TSUNAMIS – ASSESSING THE HAZARD FOR THE UK AND IRISH COAST

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Abstract: Following completion of the 2005 Defra commissioned study "The threat posed by tsunamis to the UK", this study was undertaken to investigate more specific questions raised from the previous report. The original Defra study identifies four potential tsunami sources origins, and provided first estimates for wave conditions at the UK coast for tsunamigenic events of very high, high and moderate likelihood.

This second study reviewed two of these source origins in more depth, the North Sea event and a Lisbon-type event, with their consequence impact compared with regard to hazard. Previously proposed source terms for a 1755 Lisbon event was assessed and three simple models considered that could be used to study the impact of a tsunamigenic earthquake of a similar size, and in a similar region to the 1755 source, on the UK and Irish coastline. The resulting sea level displacements were used as initial conditions in a numerical model to propagate the initial disturbance to nearshore. A further numerical model propagated the tsunami to the shoreline and provided estimated of water level elevations on the Southern Irish coast, the Cornish coast and in the Bristol Channel. Information regarding the tsunami magnitude at the coast was then used to assess hazard.

This paper focuses on one of the hypothesised Lisbon type events, the propagation of the tsunami from source to shoreline and the consequence of an impact on the coastlines of south-west England and southern Ireland.

INTRODUCTION

In early 2005, the Department for Environment, Food and Rural Affairs (Defra) commissioned the study "The threat posed by tsunamis to the UK" (Defra, 2005) following the earthquake off the northwest coast of Sumatra and the consequent devastating tsunami of the 26 December 2004. The initial study identified four potential source origins (North Sea, Celtic Sea, offshore of Lisbon and La Palma in the Canary Islands) and provided first estimates for wave conditions at the UK coast (Musson, 2005). The second study was commissioned by Defra in August 2005, with the following objectives:

- Refinement of the potential impact envelope in South-West England, South Wales, the Bristol Channel, southern and western Ireland from Lisbon-type events;
- Further consideration of the difference between tsunami-type events and storm surge waves in terms of coastal impact;
- Investigation of typical impacts of near-coast events e.g. North Sea beaches and other facilities seaward of defences including expected wave heights, celerities and therefore degree of hazard.

This paper summarises the derivation of the Lisbon-type event source models, the propagation of one of these sources models (model B), from its initial sea level displacement to shoreline, and the consequence of hazard on the Cornish coast.

This study was performed by a large team, comprising of individuals from HR Wallingford, British Geological Survey and the Proudman Oceanographic Laboratory.

SOURCE TERMS

The first stage of the study was to review the tectonics in the area between Gibraltar and the Azores. The Azores-Gibraltar fault zone (AGFZ) is the westernmost continuation of the boundary between the Africa and Eurasia plates. In considering a repeat of the 1755 Lisbon earthquake, the section of fault which extends from the Madeira Tore rise in the west, to the Strait of Gibraltar in the east was reviewed (Figure 1). Structurally, this area is complex, with bathymetry characterised by a series of ridges and seamounts, such as the Gorringe Bank, separated by significant depressions such as the Horseshoe and Tagus abyssal plains. Seismicity on the eastern segment occurs over a broad region (~ 250km) and indicates active WNW-ESE compression, with crustal shortening accommodated on numerous thrust faults (Buforn *et al.*, 1988; Sartori *et al.*, 1994). This compression results in earthquakes with significant vertical slip, of a type that can result in tsunami generation.

The process of locating the 1755 earthquake accurately has proved to be somewhat problematic, despite the wealth of historical data available. Conflicting information regarding the distribution of intensities, origin time, the timing of strong shaking and tsunami arrivals (Johnston, 1996), and the diffuse distribution of earthquakes along this part of the AGFZ (Zitellini *et al.*, 2001) lead to large uncertainties, and the range of possible epicentres spans around 500km. Consequently a large number of source models have been proposed for the 1755 Lisbon earthquake. The problem of determining hypocentre location, source mechanism and rupture dimensions appears to be underdetermined, therefore, a large number of models can be found that partially match the macroseismic and tsunami observations.

