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# Numerical Modelling of Inland Flood Inundation from Cyclones and Tsunamis and Development of Flood Mitigation Options

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**ABSTRACT**

Natural hazards like cyclones and tsunamis are now more frequent with higher intensity than in the past due to global warming. Flooding from cyclones and tsunamis cause significant loss of life and damages properties, ecosystems, businesses and coastal facilities. In this paper initially flood risks from cyclones and tsunamis were assessed for a seafront development project. Then cyclone and tsunami conditions were derived at the project site using numerical models. Numerical modelling of wave overtopping (run-up) was carried out using the Amazon model and the inland flood inundation modelling was carried out using the MIKE21 Flow Model. Thereafter, flood mitigation options were developed to prevent flood water entering the project site. The methodology described in this paper for inland flood inundation modelling study and development of flood mitigation options adopted by Royal HaskoningDHV (RHDHV) could also be applied to similar projects around the world.

**Key words:** Flood, Inundation, Flood Defence, Cyclone, Tsunami, Wave, Storm Surge, Sea Level Rise, Numerical Modelling, Royal HaskoningDHV

## 1. INTRODUCTION

### Coastal Population

Cities are built in the coastal areas as this provides opportunities for trade, jobs and transportation. People also live near the coast for recreational purposes such as surfing, sailing, fishing, swimming or walking.

Over 700 million people live in low-lying coastal areas and Small Island Developing States exposed to extreme sea-level events [1]. Approximately 10 per cent of the world's population (more than 600 million people) live in coastal areas that are less than 10 meters above sea level and approximately 40 per cent of the world's population (nearly 2.4 billion people) live within 100 km (60 miles) of the coast [2].

An estimated 11 to 15 per cent of the population of the Small Island Developing States live on land with an elevation of 5 meters or lower and that a sea level rise of half a meter could displace 1.2 million people from low-lying islands in the Caribbean Sea and the Indian and Pacific Oceans with that number almost doubling if the sea level rises by 2 metres [2].

Annually, an average of 21.5 million people have been forcibly internally displaced by sudden weather-related hazards since 2008 [2].

### Flooding in the Coastal Areas

Flooding from cyclones and tsunamis are possibly the most recurrent natural disaster impacting large areas. These are more frequent and with higher intensity due to global warming. The main causes of floods are heavy rainfall and conditions of catchment area, inadequate drainage or breach in flood control structures (such as embankments and levees). Constructions on riverbeds, poor planning and implementation, poor storm-water drainage and sewerage systems are the main causes of urban flooding. Poor permeability of soil causes flash floods because flood water fails to seep down to deeper layers. Rapid urbanization and a growing tourism sector in the regions prone to cyclones and tsunamis are also putting more people at risk.

Between 80-90% of all documented disasters from natural hazards during the past 10 years have resulted from floods, droughts, tropical cyclones, heat waves and severe storms [3]. Floods affected more than 2 billion people worldwide between 1998-2017 [3]. Drowning accounts for 75% of deaths in flood disasters [3]. An estimated 50 per cent of the world's population will live in coastal areas exposed to flooding, storms and tsunamis by 2030 [1].

**Damages from Cyclones**

Cyclones are characterised by destructive winds, storm surges and torrential rain causing massive community disruption. During the last two centuries, cyclones have been responsible for the deaths of about 1.9 million people worldwide [4]. It is estimated that 10,000 people per year perish due to tropical cyclones [4]. Bangladesh is especially vulnerable to tropical cyclones with around 718,000 deaths in the past 50 years [5]. The deadliest tropical cyclone in Bangladesh was the 1970 Bhola Cyclone, which had a death toll of up to 500,000 [6]. At least 138,000 people were killed and as many as 10 million people became homeless during the 1991 Cyclone in Bangladesh [7]. Deaths per year from tropical cyclones globally and at various regions are provided in Table 1 [4]. A list of the deadliest tropical cyclones reported in [6] (sources - NOAA, MDR) is provided in Table 2.

**Table -1 Deaths per year from tropical cyclones [4]**

| Regions | Deaths per year |
|---|---|
| Australia | 5 |
| United States | 25 |
| East Asia | 740 |
| Globally | 10,000 |

**Table -2 List of the deadliest tropical cyclones [6]**

| Rank | Name and Year | Region | Fatalities |
|---|---|---|---|
| 1 | Bhola 1970 | Bangladesh | 500,000 |
| 2 | India 1839 | India | 300,000 |
| 3 | Nina 1975 | China | 229,000 |
| 4 | Bangladesh 1991 | Bangladesh | 138,866 |
| 5 | Nargis 2008 | Myanmar | 138,373 |

**Damages from Tsunamis**

Tsunamis are rare but extremely deadly events. A total of 58 tsunamis have claimed more than 260,000 lives (an average of 4,600 per disaster) in the past 100 years which is more than any other natural hazard [1]. Tsunamis caused more than 250,000 deaths globally between 1998-2017 including more than 227,000 deaths due to the Indian Ocean tsunami in 2004 [8]. A total of 251,770 deaths and US$280 billion financial damage from tsunami events during 1998-2017 have been reported by the United Nations Office for Disaster Risk Reduction [9]. Tsunamis have accounted for almost 10 percent of economic losses over the past two decades setting back development gains especially in countries that border the Indian and Pacific Oceans [1].

As reported in [10], the 1960 Valdivia earthquake ($M_w$ 9.5), 1964 Alaska earthquake ($M_w$ 9.2), 2004 Indian Ocean earthquake ($M_w$ 9.2) and 2011 Tōhoku earthquake ($M_w$ 9.0) are recent examples of powerful megathrust earthquakes that generated tsunamis (known as teletsunamis or distant tsunamis) that can cross entire oceans. The 2004 Indian Ocean tsunami was among the deadliest natural disaster in human history with at least 230,000 people killed or missing in 14 countries bordering the Indian Ocean. The 2011 tsunami in Japan resulted to 15,894 deaths, 6,152 injured and 2,562 people missing. The 2011 tsunami damaged many buildings, dams, bridges, nuclear power stations and many other infrastructures. The World Bank's estimated economic cost due to the 2011 tsunami was US$235 billion, making it the costliest natural disaster in world history. As reported in [11], deaths from the 1945 earthquake in the Makran Subduction Zone that generated tsunamis along the coastlines of Iran and Pakistan were reported to be as many as 4,000 people. Furthermore, the tsunami caused catastrophic damage to properties and other coastal facilities. A list of the top deadliest tsunamis since 1900 reported in [12] is provided in Table 3.

