Wave emplaced Boulders: Implications for development of 'prime real estate' seafront, North coast Jamaica.

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With Jamaica's economy strongly dependent on tourism and marketed around white 'Sea',' Sand' and 'Sunshine', there continues to be increased pressure to develop coastal areas. The drive to develop such areas, and the rapid pace of developments (some of which are illegal (Gleaner, 2005)), have at times meant that attention paid to the potential impact of storm surge and tsunami has been inadequate (Tomlinson, 2011). As highlighted by the Planning Institute of Jamaica (PIOJ) (2012), as a result of increased coastal development, risk to life and property is very likely to be exacerbated from sea-level rise and storms and therefore needs to be addressed with urgency. Insufficient recognition of these geohazards has resulted in damage to the built environment (see Figure 1), loss of lives, economic hardship and damage to local economy (PIOJ, 2004). Large parts of the coastal area currently being developed have never been inhabited and as such there is limited record of storm surge and/or tsunami impacts on these coastlines. Developers in Jamaica do not always exhibit awareness of such geohazards and where they are aware of these there is limited information to inform development, particularly set back distances and height and type of coastal defences required. The Town and Planning Department (TPD) guidelines (TPD,1957) stipulates setbacks based solely on the elevation above Mean Sea Level (MSL) and slope gradient but does not take into consideration the effect of bathymetry and the site-specific characteristics related to the coastal hazard or risks faced (OAS, 1999). The suggested guidelines are not always useful to developers, who want to maximise the use of prime real estate land whilst reducing the risk to development.

This paper explores the use of wave-emplaced boulders to determine the wave heights from potential storm surges on the North Coast of Jamaica. The field area is a 2km length of coastline being developed for luxury homes and guest houses. As most of this specific area was undeveloped prior to 1960, there are no historical written records of storm surges and/or tsunami impact and as such the study of wave-emplaced boulders may be the most feasible source information to inform and guide developments. This research aims to undertake geomorphic mapping of the proposed study area, to determine the presence, location, spatial distribution, size, density and volume of wave emplaced boulders along a 2 km stretch of coastline earmarked for development, to determine the approximate wave heights associated with storm and/or tsunami waves that are required to deposit them and to discuss the implications for development.

Insert Figure 1 here

Figure 1 Damage to residential buildings at Caribbean Terrace by storm waves

2. Setting

The island of Jamaica is located in the Caribbean Sea, approximately 90 miles south of Cuba (18 15 N, 77 30 W) (see Figure 2). Jamaica is mostly mountainous, especially in the interior, with the Blue Mountains reaching an elevation of 2260 metres. The mountainous areas are bounded by narrow coastal alluvium and limestone plains. Geologically the island is relatively young, with the oldest rocks (limestones, volcanoclastic and schist) of Cretaceous age (140-60 million years ago). These Cretaceous rocks typically formed inliers that are predominantly flanked by Eocene/mid-Miocene limestone (70-13 million years) (Mitchell, 2002). The limestone accounts for approximately seventy percent of the land surface and is the dominant lithology of the island (see Figure 3). 'Raised' reefal limestone of Holocene age is found along the coastline as well on coastal platforms (Digerfeldt. and Hendry, 1987)

Jamaica experiences a tropical climate and lies within the Atlantic hurricane belt. Annually, between the months of June and November, the island is affected by tropical storms, some of which typically develop into intense hurricanes. Accompanying these storms are waves of over six metres, which have had devastating impacts on coastal communities (ECLAC, UNDP & PIOJ, 2004). Tsunami occur less frequently in Jamaica. The last recorded tsunami affected the island in 1907, when wave with heights of over 3m inundated the coastlines within the vicinity of the current proposed development site (Lander *et al*.,2002). Developments within coastal areas that are subjected to storm surges and tsunami can pose significant engineering challenges due to wave impact and flood waters (Manning, 2007, Tomlinson, 2011).

Insert Figure 2 here

Figure 2 Location of Jamaica.