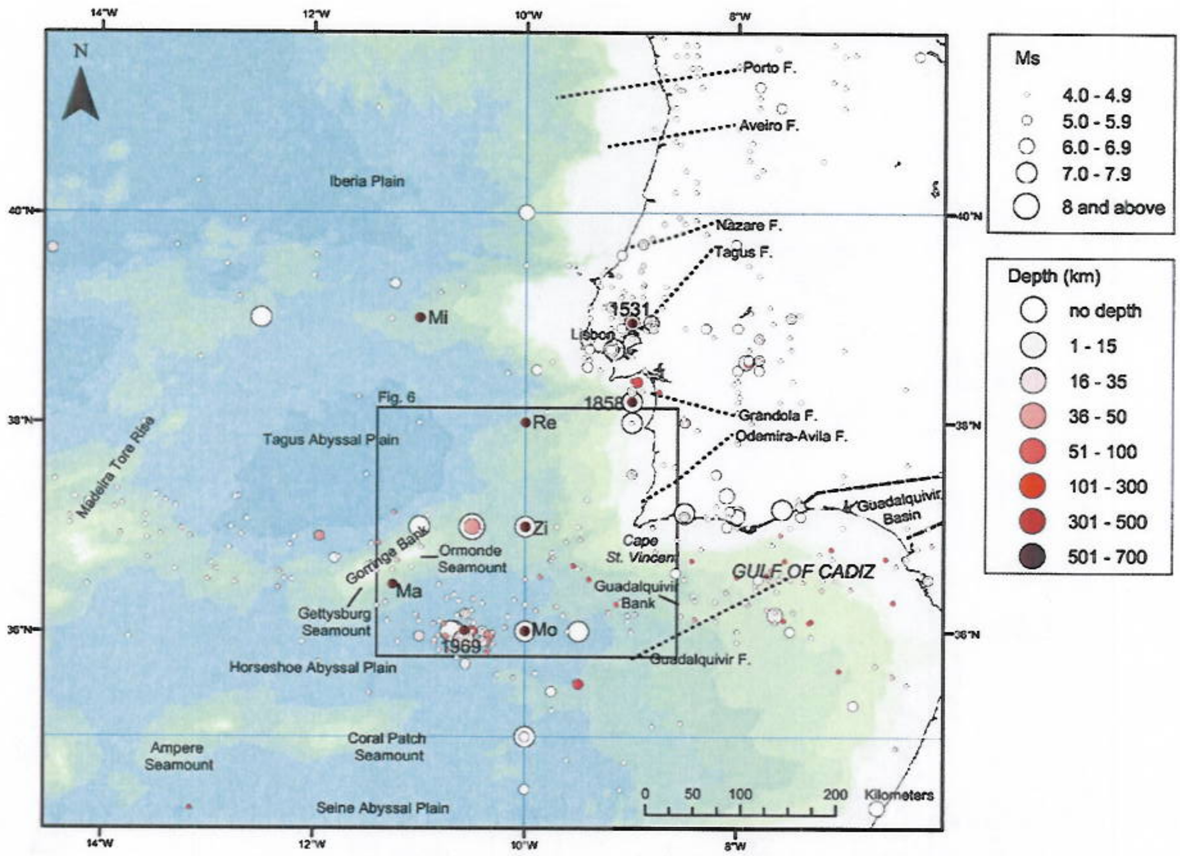

Figure 1 Map of the Azores-Gibraltar fracture zone, east of the Madeira Tore rise.

As the exact source of the1755 Lisbon earthquake remains unknown, we could not simply model a single source. This therefore led to the following three models being proposed:

Model A Epicentre of the 1969 earthquake in the Horseshoe Abyssal Plain, southeast of the Gorringe Bank. The orientation of the fault is southwest-northeast;

Model B Epicentre north of the Gorringe Bank, related to the tectonic uplift of the region. The orientation of the fault is west-east;

Model C — Epicentre is located southwest of Lisbon, offshore but closer to the Iberian coast than model A and model B. The fault orientation is north-south.

The fault orientations and locations for these three models are shown in Figure 2.