**Table -3 List of the top deadliest tsunamis since 1900 [12]**

| Rank | Year and Name | Region | Fatalities |
|---|---|---|---|
| 1 | 2004 Indian Ocean tsunami | Indian Ocean | 230,210 |
| 2 | 1908 Messina tsunami | Messina, Italy | 123,000 |
| 3 | 2011 Tōhoku tsunami | Japan | 18,550 |
| 4 | 1960 Valdivia tsunami | Valdivia, Chile, and Pacific Ocean | 6,000 |
| 5 | 1976 Moro Gulf tsunami | Moro Gulf, Mindanao, Philippines | 5,000 |
| 6 | 1945 Balochistan tsunami | Arabian Sea, Indian Ocean | 4,000 |
| 7 | 1933 Sanriku tsunami | Sanriku, Japan | 3,068 |
| 8 | 1952 Severo-Kurilsk tsunami | Severo-Kurilsk, Kuril Islands, USSR (Russia) | 2,336 |
| 9 | 1998 Papua New Guinea tsunami | Papua New Guinea | 2,200 |
| 10 | 1946 Nankai tsunami | Nankai, Japan | 1,500 |
| 11 | 1944 Tōnankai tsunami | Tōnankai, Japan | 1,223 |
| 12 | 2006 Pangandaran tsunami | South of Java Island | 800 |
| 13 | 2010 Chile tsunami | Chile | 525 |
| 14 | 1906 Ecuador–Colombia tsunami | Tumaco-Esmeraldas, Colombia-Ecuador | 500 |

**Damages from Flooding**

High water levels during a cyclone or a tsunami may cause floods and submergence of low lying areas and can lead to mudslides and landslides in mountainous areas causing loss of life and property. The resulting floods, standing water and coastal inundation pollute drinking water sources and spread water-borne diseases (such as cholera, typhoid or malaria) leading to outbreak of epidemics. Flooding causes significant loss of life and damages properties, ecosystems, businesses and other coastal facilities.

Damages from flooding also include injuries, chemical hazards, mental health effects, disrupted health systems, facilities and services and damage to basic infrastructure (such as food and water supplies, and safe shelters).

**Applications of Numerical Modelling Results**

Numerical modelling results of cyclones and tsunamis are used for deriving robust design conditions for coastal and marine structures and facilities. The numerical modelling results are also used for emergency planning and decision-making to estimate potential loss of life, damage to properties and marine facilities and to develop rescue and mitigation measures and plan clean-up operations.

**Flood Mitigation Measures**

Flooding can be controlled either through constructing nature based soft defences (such as beach nourishment and beach management using vegetation, sandbags, geo-tubes and sand fences) or by constructing hard defences (such as seawalls, revetments, levees, groynes and breakwaters). Strict implementation of Coastal Zone Regulations, efficient early warning systems and building safe shelters and cyclone/tsunami resistant structures are important mitigation measures to reduce the risk.

**The Present Study**

This paper is based on a confidential seafront development project completed by Royal HaskoningDHV. Initially flood risks from cyclones and tsunamis were assessed. Then cyclone conditions (waves and surge) and tsunami levels were derived at the project site using numerical models. Numerical modelling of wave overtopping (run-up) was carried out using the Amazon model and inland flood inundation modelling was carried out using the MIKE21 Flow Model. Thereafter flood mitigation options were developed to prevent flood water entering the project site.

The methodology described in this paper for inland flood inundation modelling study and development of flood mitigation options adopted by Royal HaskoningDHV could also be applied to similar projects around the world. The key steps adopted in the present study for inland flood inundation modelling study and development of flood mitigation options are illustrated in Figure 1.

## 2. FLOOD RISK ASSESSMENT FOR THE PROJECT SITE AND FLOODING MECHANISM

Literature search was carried out to identify the historical cyclones and tsunamis in the project area. It was found that the project site was affected by cyclones and tsunamis in the past. It has been identified that the front of the project site is at direct risk to flooding from the sea. The back of the site is at risk to fluvial flooding. The two sides of the site are at risk to fluvial flooding as well as flooding from the sea.

## 3. CYCLONE CONDITIONS AT THE PROJECT SITE

The project site was affected by numerous cyclones. However, literature search suggested that the site was worst affected by Cyclone Gonu during 1-8 June 2007. It was a Category 5 cyclone with a maximum 3 minute sustained wind speed of 240 km/h and the lowest pressure of 920 hPa (mbar) [13]. The tracks of Cyclone Gonu is shown in Figure 2 [13].

Data of Cyclone Gonu was obtained from the Joint Typhoon Warning Centre (JTWC) [14]. Wind and pressure fields for Cyclone Gonu were then generated from these data using the MIKE21 Toolbox developed by DHI [15]. Cyclone wave generation and propagation were carried out using the Coupled Model FM developed by DHI [16]. The Coupled Model FM consists of the MIKE21 Spectral Wave (SW) [17] for wave modelling and the MIKE21 Flow Model FM [18] for the tidal modelling. The wave and the tidal models exchange information during simulations as and when necessary and, therefore, provide better prediction. The MIKE21 Spectral Wave model obtains tidal information from the MIKE21 Flow Model and the MIKE21 Flow Model obtains radiation stress from the MIKE21 Spectral Wave model during a Coupled Model simulation.

The MIKE21 Spectral Wave (SW) model simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas. Fully spectral formulation was used with in-stationary time formulation. The higher order numerical scheme was used in the study to improve accuracy in model results. Wave diffraction, wave breaking, bottom friction and white capping were included in the model simulations. Quadruplet wave interaction was also included in the simulations. JONSWAP fetch growth empirical spectral formulation was used.

The MIKE21 Flow Model is based on the numerical solution of the two-dimensional shallow water equations - the depth-integrated incompressible Reynolds averaged Navier-Stokes equations. Thus, the model consists of continuity, momentum, temperature, salinity and density equations.