Insert Figure 3 here

Figure 3 Generalised geology of Jamaica (compile from data provided by Mines and Geology Division, Jamaica).

2.1. Study area.

The study area is approximately, 5 km east of Discovery bay and is known locally as Diary. There are both residential and commercial guest houses located to the west of the study area. The popular tourist destination “Green Grotto Caves” is located approximately 1.5 km to the south. Just to the immediate west (approximately 500m) is a white sand beach in the vicinity of the old fort (see Figure 4) which is extensively used for recreational purposes by both residents and tourists. The residential buildings just to the west of the proposed 2km stretch of seafront, earmarked for development, have seawalls of height of around 2 metres on their seaward side. There is a minor road just beyond the built-up area towards the east. Beyond this point (see Figure 4), the area is highly vegetated and has no infrastructure in place.

Insert Figure 4 here

Figure 4 Location of study site at Dairy, St Ann (Base information from Survey Department of Jamaica [SDJ], 2004).

2.2 Storm surge and its impact on the Jamaican coastline

The damage caused by storm surge associated with Hurricane Sandy in December, 2012, is a timely reminder of the far-reaching impact of such events on the built environment of the Jamaican coastline. Since 1980, storm surges associated with the passage of Hurricanes Allen (1980), Gilbert (1998), Ivan (2004), Dennis (2005), Emily (2005) and Dean (2007) (Robinson and Khan, 2011) have resulted in damage to: buildings, infrastructure, utilities, boats, beaches and reefs. Wave heights associated with storms range from less than 1m (e.g. Hurricane Sandy 2012) to over 9m associated with Hurricanes Ivan and Dean (see Figure 5). Waves with heights as much as 13m associated with the passage of Hurricane

Dean were recorded at Sandshore, Manchioneal, Portland on the northeast coast of the island (PIOJ, 2012). Each year, damage as result of storm waves associated with the passage of hurricanes and tropical storms results in billions of Jamaican dollars in losses (ECLAC, UNDP & PIOJ, 2004). Using Portland Cottage as an example, in 2004, during the passage of hurricane Ivan, storms waves with height of over 9m were generated affecting buildings as far as 2km inland (PIOJ, 2004). In this area 105 houses were damaged and most required significant refurbishment before they were habitable again (see Figure 6). The Portland Cottage development is a prime example of the consequences of development in highly vulnerable coastal areas and points towards the need for sound scientific data to inform the developments in the coastal zone (PIOJ, 2004).

Insert Figure 5 here

Figure 5 Storm wave height (m) associated with some major Hurricanes from 1980 to 2012 and areas affected by the 1907 tsunami (Tsunami data modify from Cornish, 1908)

Insert Figure 6 here

Figure 6 Widespread damage to buildings (with some ripped from their based, leaving only the foundation) and land surface stripped of vegetation due to storm waves at Portland Cottage in 2004.

2.3 Threat of Tsunami in the Caribbean and Jamaica

Tsunami in the Caribbean have been generated as a result of earthquakes, volcanic activity and submarine and subaerial landslides (Lander *et al.*, 2002). The Caribbean plate is geologically active (earthquakes and volcanoes) and in the past several earthquakes have been generated around its boundary and intra–plate faults, which has led to tsunami (McCann, 2005). The margin of the Caribbean plate runs parallel to the Lesser Antilles in the east of the Caribbean sea, extending along the islands of the Greater Antilles from Puerto Rico, passing Jamaica, down to Honduras. Near the Leeward Islands in the east it forms a subduction zone with the North American Plate. This area has been the site of three major earthquakes in 1969,1843 and 1974 (McCann 2005). Any large tsunami generated within this area is likely to traverse the Caribbean Sea in is less than 3 hours and would affect Jamaica (Weissert, 1990).

