 12 m, maximum wave runup predicted using the algorithms of ACES (CERC, 1984) is approximately 4.2 m above the local water level (which itself is affected by astronomical tides, wind setup and barometric setup), with 2% of wave runups exceeding 3.9 m. For a nearshore water level of 4 m above mean sea level, this would result in a flow depth of around 2 m at the ocean side of the crest of the atoll (reducing with distance inland). It should be noted that more data is required to undertake a more thorough assessment. However, based on the crude estimate provided here, raising the homes by 2 m would be sufficient to reduce significantly inundation for all the homes inland of the crest of the atoll.

Table 7 illustrates the effect of raising the existing floor levels of the housing by 2 m. Housing in Hazard Categories 1, 2a, 2b and 3a would no longer be subject to overfloor inundation and would therefore suffer only minimal damage, provided their foundations are designed to resist scour. Housing currently in Categories 3b and 4 may move to a lesser category, based on the reduction in overfloor depth achieved by raising the floor level.

Table 7 – Equivalent hazard category limits for 25%, 50% and 75% reduction in wave forces

House Raised by 2 m		**Damage as a percentage of value of building[5]**		
Old category	**New equivalent category limits**	**Building A**	**Building B**	**Building C**
Category 1	None	<2%	<2%	<2%
Category 2a	None	<2%	<2%	<2%
Category 2b	None	<2%	<2%	<2%
Category 3a	None	<2%	<2%	<2%
Category 3b	Category 1 (depth <2.5 m, speed <0.5 m/s) Category 2b (depth 2.5 – 3 m, speed <0.5 m/s) Category 3b (depth >3 m, speed <0.5 m/s)	2 – 22%	2 – 22%	2 – 22%
Category 4	Category 2a (2.5 <depth, speed >= 0.5 m/s) Category 3a (depth 2.5 – 3 m, speed > 0.5 m/s Category 4 (depth > 3m, speed > 0.5 m/s	2 – 100%[A]	2 – 100%[A]	2 – 100%[A]

Notes: A – If velocity exceeds 2 m/s complete building failure is possible. As there is no upper limit to depth and velocity the upper damage range is 100%

It should be noted that the house foundations can be designed to resist scour and erosion due to wave overtopping. The scour of the foundations will depend on the soil properties and the depth to bedrock. Scour potential would be reduced if a seawall is constructed due to the reduced velocity and reduced beach erosion.

Based on the review of the literature, raising of the homes would be an effective method of reducing storm damage, provided that the foundations can resist scour, as damage appears to be related more to the depth of flow. Reduction in flow velocity by construction of a seawall would reduce the probability of catastrophic failure of the houses in a large storm event but not reduce the effects of inundation damage.

3.4.1 Resilience of the house types over time

Based on the review of literature, the resilience of the various house types can be categorised as follows:

- House Type A – As this type of house is built at ground level, it will be the least resilient of the three housing types, being subject to the highest horizontal forces and the highest over-floor

[5] Assumes that the building foundations are resistant to the effects of scour.

inundation depths (as well as more frequent inundation). However, the concrete construction is more resilient than similar sized housing constructed of brick veneer or timber;

- House Type B – Raising house type A by 1 m would reduce the incidence of over-floor inundation. However, attention needs to be given to the foundation design to enable the homes to resist scour – for new buildings, consideration should be given to piling the foundations (ensuring adequate engineering design of the piling).
- House Type C – As this type of house is rated against cyclonic winds, it should theoretically have a high resistance to horizontal forces from storm surge flows. As the house is 1.5 m above ground level, it will also be theoretically subject to the least inundation damage of the three housing types. This type of housing also has the advantage of being re-locatable in the future should increases in inundation frequency, depth and velocity eventuate from the effects of climate change.

4 CONCLUSIONS

This report has presented several techniques for undertaking damage assessments to houses, relevant to the assessment of storm surge at Rangiroa. It was found that damage is proportional to depth, with high velocities providing a threshold at which failure of a building can occur.

Practical measures for reducing flood damages at Rangiroa would include:

- Construction of new houses so that they are rated for cyclonic winds (as these would be more likely to resist damage due to floodwaters)
- Construction of new buildings to be raised above ground level (as per Building Type B and C)
- Construction of new buildings further inland from the ocean shoreline (i.e. staged retreat from the beach) – this could be facilitated by use of pre-fabricated buildings that can be relocated in the future
- Design foundations for new buildings to resist scour from high velocity flows
- Where practical, raise existing buildings above ground level. This may be difficult to achieve with concrete housing but may be possible with pre-fabricated MTR style buildings.

While a seawall can be designed to reduce the velocity of the flows and reduce wave overtopping of the atoll, this would provide damage reduction benefit if the flow velocity can be reduced below 2 m/s, would reduce the probability of scour around the building foundations and reduce the probability of catastrophic failure of the building. However, if the depth of flow is unchanged, the percentage damage to the buildings caused by inundation would be unaffected by the presence of the seawall.

It is suggested that the following activities be carried out to provide a more thorough assessment of building damage at Rangiroa:

- Undertake pre and post-storm survey of the buildings and put together a database of buildings in Rangiroa
- Record and assess post-storm damage to buildings by inspection
- Undertake photogrammetry analysis, geotechnical investigation (drilling of boreholes) and storm erosion modelling to assess the potential for scour and beach erosion. This information can be used to design standard piled foundations to resist scour and thus reduce damage to buildings in high-velocity storm surge events
- Undertake wave runup analysis to assess appropriate floor levels for future new buildings at Rangiroa.

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