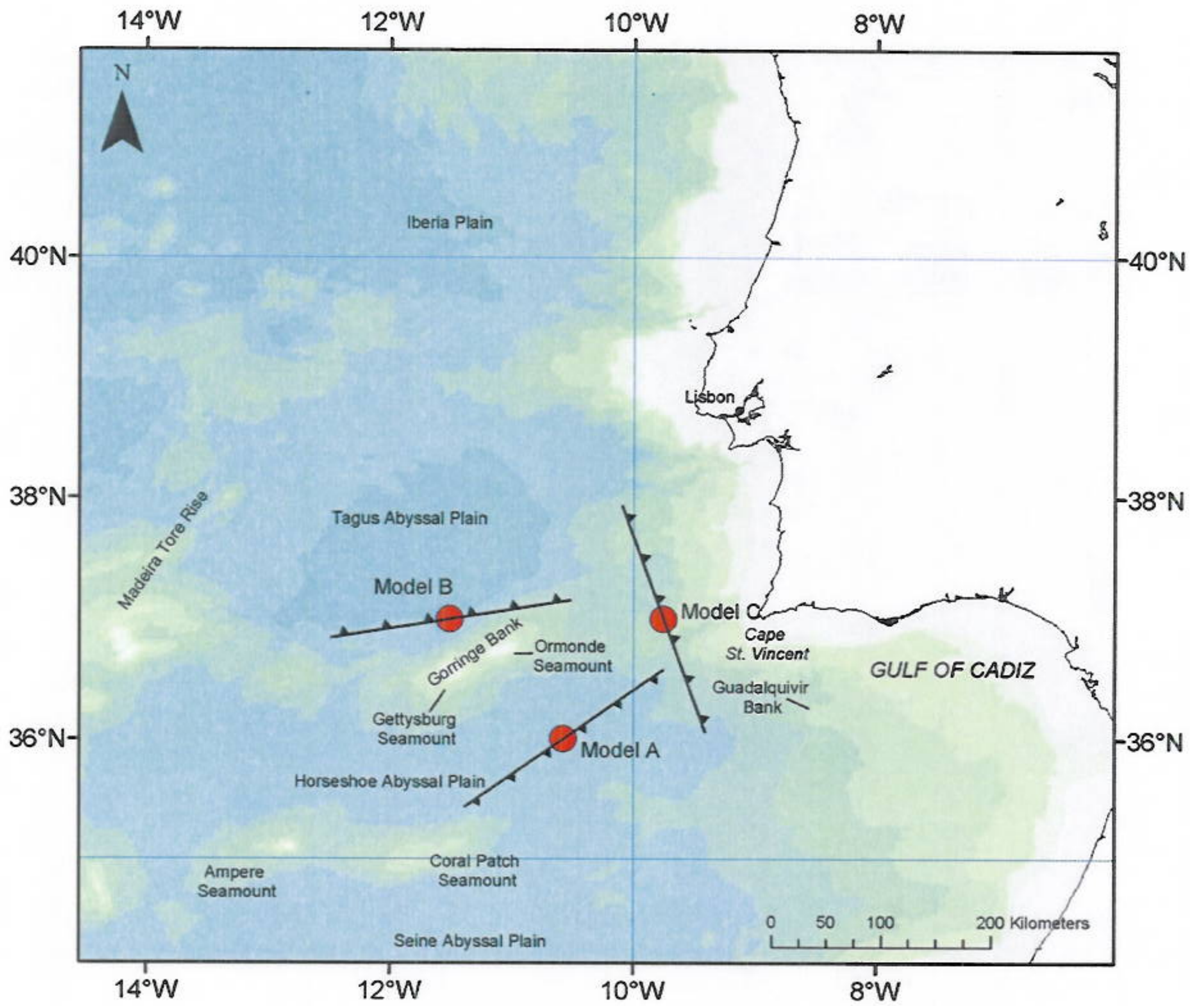

Figure 2 — Location and orientation for the three source models proposed.

Once the location and orientation of the source models were known the possible magnitude of the events required investigation. Previous literature suggests that the magnitude of the 1755 earthquake ranged from 8.5 to 9.0 M_W (M_W = moment magnitude). Extreme magnitudes of $\geq$ 9.0 M_W were excluded, since earthquakes of this size are only likely to occur in subduction zones. There is no credible evidence of a subduction zone off the southwest coast of Lisbon. This led to source magnitudes of M_W = 8.5 $\pm$ 0.2 being used in models A – C. These two different earthquake magnitudes (8.3 and 8.7 M_W) were used as inputs for each of the three of the models discussed above to derive the width, W, length, L, and average slip, D. Estimates of the surface displacement were then calculated as a function of fault length and width, using the analytical expressions of Okada (1985), for each model.

The sea level displacement for model B, with earthquake magnitude 8.7 M_w, is reviewed in the remainder of this paper.

PROPAGATION TO NEARSHORE

The numerical model chosen to propagate the tsunami away from the immediate source was the POL CS3 12km grid model, which solved the non-linear shallow water (NLSW) equations. The model was used to propagate the tsunami wave to the UK continental shelf. The CS3 model used radiating conditions at the lateral boundaries of the computational domain, allowing the resulting tsunami wave to propagate freely out of the domain, were required, without effecting the computation within. A full description of the model is given by Flather (2000). The same model is in routine use for storm surge warning as part of the Storm Tide Forecasting System (STFS). Results of the wave propagation from model B, for an 8.7 M_w earthquake, are presented in Figure 3.

The simulation of model B (Figure 3) examines the propagation of the tsunami wave from a source location north of the Gorringe Bank, originally proposed by Johnston (1996). The 8.7 M_W event gave rise to tsunami amplitude of approximately 0.5m approaching the UK continental shelf, after two hours. This source model, with its east-west fault orientation, results in the tsunami wave undergoes less refraction (and therefore energy loss) as it propagates towards the UK continental shelf break.

The effect of the state of the tide was also investigated and shown to have no significant impact on the generation, or immediate propagation of any disturbance.