Jamaica is a Caribbean island which has a history of tsunami. Since 1688, there has been a written record of possibly seven tsunami affecting the island (see Table 1). Most of these were of intensity of 2.0-3.0 (meaning height 4-8m on coastal line of 200-400km) on the Imamura-Soloviev scale (Zahibo *et al*., 2003). Based on the account in Lander *et al.* (2002), these tsunami were the result of earthquakes. The earthquakes may have directly initiated the tsunami and/or in some instances triggered submarine landslides, the subsequent motion of which resulted in tsunami generation. This is based on the time of earthquakes, the short time it took the wave to arrive at some of islands coast and offshore cable breaks, which strongly suggest the initiation of the tsunami by triggered submarine landslide closer to the coast than the epicentre of the earthquake, This might be the case of the tsunami that affected the north-east coast in 1907, following the earthquake. In general, the tsunami which have impacted Jamaica near island ones are localized in their effect and tend to affect the coastline within a 150km radius (see Figure 7).

The 1907 tsunami significantly affected the north coast of Jamaica. Based on the mapping by Cornish (1908), the study area was possibly inundated with waves of up to 2.8m high (see Figure 5). Mapping of boulders may help to validate these wave heights as well as provide scientific evidence of additional events (Peters and Jaffe, 2010).

Insert Figure 7 here

Figure 7 Origin of Jamaican tsunami (based on Data from Lander *et al.*, 2002**)**

Insert Table 1 here

Table 1 Maximum wave heights of historical tsunami affecting the coast of Jamaica (Modified from Zaibo *et al*., 2003, Lander *et al.*, 2002)

2.4 Current Regulations Regarding Set-Back

Guidelines for building along the coastline are stipulated by the Town Planning Department (TPD) in Jamaica. The ‘setback regulations’ (TPD, 1957) specify the distance from the High Water Mark for which permanent structures, particularly buildings may be constructed. Presently, setbacks distances are based on the slope gradient of the shoreline. There are three categories of setback distances based on the criteria specify by TPD. These are as follows:

i). A setback distance of 6m from the HWL if the slopes are equal to or steeper than 1(V):1(H). This category includes locations with a cliff face and implies a backshore elevation of over 7m. The reasoning is that the landward area is high enough to withstand storm surge waves and associated flood waters (OAS, 2001). This category therefore describes a shoreline that has good resistance to flooding from storm surge.

II). A setback distance of 15m for shoreline with gradients between 1:4 and 1:20. For the 1:4 slopes this implies a backshore elevation above the MSL of approximately 4m. The 1:20 gradient implies a backshore elevation of approximately 75cm. The TPD guidelines rationale is that such coastlines withstand surges ranging from approximately 0.8 – 3.8m above the HWL (OAS,1999).

iii) A setback of 30m for shorelines with slope gradient of less than 1:20. This range of slopes implies a relevance to shorelines that have a backshore elevation of approximately 1.5 metres. These are very low lying relatively flat areas, which would be prone to coastal flooding and storm surges with wave heights of over 0.5m.

3. Geomorphological mapping of wave emplaced boulders

Geomorphological mapping is routinely used for most site investigations, but it is usually restricted within the site description (e.g. elevation and general topographic features) (see Fookes *et al.*, 2007). Geomorphological mapping can help to inform land-use planning (PIOJ, 2004) and mitigate the threat from tsunami and storm surges on the Jamaican coastline. Although careful geomorphological mapping has the potential to provide detailed site-specific information that can reduce the need for costly geotechnical investigation, this is generally under-utilised. In tropical coastal environments where there is a combined geohazard threat from flooding and damage due to storm surge and tsunami waves, geomorphological mapping may be effectively used to identify and map the extent of storm surge/tsunami boulder ridges to provide guidance on safe ‘setback’ distances and the wave heights against which the built environment should be protected (OAS, 1999).

In this study, geomorphological mapping was done on a scale of 1:1000, using detailed topographical maps, IKONOS satellite imagery (5m resolution) and Google Earth imagery as basemaps. Traversing was done on existing footpaths and, in some cases, along 10 space grid lines, where access was available.