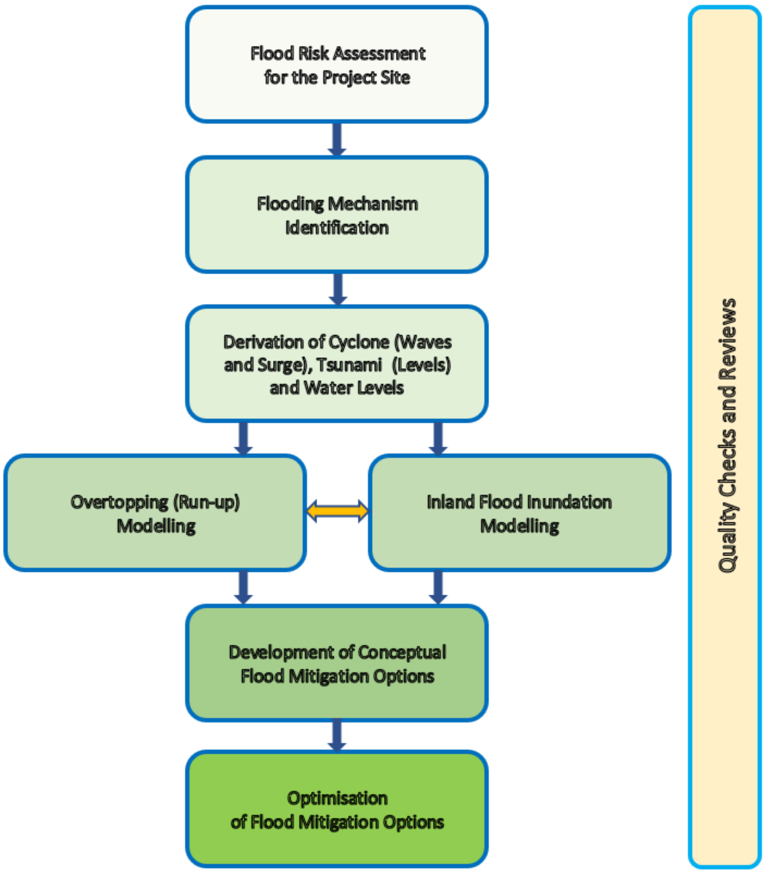


**Fig. 1** Steps in a typical inland flood inundation modelling study

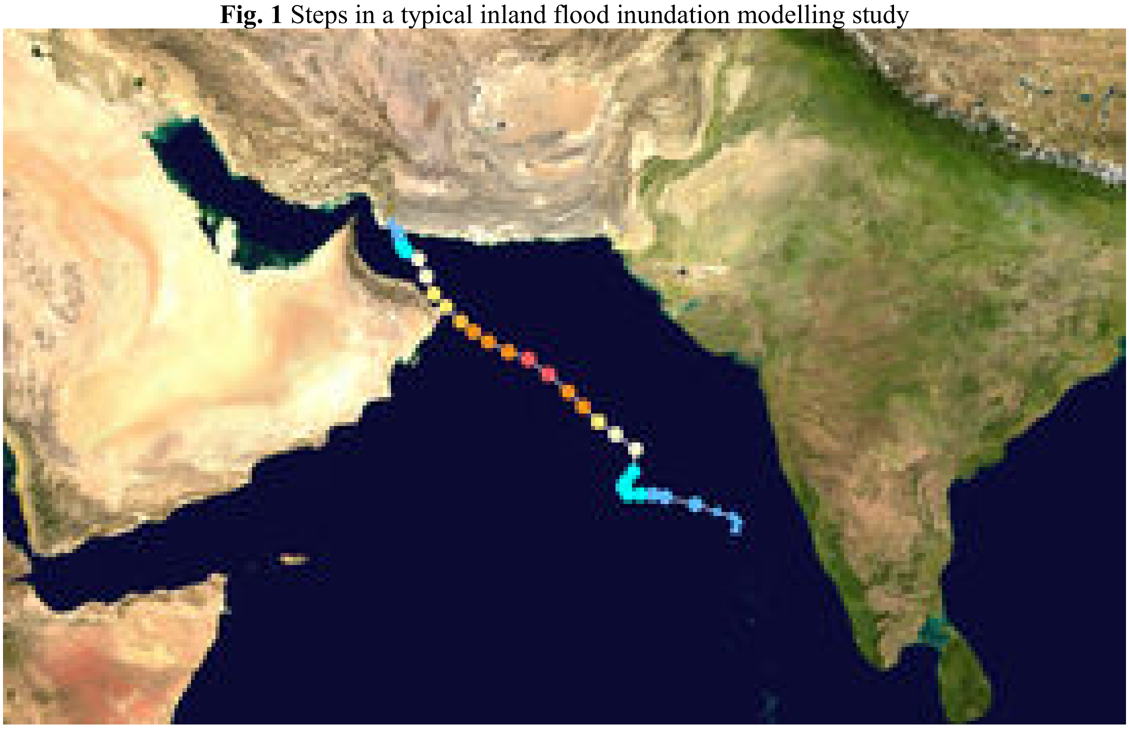

**Fig. 2** Tracks of Cyclone Gonu [13]

Flexible (triangular) mesh was used with variable mesh size distribution to obtain accuracy in the model results. This allows to use fine mesh at the areas of interest and at shallow areas where changes in coastal processes occur quickly and within short distances. A coarser mesh is used for deeper and less important areas which reduces computational time. The bathymetry of the entire model domain was obtained from [19]. Model bathymetry at the shallow waters was obtained from survey data.

Instantaneous waves (heights and directions) and the maximum wave heights from Cyclone Gonu are shown in Figures 3 and 4 respectively. Maximum surge from Cyclone Gonu is shown in Figure 5.