PROPAGATION TO SHORELINE

The resulting waves at the continental shelf were now required to be propagated to the UK and Irish coasts. In order to simulate tsunami propagation to the shoreline it is necessary to have a finer grid model than for the numerical propagation from source. Therefore, the TELEMAC-2D flow model was used, which utilized wave data (free-surface elevation and depth-averaged velocities), produced by the POL CS3 extended 12km grid model, as boundary conditions. The resulting tsunami input wave was then transformed up the continental shelf, with the refraction and diffraction effects modelled as the wave approaches the coastline. The simulated tsunami for model B had a wave period in UK and Irish coastal waters of approximately 20 minutes. Even though the wave period of the tsunami is maintained, shallow water theory states that the wave length varies proportionally to depth. It is therefore beneficial in the modelling of tsunami waves in shallow waters to use a variable grid model, allowing the number of cells per wavelength to remain approximately constant. Such a variable mesh was generated by the modelling software and used in the hydrodynamic model TELEMAC-2D.

The propagation of the model B (8.7 M_W) tsunami wave up the continental shelf and to the UK and Irish coastlines is shown in Figure 4.

Results of the TELEMAC flow model indicated that model B (8.7 M_W) produced the highest wave elevations along the UK and Irish coastline (compared to models A and C), specifically the Cornish coast and southern Ireland. The model run produced maximum wave values of 1-2m around the majority of Cornwall, with 3-4m identified between Penzance and Lizard Point, as shown in Figure 5 where the y-axis is the computed maximum tsunami wave height at the computational points around the Cornish coast (x-axis). Along the south coast of Ireland, wave elevations were also consistently 1-2m, with a number of areas (Ross Carbery and Kinsale) recording wave elevations of greater than 2.5m.

The effect of tide on the tsunami elevation at the coastline was also reviewed and results indicated that the maximum wave elevation was relatively consistent along the coast for both the low and high tidal conditions. Local maxima between Penzance and Lizard Point, varied slightly in magnitude and location, although maximum water elevation remained approximately 4m. It should be noted that the mesh resolution at the coast is approximately 1km, so any further localised effects will not be resolved in the model.