3.1 Topography of the area

The development site is approximately 2km x 550m, and bounded to the North by the Caribbean Sea. In most sections cliffs are evident with slopes of between 60 and 90 degrees (see Figures 8). The cliff height varies between 3 and 10 metres. The backshore area in the vicinity of the cliff show extensive raised reef terraces, which form platforms in some areas. The raised reefs are highly jointed, with evidence of fresh surfaces from which limestone blocks appear to have been torn.

Beyond the cliff towards the south, the land surface has a gentle slope with a gradient not exceeding five degrees. Gradient generally increases in southern direction. In the north this gentle gradient is interrupted by a relatively steep (30 degrees) conspicuous boulder ridge (see Figure 9) that divides the site into two distinctive areas. In the north the surface lacks well-developed vegetation (probably as a result of the action of repeat/frequent wave action) and displays typical tropical karstic 'honeycomb' features (see Figure 10) and blow holes. In the south, the honeycomb features are less evident, with very thick vegetation cover. Surface rills, channels and collapsed subterranean structures dominate the more southern section of the site (see Figure 11). The distinctive mapped boulder ridge is discussed in further detail below in Section 3.2.

Based on TPD regulations, the presence of a cliff and backshore elevation of over 7m would mean this area would require a setback distance of 6m (see Section 2.4) and would be able to withstand the effect of storm surges. The calculation of wave height based on boulder maps will help to determine whether this guideline is suitable.

Insert Figure 8 here

Figure 8 Presence of cliffs at the northern limit of the study site**.**

Insert Figures 9, 10, 11 here

Figure 9 Boulders (light grey) scattered around the site with the majority forming a ridge (where person is standing) extending in a west to east direction (left to right).

Figure 10 Typical karstic 'honey comb' feature develop toward the north of the property beyond the boulder ridge

Figure 11. Relative position of boulders and other geomorphic feature maps to the coast/coastal platform (contour data taken from SDJ, 2004)

3.2 Wave-emplaced deposits

Large boulders of marine origin are located around the coastline of Jamaica. Robinson *et al.,* (2006; 2008), Rowe *et al.* (2009) and Khan *et al.,* (2010) have contributed to the discussion on boulder emplacement along the Jamaican coastline by storm or tsunami. They have included reports regarding the movement of inventoried boulders by hurricane storm waves (Rowe *et al.,* (2009) and Khan *et al.*, (2010)). In general, deposition of large boulders of marine origin along coastlines without a history of glaciations is attributed to either slope instability, tsunami or storm surges. In the absence of evidence of slope instability such deposits are normally attributed to storms (e.g. associated with hurricanes) and/or tsunami (Etienne and Paris, 2010). Differentiating between a storm surge or tsunami mechanism for the deposition of boulders has been a topic of discussion among tsunami scientists (Scheffers and Kelletat, 2003; Nott, 2003; Morton *et al.,* 2008; Bridge, 2008). The differentiation is especially difficult in locations where both storm surge and tsunami regimes impact the shoreline and both types of deposit are found together (Felton, 2002; Goto *et al.,* 2010).

3.2.1. Boulder mapping

Field mapping of surface deposits indicate that they are predominantly reefal limestones, The deposit may best be described as biomicrite (Folkes, 1962) with corals being the dominant macro-fossils embedded in a micritic matrix. These reefal limestones are beige to white in colour and generally mostly angular in shape indicating minimal reworking. However, the smaller boulders (>15cm in diameter) tend to be more rounded, suggesting the possibility that they have moved by repeated wave action. The similarity of the boulders found within and around the boulder ridge and the lithology of raised reef terraces around the cliff are of similar composition. This would suggest that the sources of the boulders is the reef terraces/platform located seaward of the site. In addition, by examining the surface morphology of some boulders, it is possible to identify the exact area of the platform from which they were plucked. Based on this field evidence it has been concluded that intense wave action associated with storms and/or tsunami has transported sediment from the marine near-shore environment to the terrestrial environment.