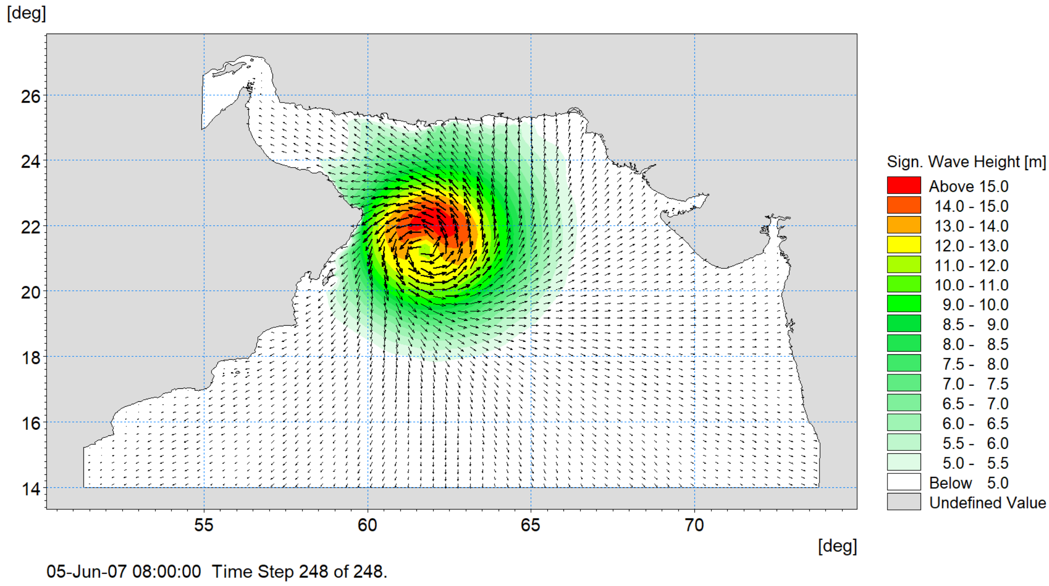


**Fig. 3** Instantaneous waves from Cyclone Gonu

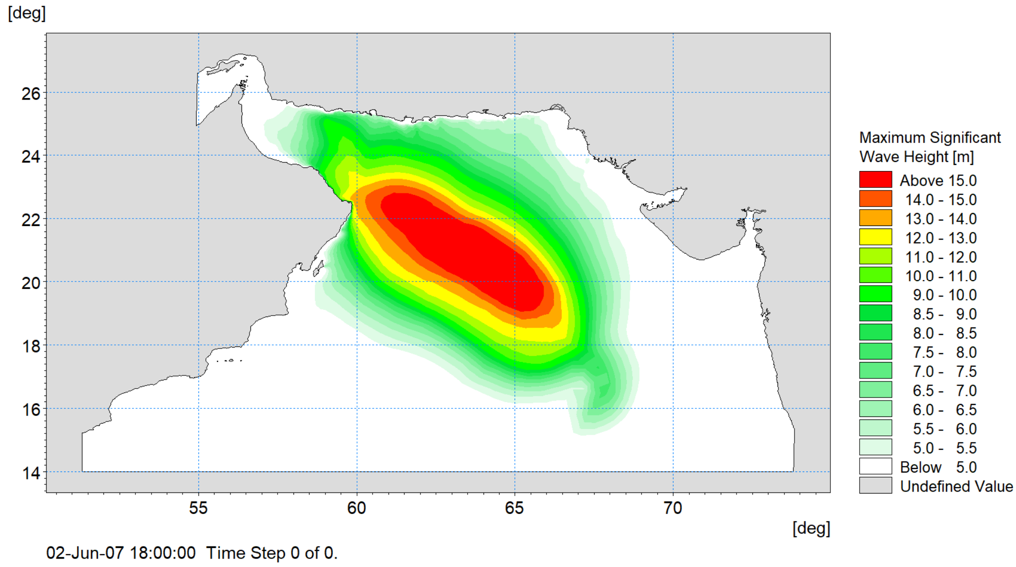


**Fig. 4** Maximum significant wave heights from Cyclone Gonu

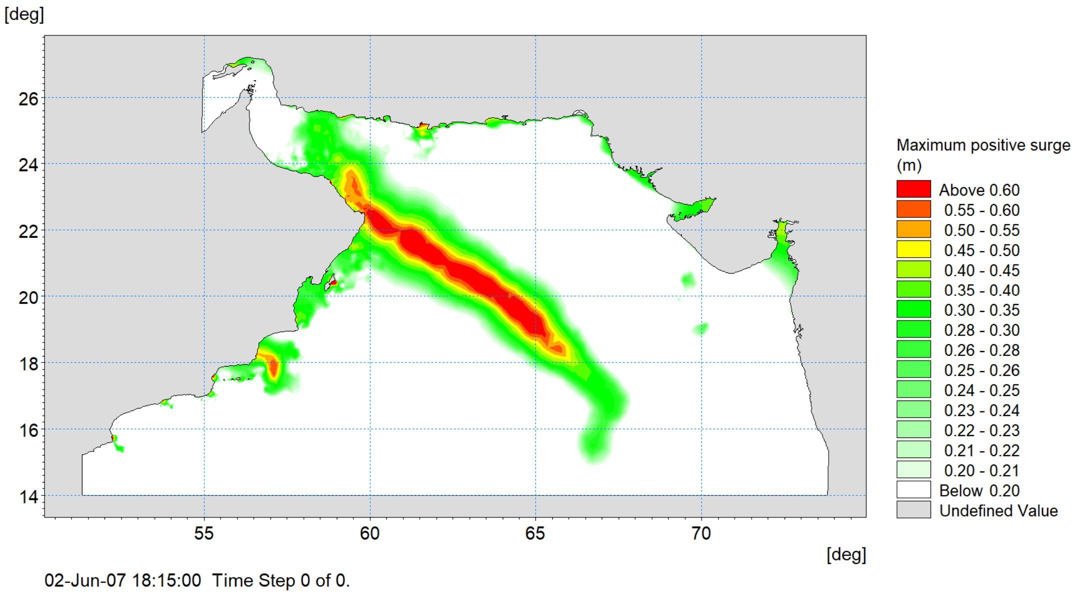


**Fig. 5** Maximum positive surge from Cyclone Gonu

## 4. TSUNAMI CONDITIONS AT THE PROJECT SITE

The project site is affected by tsunamis generated by earthquakes in the Makran Subduction Zone where a major event occurred on 27 November 1945. Initial tsunami levels for 1 in 100 year return period condition (Mw = 8.0) were generated using the MIKE21 Toolbox [15]. The earthquake parameters of the 1945 event obtained from [20] were used to generate these initial tsunami levels. These initial tsunami levels were used to drive the tsunami model. The location of the earthquake was placed on the Makran Subduction Zone but directly in front of the study site to represent the most critical location (the worst case scenario).

The numerical modelling of tsunami wave propagation was carried out using the MIKE21 Flow Model FM [18] to derive tsunami levels at the project site. A flexible (triangular) mesh was used with variable mesh size distribution to obtain accuracy in the model results. Particular attention was given to the project site and around the Makran Subduction Zone. Model bathymetry was obtained from the C-Map Database [19]. The model domain and bathymetry are shown in Figure 6. Time-series of tsunami levels extracted from the model results in front of the project site at various water depths are shown in Figure 7.