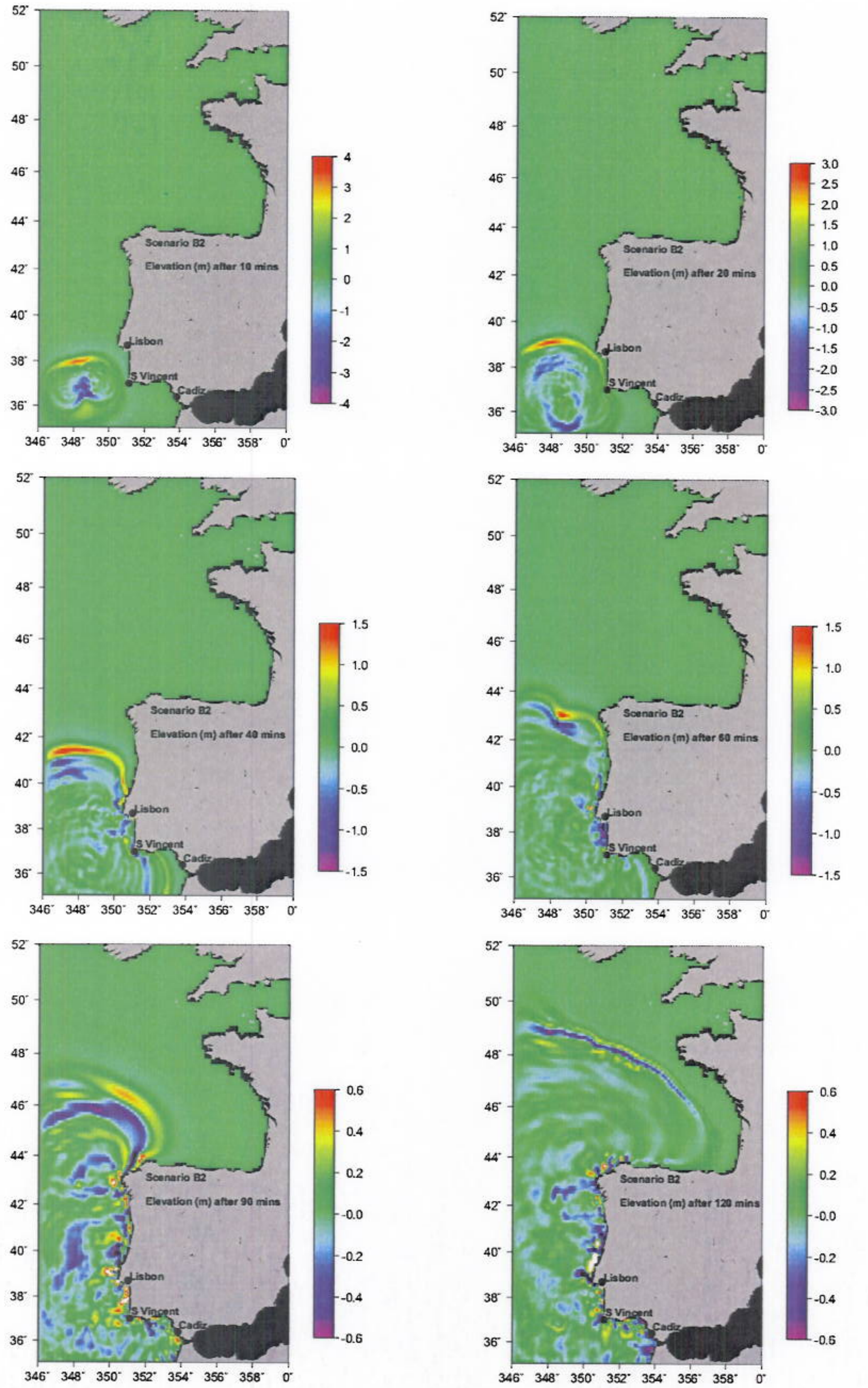

Figure 3 Surface elevation of model B tsunami wave propagating from source location
(Note: colour scale differs between plots)

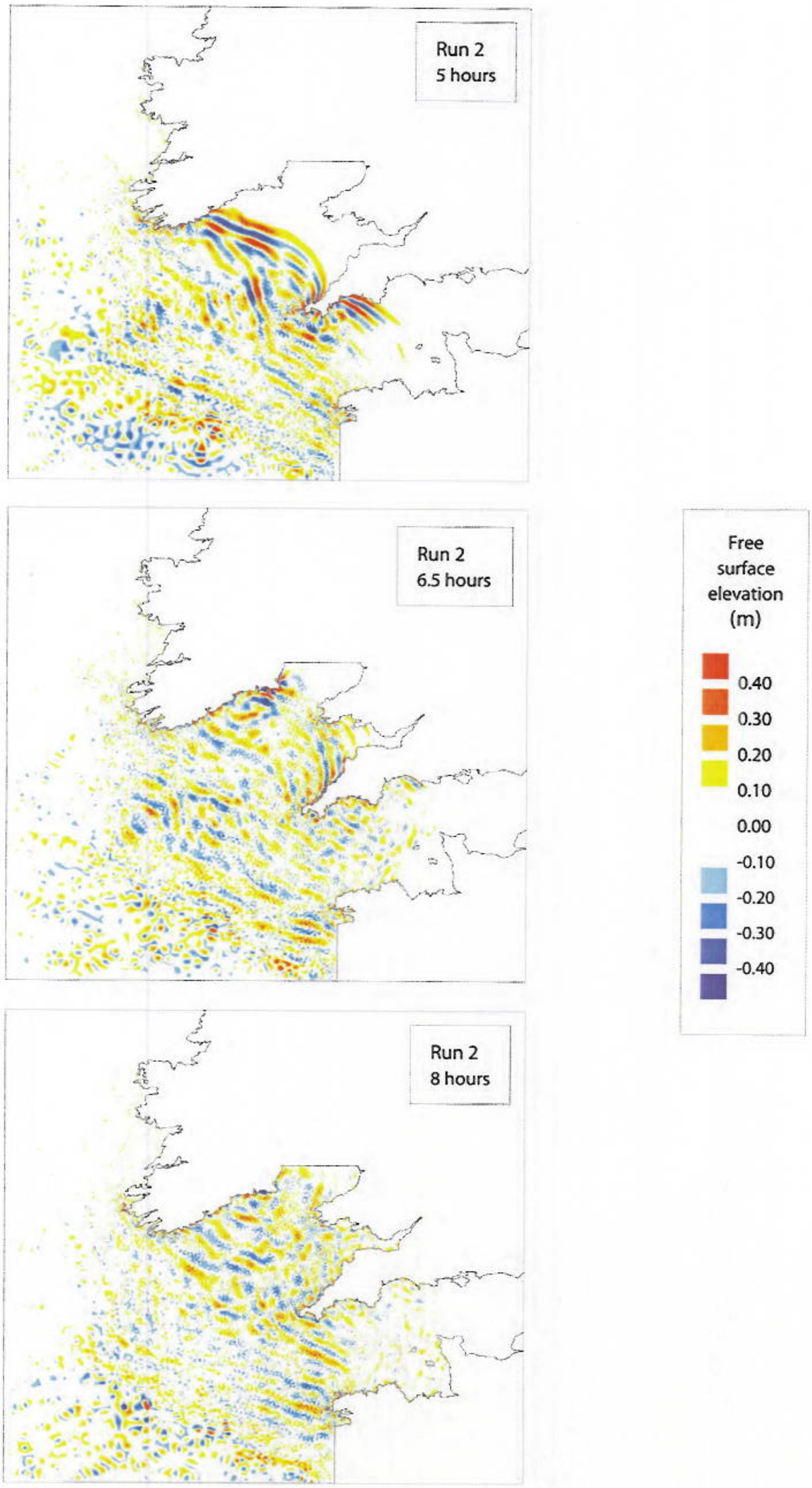

Figure 4 Surface elevation of model B tsunami wave propagating up the UK continental shelf and towards the coastline.