3.2.2 Boulder ridge

The boulders mapped form a distinctive boulder ridge. These boulders are located between 45-128m from the coastline (as defined by SDJ, 2004) in the north. Its height vary above the ground (bedrock geology) from 2.4m towards the west to 1.5m towards east of the study area. The ridge is also much wider (6.8m) in the west than in the east (4.5m). The largest boulders (>2m) are found only in the western section of the site. As the ridge progresses eastwards the boulders get progressively smaller and widely spaced. As such towards the west the ridge is highly compacted, with limited gaps, whereas in the east it form discontinuous mounds with large gaps between them. It is surmised that this boulder ridge (see Figures 9 and 11) represents the average extent of storm wave action, as these boulders were thrown onshore and moved further inland during major storm and/or tsunami events. The boulders are typically deposited by intensive storm activity and/or geophysical events (e.g. tsunami) that deposit rocks already submerged and/or ‘plucked’ large blocks of rock from the coastal platform and move them ashore. Subsequent wave action moves the boulders to points of equilibrium along the shoreline. The accumulation of these boulders over time forms the ridge, which could provide vital evidence of the spatial extent of historical storm/tsunami waves. The boulder ridge appears to be acting as a barrier to flooding as a result of wave overtopping and possibly could serve as a ‘natural’ guide for establishing setback distances in the absence of other data (e.g. storm surge/tsunami models, historical records), beyond which no permanent buildings should be erected on the seaward side, unless other defences are put in place (Robinson *et al*., 2008; Rowe *et al*., 2009). The boulders mapped are up to 2.1m in diameter and if similar sized boulders are thrown landward during future storm/tsunami event they could cause extensive damage to built structures.

3.3 Wave height calculations

Undertaking topographical and geomorphological mapping helped to identify storm/tsunami deposits, which in turn helped to determine the potential height of the waves required to initiate movement for subsequent deposition by either storm surge or tsunami. As highlighted by Nott (2003; pg 1) ‘The pre-transport environment of a coastal boulder along with its shape, size and density determines the height of wave required for it to be transported’.

The methodologies developed by Nott (2003), were utilised for the calculation of waves produced by both storm and tsunami that could have deposited boulders found in the boulder ridge. The initial survey of the boulder ridge, with five 10 x 10m grid across its length, indicated that there were generally three populations of boulders. There were very large boulders, >2m, mostly isolated away from the ridge (see Figure 11); medium size boulders, between 0.5- 2m; and smaller boulders, less than 0.5m. Boulders less than 0.5m dominate (62%); followed by those between 0.5-2m (23%); and the very large boulders, greater than 2m, made up just 5% boulder population. Using the approximate proportions indicated above, 100 boulders were then sampled. Detailed measurements (see Figure 12 and Table 2), including their A, B and C axes, lithology and density was done for each sample. These measurements were then used to determine what the required wave height from either a tsunami or storm would have to be to transport them to their current location.

Insert Figure 12 here

Figure 12 Example of dimensions of boulders being measured

In order for boulders to be deposited by tsunami/storm surges they have to be already present as source material ready to be either, ripped from a rocky shoreface (see Figure 13), or as loose boulders already formed and waiting to be moved from the sea to the shore or from the shore further inland. The position that the boulder is in prior to being deposited is important in determining the distance it may be deposited inland (Nott, 2003). A boulder already detached and submerged in the water (see Figure 14) will more likely to be carried further than one which first has to be ripped from the platform (joint-bounded)(see Figure 13). For this research, two scenarios are determined; whether the boulders were submerged before deposition (Equations 1 & 2); or whether they were a 'joint bounded' part of the platform and had to be detached first before being deposited by a storm or tsunami wave (Equation 3 & 4). Equations 1 and 2 below, used to determine tsunami and storm wave height for the two scenarios mentioned above, were taken from Nott (2003, p. 271).

Insert Figures 13 and 14 here

Figure 13. Boulder removed from limestone platform by wave action from Hurricane Dean in August, 2007. Person standing is 1.8m tall.