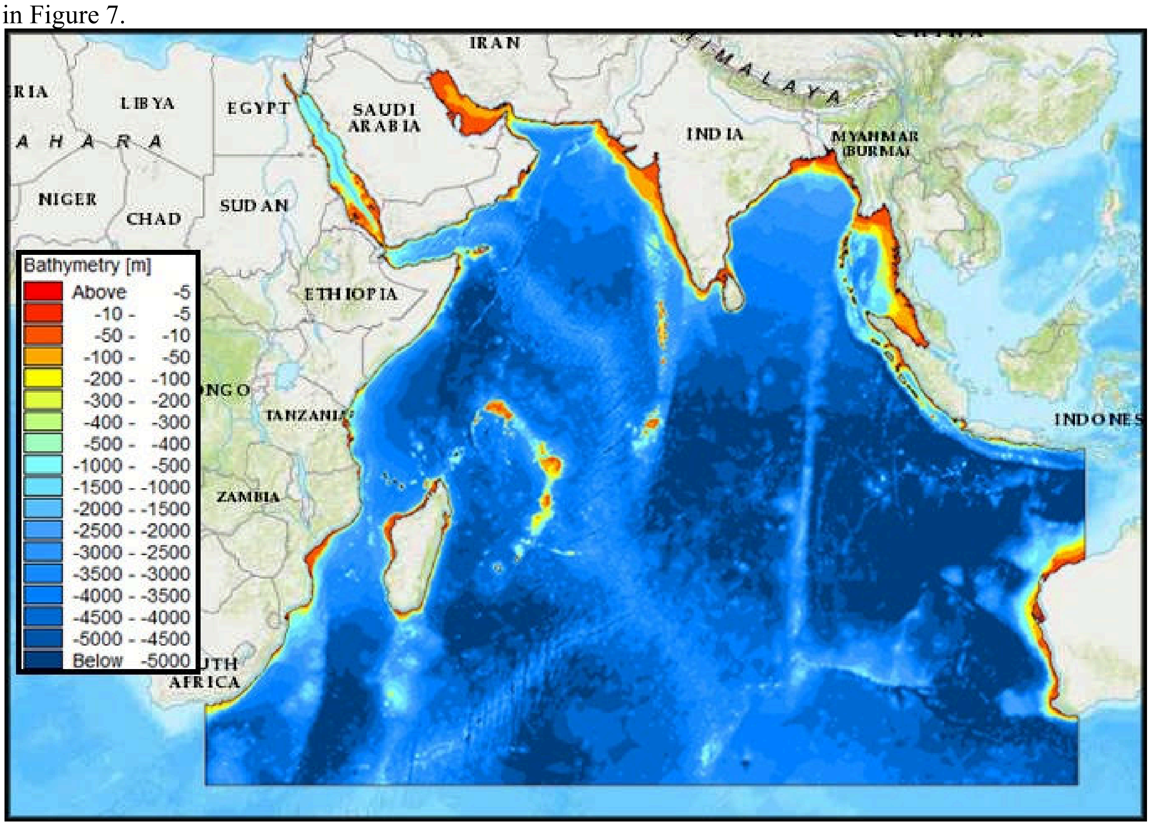


**Fig. 6** Tsunami model domain and bathymetry

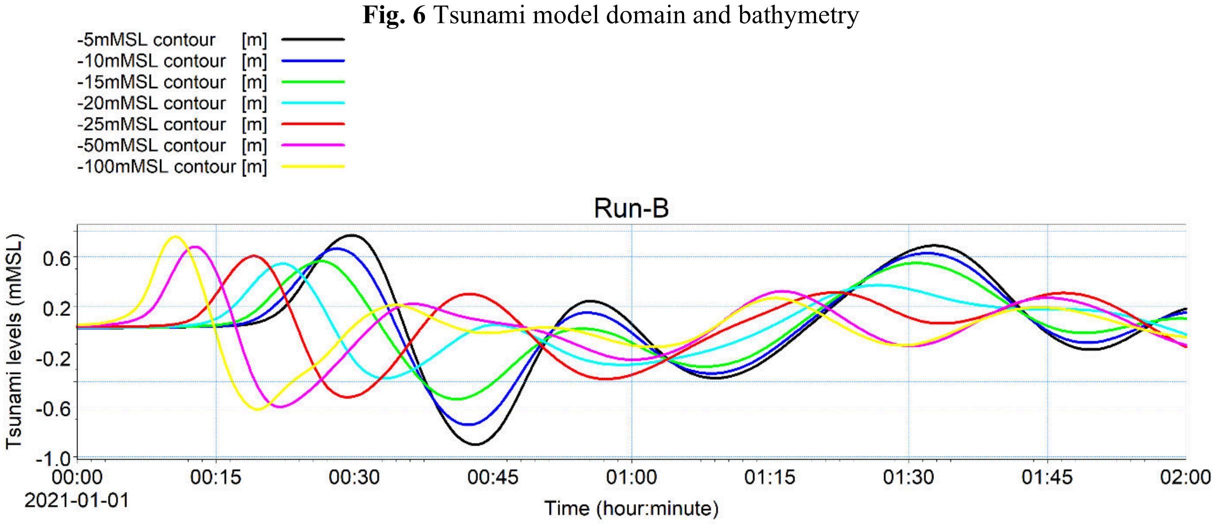


**Fig. 7** Tsunami levels at various water depths in front of the project site

## 5. WATER LEVELS AT THE PROJECT SITE

The study was carried out for three water levels, namely present day water level, 50 year sea level rise and 100 year sea level rise. The astronomical tide levels (e.g. MHHW) were obtained from [21] and the sea level rise was obtained from [22]. Surge from Cyclone Gonu is 0.31m. The water levels for cyclones and tsunamis used in the present study are shown in Tables 3 and 4 respectively.

**Table -4 Water levels for cyclones used in the study**

| Criteria | MHHW | Cyclone Gonu surge | Sea level rise | Total water level |
|---|---|---|---|---|
| Present day | +0.9m MSL | 0.31m | 0 | +1.21mMSL |
| 50 year sea level rise | +0.9m MSL | 0.31m | 0.32m | +1.53mMSL |
| 100 year sea level rise | +0.9m MSL | 0.31m | 0.85m | +2.06mMSL |

**Table -5 Water levels for tsunami used in the study**

| Criteria | MHHW | Sea level rise | Total water level |
|---|---|---|---|
| Present day | +0.9m MSL | 0 | +0.9mMSL |
| 50 year sea level rise | +0.9m MSL | 0.32m | +1.22mMSL |
| 100 year sea level rise | +0.9m MSL | 0.85m | +1.75mMSL |

## 6. OVERTOPPING (RUN-UP) MODELLING

Numerical modelling of wave overtopping (run-up) from cyclones and tsunamis was carried out using the Amazon model [23] to determine the beach crest level required to prevent flood water entering the project site. Amazon is an advanced wave overtopping and run-up model based on solving non-linear shallow water equations. The main advantage of this model is that it can be applied to irregular beach profiles so that nonlinear processes of wave run-up including tsunami wave run-up can be accurately simulated.

Initially the existing (baseline) beach profile was used in the model simulation. Then the beach crest level was raised gradually to stop wave overtopping. Amazon model requires a cross-shore profile. Topography from survey data and seabed levels from C-Map [19] were obtained to prepare this cross-shore profile. The cross-shore profile for cyclones was extended up to -3.7mMSL. The cross-shore profile for tsunamis was extended further (up to -10mMSL) to stabilise the model.

The present day water level and the sea level rises for the next 50 years and 100 years were considered in the modelling study as in Tables 3 and 4. The design life of both 50 years and 100 years were considered for the facilities. The design standard was 1 in 100 year. The input cyclone wave and maximum tsunami level used in the study are provided in Table 5.

**Table -6 Cyclone wave and maximum tsunami level used in the study**

| Criteria | Significant wave height, $H_{m0}$ (m) | Peak wave period, $T_p$ (s) | Maximum levels |
|---|---|---|---|
| Cyclones | 2.50 | 13.0 | - |
| Tsunamis | - | - | 0.70m |

Sample screen shots from overtopping modelling from cyclones and tsunamis are shown in Figures 8 and 9 respectively. Overtopping rates for cyclones and tsunamis are provided in Tables 6 and 7.