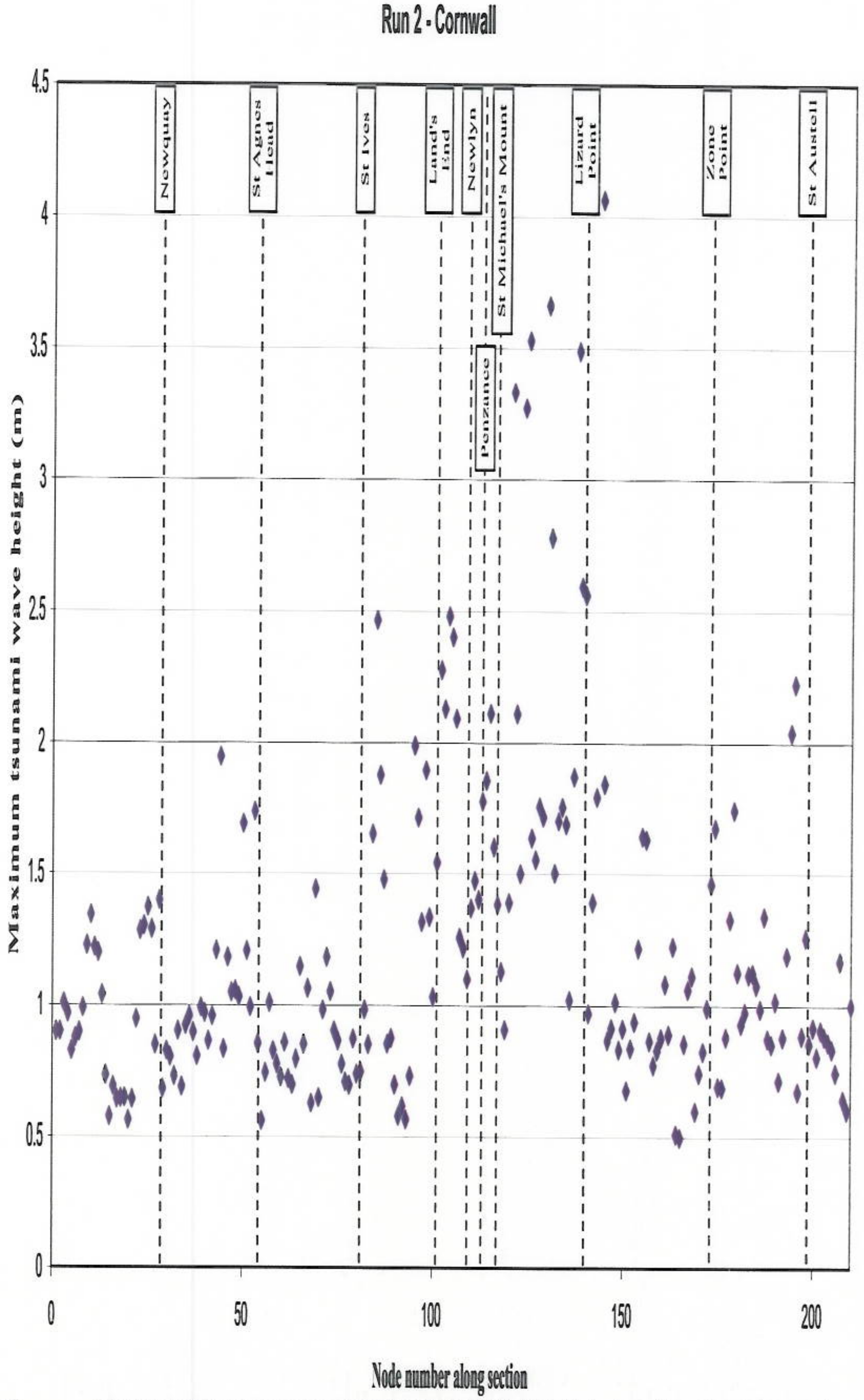

Figure 5 Maximum tsunami wave elevation (model B, 8.7 M_w) along the Cornish coast.