Figure 14. Submerged boulder adjacent to a cliff face being measured

Determining wave height based on if the boulders were submerged before deposition.

$$H_t \geq \frac{0.25\left(p_s - p_w / p_w\right) 2a}{¿¿}$$

Where $\boldsymbol{H_t}$ = height of Tsunami Equation 1

$$H_s \geq \frac{(p_s - p_w / p_w) 2a}{¿¿}$$

Where H_s = height of Storm wave Equation 2

Determining wave height based on if the boulders were part of a fault-bounded platform.

$$H_t \geq \frac{0.25 (p_s - p_w / p_w) a}{C_1}$$

Where H_t = height of Tsunami Equation 3

$$H_s \geq \frac{(p_s - p_w / p_w) a}{C_1}$$

Where H_s = height of Storm wave Equation 4

Where p_w = density of water at 1.02 g/ml (this could increase when sediment such as sand is incorporated in the flow), p_s = density of boulder at 2.4 g/cm3, C_d = coefficient of drag = 2, C_1 = coefficient of lift = 0.178, ***a***= A-axis of boulder, ***b***= B-axis of boulder, ***c***= C-axis of boulder.

Calculating Wave Height for Tsunami and Storm Wave

Utilising Equations 1- 4, the wave heights required to initiate the movement of the boulders found in the boulder ridge by storm wave and tsunami were determined. Tsunami wave calculated required to move the Dairy boulders range from 9cm to 10.43m (see Table 2). Wave heights associated with storm surges range from 41cm for the small boulders nearer to the sea to 10.43m for the largest boulders. Generally, as expected the wave heights required by tsunami to emplace these boulder is far less than those possible associated with storms (see Table 2).

The largest boulder mapped was 2.10 metres (a-axis) with a mass of 13.99 tons (see examples in Table 2). If this boulder was still a part of the raised reef platform, that is joint-bounded before being deposited, it would have required a storm surge with wave heights of 1.9m and a tsunami with waves of 0.43m to initiate movement. However, if this boulder was already detached, it would have required a storm surge wave of 10.4m and a tsunami height of 2.6m. It is difficult to determine the state these boulders were in before being deposited and as such, the wave heights determined can only act as extreme cases.

Insert Table 2 here

Table 2 Wave heights (m) calculated assuming boulders were submerged or joint bounded blocks before being transported

4. Implications for development

Observations following hurricanes and the occurrence of storm surges, indicated that these boulders are could have been deposited by waves associated with storm surges. Observations after the 2004 Indian Ocean tsunami also highlighted that such boulders may also be deposited by waves associated with tsunamigenic processes (USGS, 2005). Whilst it could not be determined whether these deposits were deposited by waves associated with tsunami and/or storm surges, the spatial extent these boulders were carried and deposited inland could be determined. Wave action most definitely would need to be active up to the extent of where the large boulders in particular were deposited. The size of the large boulders, were unlikely to be moved by simply rolling (particularly as gradient increased from the shore) and reworking by normal wave action (MSL is between 3m and 10m below the elevation boulders were deposited). The inland limit of the boulders could possibly be used as the minimum setback limited for building in this location. The lack of vegetation on the seaward side of the boulder ridge is also strong indication of this area is repeatedly being affected by wave action. As indicated above, the boulders are found 45-128m inland. Based on TPD regulations, the presence of a cliff and backshore elevation of over 7m would mean this area would require a setback distance of 6m (see Section 2.4) and should be able to withstand the effect of storm surges. Our research indicates this would be not be sufficient. If developers were to adhere to this guideline without the implementation of some form of coastal defences it would mean exposing their development at significant risk of wave impact and flood from storms and/or tsunami. The TPD guidelines are clearly not based on consideration of the actual risk from coastal inundation and platform-breaking, wave bombardment at these coastlines and we would recommend that they be revisited and consider revising to incorporate hazard/risk information. In the absence of Island-wide storm surge and tsunami risk map to guide development, detailed hazard analysis needs to be done for each site before development proceeds. For this particular site, without some form of defence to protect development, we would not recommend development within 130m of the current shoreline.