**Table -7 Overtopping rates from cyclones (litre/second/metre)**

| Criteria | Baseline profile | +3mMSL beach crest | +4mMSL beach crest |
|---|---|---|---|
| Present day | 15.8 l/s/m | - | - |
| 50 year sea level rise | - | 0.9 l/s/m | 0 l/s/m |
| 100 year sea level rise | - | 8.0 l/s/m | 0.1 l/s/m |

**Table -8 Overtopping rates from tsunamis (litre/second/metre)**

| Criteria | Baseline profile | +3mMSL beach crest | +4mMSL beach crest |
|---|---|---|---|
| Present day | 41.2 l/s/m | - | - |
| 50 year sea level rise | - | 4.7 l/s/m | 0 l/s/m |
| 100 year sea level rise | - | 22.4 l/s/m | 0.5 l/s/m |

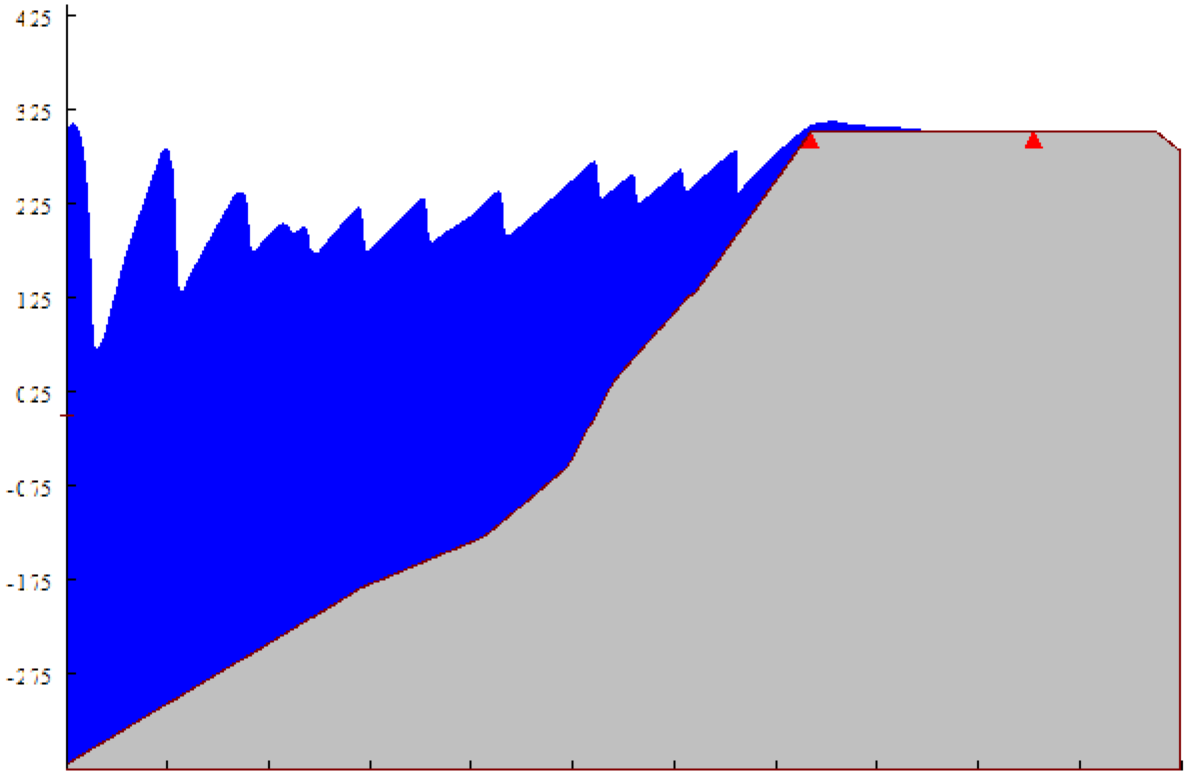

**Fig. 8** Wave overtopping (run-up) modelling for cyclones using the Amazon model

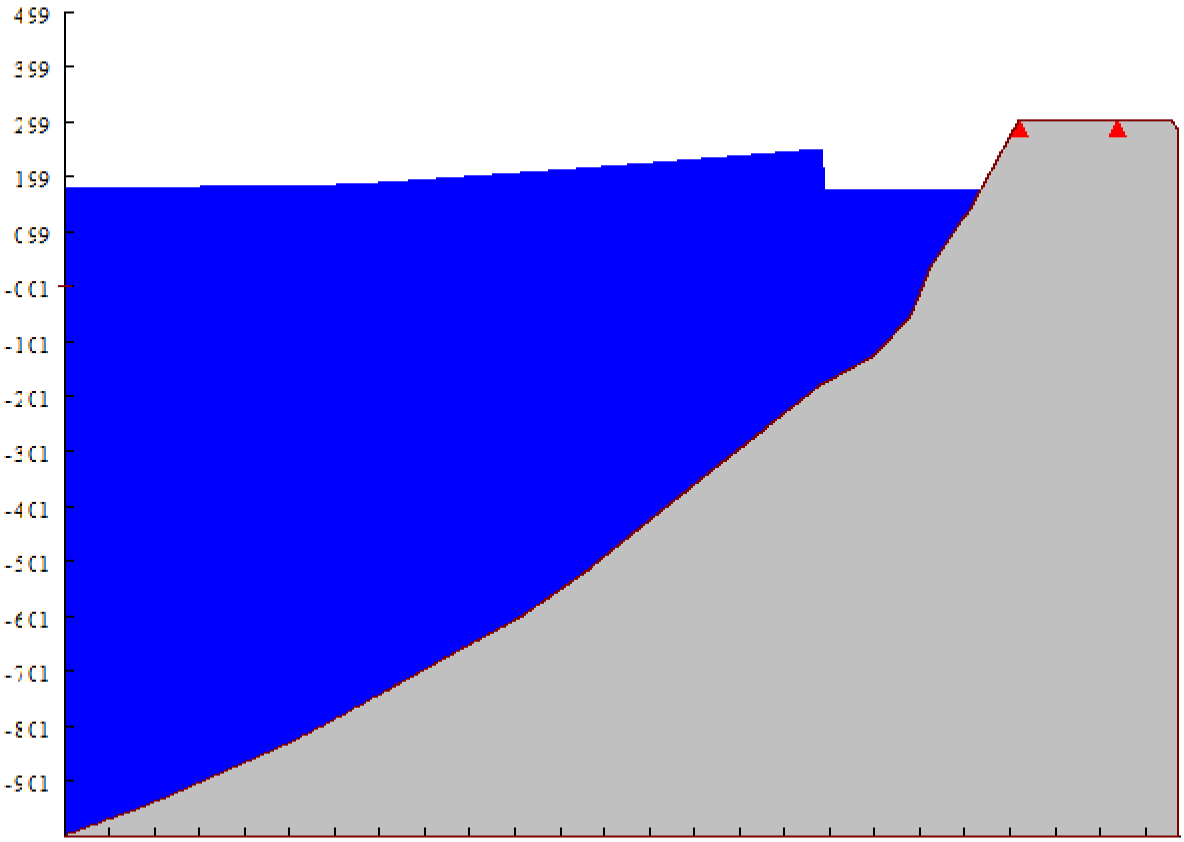

**Fig. 9** Wave overtopping (run-up) modelling for tsunamis using the Amazon model

## 7. INLAND FLOOD INUNDATION MODELLING

Numerical modelling of two-dimensional inland flood inundation modelling was carried out using the MIKE21 Flow Model FM [18] to determine the maximum flood levels around the site from cyclones and tsunamis.