ASSESSMENT OF HAZARD

The model B results were now used to assess hazard at the coastline. As the tide level generally had little effect on the overall tsunami wave elevation, the tsunamis arrival was assumed initially to coincide with mean high water springs and latterly with mean high water neaps. The tsunami elevations around the Cornish coast were now compared against 50 year and 100 year extreme sea levels presented in Dixon and Tawn (1997) "Estimates of extreme sea conditions – Final Report: Spatial Analysis for the UK Coast".

The maximum water surface elevation for model B, above still water level, around the Cornish coast is presented in Figure 6. These maximum elevations (certain locations given by a range of values) assumed firstly to occur at mean high water springs (MHWS) and secondly to occur at mean height water neaps (MHWN), are compared to the 1:50 and 1:100 year extreme sea levels (Dixon and Tawn, 1997) for the Cornish coast in Table 1.

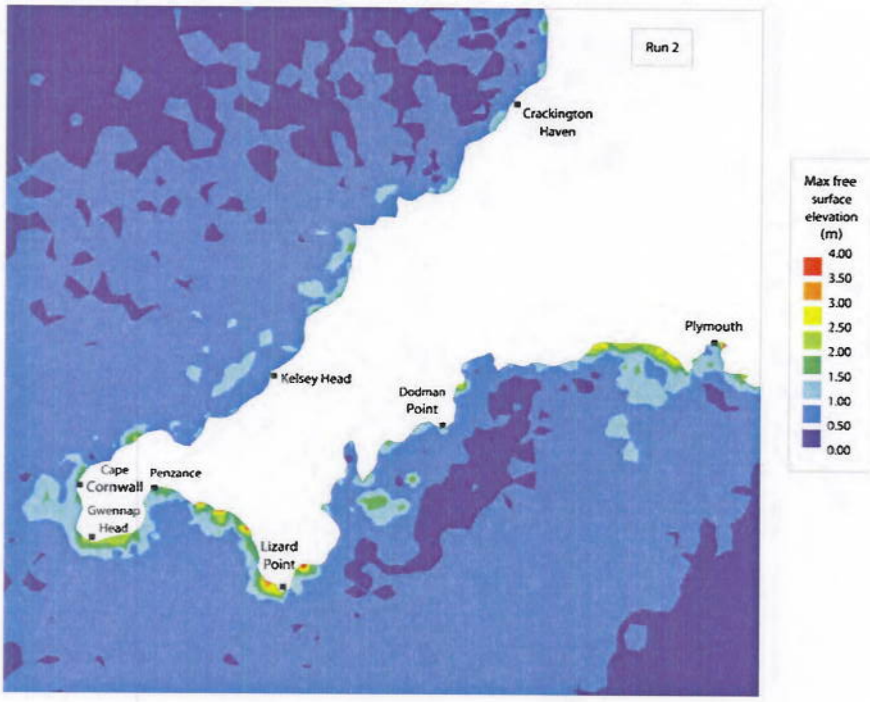

Figure 6 Maximum water elevation around the Cornish coast above still water level

Table 1 Comparison of computed tsunami maximum elevations and extreme sea levels around the Cornish coast

Location	Tide levels plus tsunami wave elevation (mODN)		Extreme sea levels (mODN) (Dixon and Tawn, 1997)	
	MHWS	MHWN	1:50 year	1:100 year
Crackington Haven	4.3	2.6	5.1	5.2
Kesley Head	4.1 to 4.8	2.4 to 3.1	4.5	4.6
Cape Cornwall	4.2 to 4.8	2.5 to 3.1	3.6	3.7
Gwennap Head	5.0 to 5.4	3.7 to 4.1	3.9	4.0
Lizard Point	5.0	3.9	3.5	3.6
Dodman Point	3.4 to 3.8	2.3 to 2.7	3.4	3.6

Results from this analysis indicated that only the most south-westerly coast of the UK may incur sea level elevations marginally in excess of the 1:100 year extreme sea level predictions.

Although a review of the water elevation around the coastline is important in assessing hazard; the flow velocities are also of consequence. A further assessment of hazard reviewed the wave elevation and flow velocity at the still water level for the tsunami wave as it ran-up and down the beach. The result of the numerical computations for model B indicated that the wave height at the Cornish and southern Irish coasts was in the region of 2m. These wave heights, and associated flow velocities for wave propagation up and down a typical 1:60 beach, were entered into a simple formula derived during a flood risk to people project (FD2321, Defra 2006) to assess the hazard level. The depth (d) and velocity (v) of the flow are input into the "hazard" equation, d*(v+0.5), which provides a look-up value for the hazard level. The degrees of hazard associated with this numerical value, from the "hazard" equation, are presented in Figure 7.

d x (v + 0.5)	Degree of Flood Hazard	Description
<0.75	Low	Caution *"Flood zone with shallow flowing water or deep standing water"*
0.75 - 1.25	Moderate	Dangerous for some (i.e. children) *"Danger: Flood zone with deep or fast flowing water"*
1.25 - 2.5	Significant	Dangerous for most people *"Danger: flood zone with deep fast flowing water"*
>2.5	Extreme	Dangerous for all *"Extreme danger: flood zone with deep fast flowing water"*

Figure 7 Hazard associated with combinations of flow depth and velocity

The results for a 2m tsunami are presented in Figure 8, which indicates that for model B Lisbon-type event (8.7 M_W) the tsunami waves reaching the Cornish and southern Irish coasts could be classified as "extreme", dangerous for all. The line plot should be reviewed as a time line, starting at the bottom left hand corner, moving up the line as the wave runs up the beach (water depth increases) and back down as the wave recedes.