Should the developer wish to implement coastal defences to reduce the potential impact on their development, it would be important for them to gain an understanding of the potential wave height against which they will need to defend. Determining the maximum wave height may help developers to better implement site specific defence mechanisms to reduce the impact of such waves and more effectively utilise sites for development.

Maximum storm wave heights of 10.4m (based on boulder fault- bounded to a platform) for storm surges and 2.6 from tsunami would present a significant challenge in effectively developing defences that are compatible with the aesthetic characteristic of the area. However, the wave heights calculated are not out of kilter with storm and tsunami wave height for the northern Jamaican coastline. Hurricane Allen, in 1980, generated +9m storm waves along the northern Jamaican coastline and places such as Buff bay approximately 15km to the east of this site (Kjerfve, *et al.*, 1986). The 1907 tsunami, which affected the northern Jamaican coastline and which was possibly generated by submarine landslides triggered by the earthquake, produced waves of up to 2.5m in height (Lander *et al*., 2002). Both the calculations for storm and tsunami waves appear to align well with observed wave height for the northern Jamaican coastline and point to the use of boulders as effective tools to determine wave heights.

5. Conclusion and recommendations

Geomorphological mapping proved an effective method in helping to identify boulder deposits emplaced by storm/tsunami wave action. The spatial extent of these boulders inland where they form a boulder ridge provide a clear indication of the minimum inundation distances of these waves. It is highly likely that waves may progress further inland beyond this ridge. As such, the extent of the ridge should be used as minimum setback distance. The setback distance in this instance would be up to 130 metres. This set back distance is significantly in excess of those suggested by TPD guidelines of 6m. The research highlights the need to identify potential hazards and their associated risk to inform risk reduction strategies for development, in order to evaluate the utility of existing guidelines in an ever-changing climate. Mapping of the boulder deposits was also useful in the determination of the maximum wave heights from both tsunami and storm waves from which defence is required. The wave heights calculated are within the range of those recorded by both tsunami and storms for the northern Jamaican coastline. This point to the potential application of mapping of wave-emplaced boulders along the Jamaican coastline to aid decision making for other sites slated for development.

Recommendations

In planning to mitigate the impacts of these waves, where the decision has been made to develop these areas, there are four general recommendations:

1. Create site-specific setbacks (of at least 130m in this location) to reduce the potential impact of waves associated with storms and/or tsunami. The boulder ridges are good markers of the extent (minimal) of potentially destructive wave action inland and may be used as minimum setback distance for buildings.
2. Utilise wave height calculations based on wave emplaced boulders mapped to guide development of coastal defences (hard and soft-walls, mounds, dunes, trees, 'green-spaces') to protect investment and maximise the proportion of the property that may be developed.
3. Where possible, leave the boulder ridge in place to act as natural defence to high-energy storm/tsunami waves and floods
4. Implement a drainage scheme to channel surface water away from development during periods of inundation by waves.

Option 1 may be the most sustainable measure as it would leave a large section of the coastline undeveloped; acting as a natural buffer. However, developers value this part of the coastline, nearest the seafront, as prime real estate and are hesitant to accept this option due to loss of land that could be developed. Installing barriers (e.g. sea walls) on the seafront impacts the natural aesthetics and the price of properties; as such this option is generally resisted by both developers and environmental lobbyists. There are much softer options, for example sand dunes, demountable barriers, rock mounds (of which boulder ridges are a naturally existing example), wetland areas and trees. These softer engineering approaches can be costly to maintain and can result in legal disputes as to whose responsibility it is to do so. As such they are not always a sustainable option in the long-term. However, combining shorter set-back distances with softer engineering methods may be a reasonable compromise provided mechanisms for their maintenance are put in place and suitable drainage to channel flood water is implemented.

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