The seaward boundary of the model domain was set at seabed level of -3.7mMSL to allow input water level to be stabilised before reaching the site. The other three boundaries were set at appropriate locations to cover the study site and its neighbouring areas to avoid boundary effects. Topography from survey data and seabed levels from C-Map [19] were obtained to derive the model bathymetry. Flexible (triangular) mesh as explained earlier was used in the model.
The present day water level and the sea level rises for the next 50 years and 100 years were considered in the modelling study as in Tables 3 and 4. The design life of both 50 years and 100 years were considered for the facilities. The design standard was 1 in 100 year. Two-dimensional contour plots of maximum flood levels from cyclones and tsunamis are shown in Figures 10 and 11 respectively. The maximum flood levels from cyclones and tsunamis along a proposed road are provided in Table 8 and shown in Figure 12. Two-dimensional contour plots of maximum total water depths from cyclones and tsunamis are shown in Figures 13 and 14 respectively.

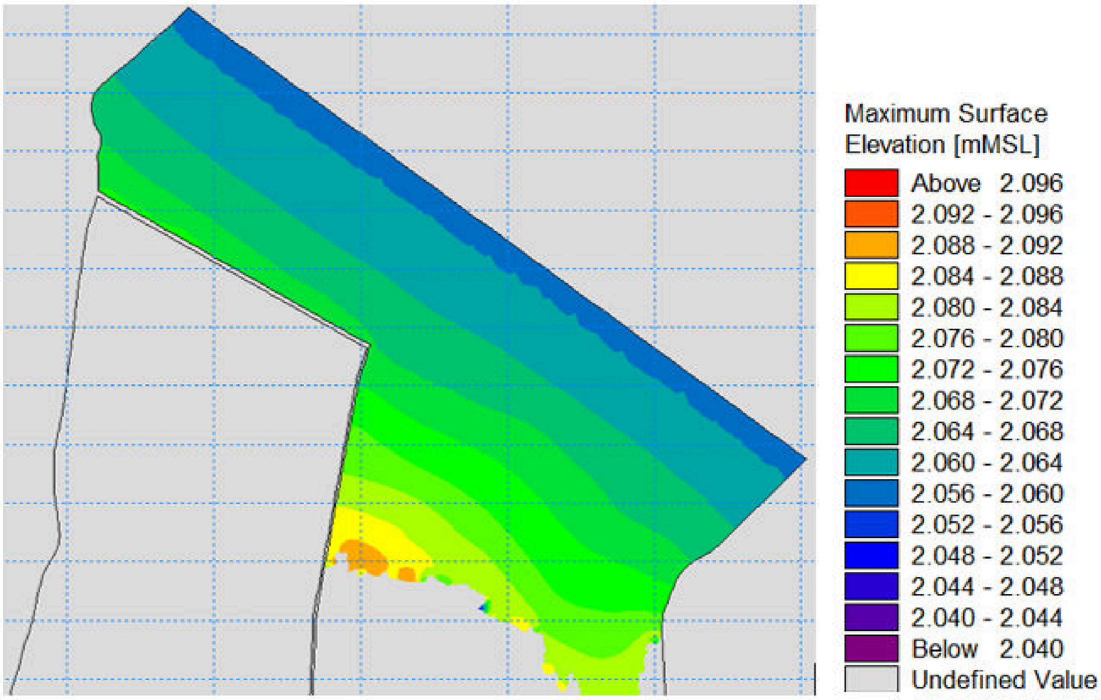


**Fig. 10** Maximum flood levels from cyclones using the MIKE21 Flow Model

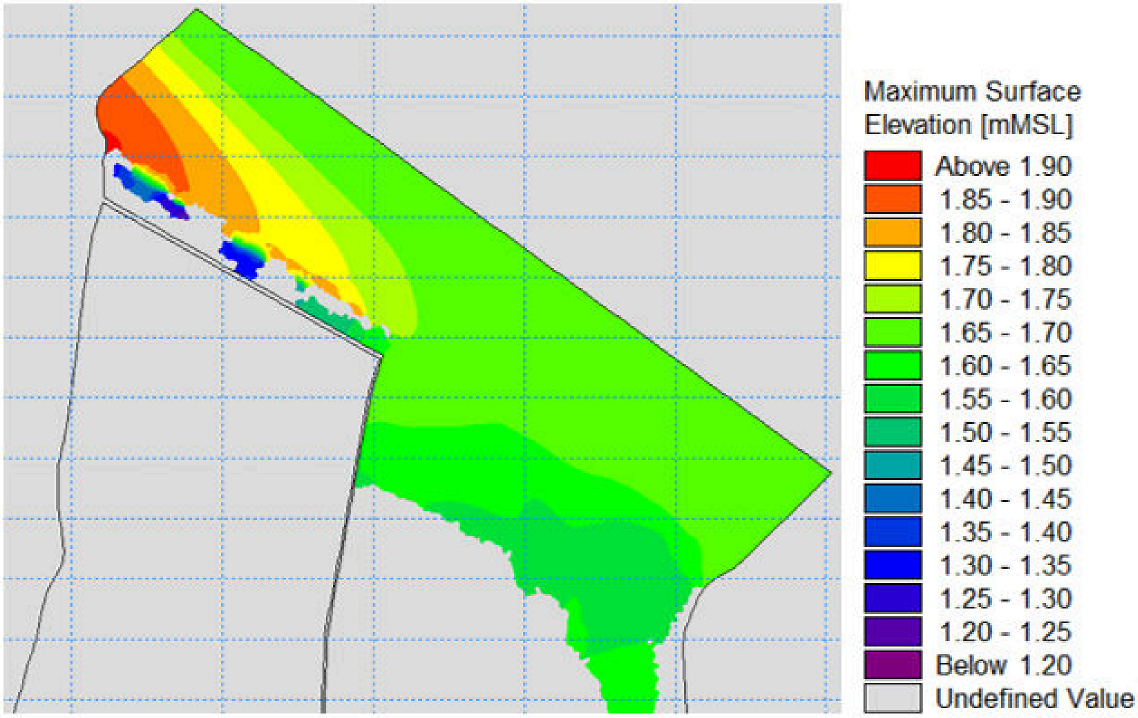


**Fig. 11** Maximum flood levels from tsunamis using the MIKE21 Flow Model

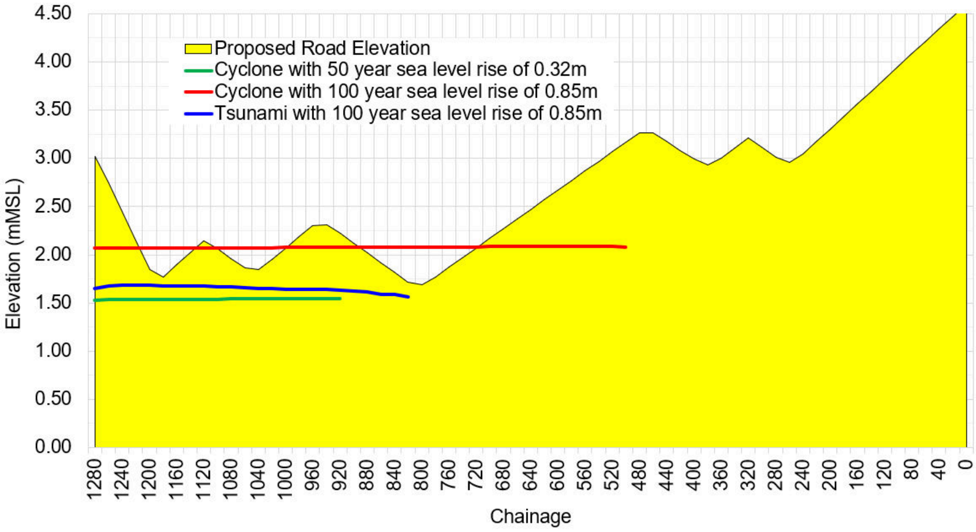