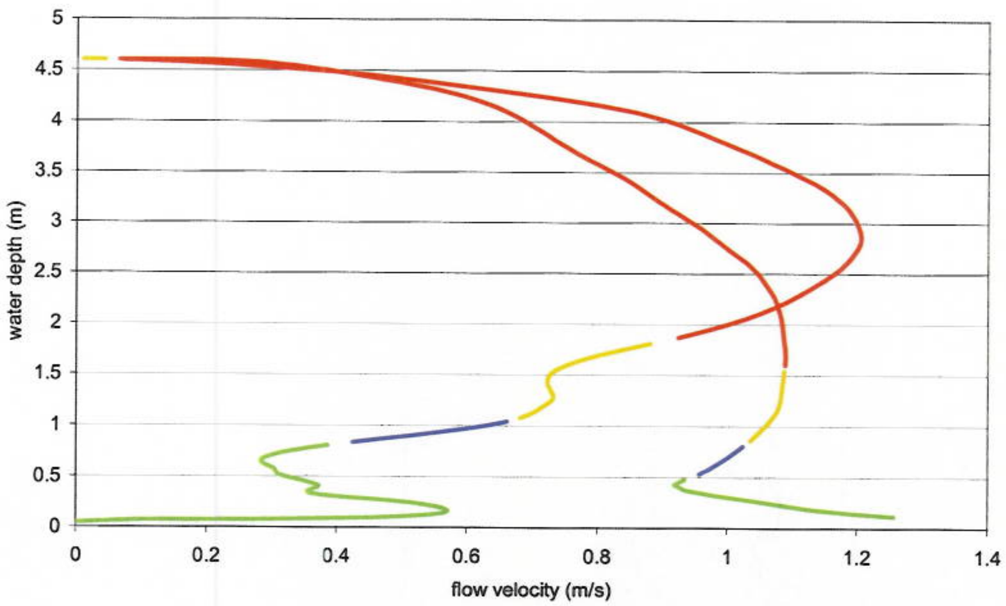

Figure 8 Hazard level associated with a 2m tsunami generated by the Lisbon-type event, the colour coding of the line plot relates to the hazard level defined in Figure 7

Finally, travel times from the origin of the tsunami source to the UK coast were reviewed. For the Lisbon-type tsunami, travel times are approximately four and a half hours to the Cornish and southern Irish coast, allowing enough time for the general public to be notified of the potential hazard providing a suitable mechanism were in place.

CONCLUSIONS

This paper has presented results for a 1755 Lisbon-type tsunamigenic earthquake event. Following the derivation of the source terms, the sea-level displacement for model B was simulated, using numerical modelling, from its original source to the UK and Irish coast. The numerical model results indicated than on average the maximum wave elevation of the tsunami was in the region of 1-2m, although predicted maximum wave elevations at the most south-westerly coast of the UK were approximately 4m. An assessment of hazard was undertaken using the results of the modelling and consequently identified that only these south-westerly regions (Cape Cornwall to Lizard Point) marginally exceed 1:100 year extreme sea level predictions. A review of the water elevation and velocity of the tsunami wave also identified that the wave would be hazardous to individuals on the beach once the water level exceeded approximately 1m in depth.

The main conclusions of the paper are presented below:

- The most exposed areas of the UK and Ireland, for a Lisbon-type event, are the Cornish coast and southern Ireland.
- Simulated wave elevations on the Cornish and southern Irish coasts are typically in the range of 1-2m, with localised amplification enhancing the elevations to approximately 4m.
- Effects of the tide have been studies on the initial propagation and inundation of the tsunami wave, no significant effect on the wave elevation has been noted.
- Assessment of hazard results indicate that only the most south-westerly coast of the UK may incur sea level elevation marginally in excess of the 1:100 year extreme sea level predictions.
- The hazard level for an 8.7 M_W Lisbon-type event could be "extreme", dangerous for all, over much of the Cornish coast and southern Ireland.
- If a Lisbon-type event, large enough to be tsunamigenic, occurred than the travel time for the wave to the UK coast should be sufficient to warn the general public, assuming a mechanism is in place.

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