**Fig. 12** Maximum flood levels from cyclones and tsunamis along a proposed road

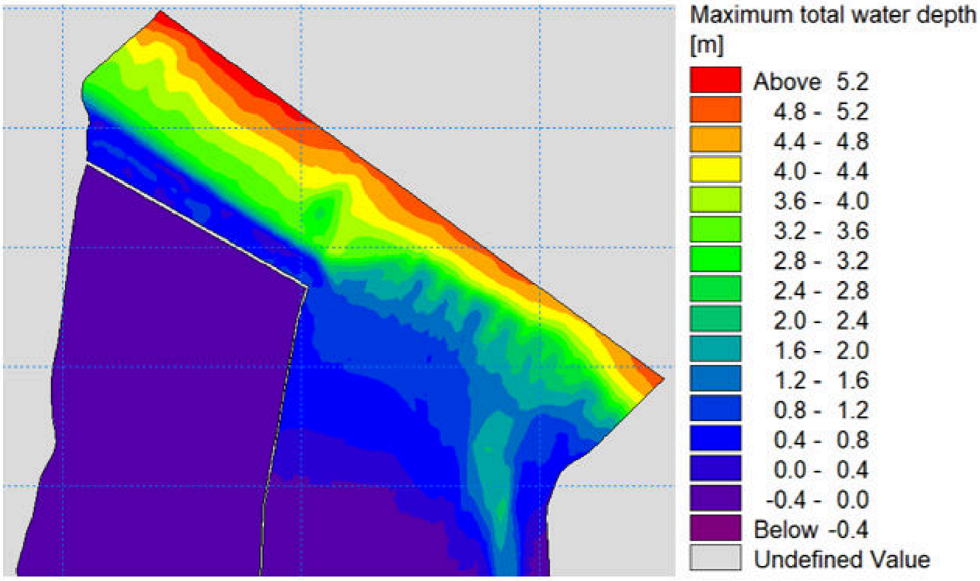


**Fig. 13** Maximum total water depth from cyclones using the MIKE21 Flow Model

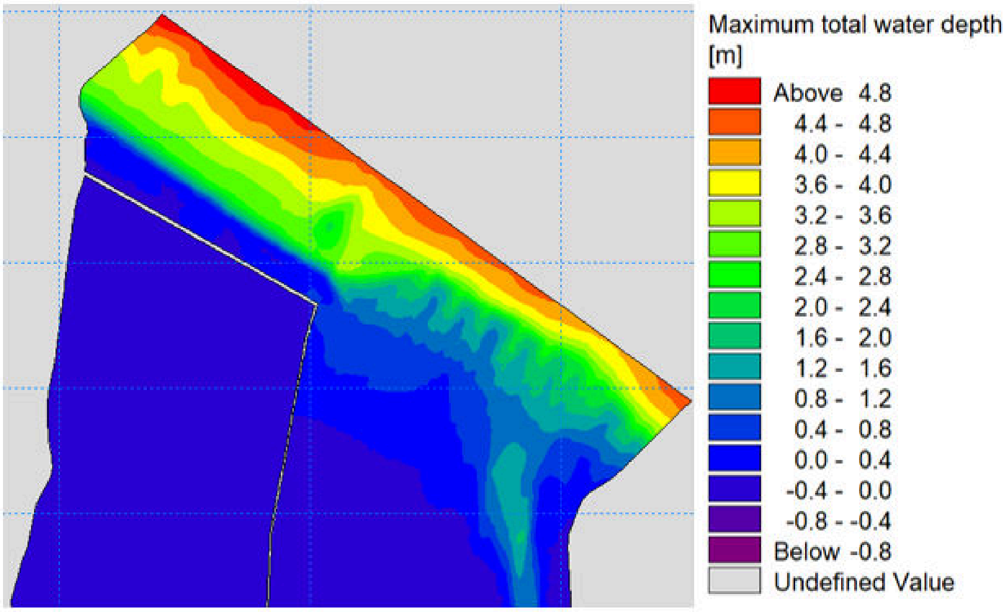


**Fig. 14** Maximum total water depth from tsunamis using the MIKE21 Flow Model

**Table -9 Maximum flood levels from cyclones and tsunamis along a proposed road**

| Sea level rise criteria | Maximum flood levels from cyclones | Maximum flood levels from tsunamis |
|---|---|---|
| No sea level rise | +1.22mMSL | +0.88mMSL |
| 50 year sea level rise | +1.55mMSL | +1.20mMSL |
| 100 year sea level rise | +2.09mMSL | +1.70mMSL |

## 8. DEVELOPMENT OF CONCEPTUAL FLOOD MITIGATION OPTIONS

The numerical modelling results were used to develop the conceptual flood mitigation options. The mitigation option along the coastal frontage consists of raising and widening the beach crest in conjunction with the construction of a "back stop" wave wall and a buried revetment (to protect the wave wall from being undermined). The mitigation options along the other sides of the project site include either constructing low bunds or sheet piling along the outer part of the boundary roads. Figure 15 shows an example of the conceptual flood mitigation options developed to stop flood water entering the project site. This scheme includes sand nourishment, rock revetment and wave wall.

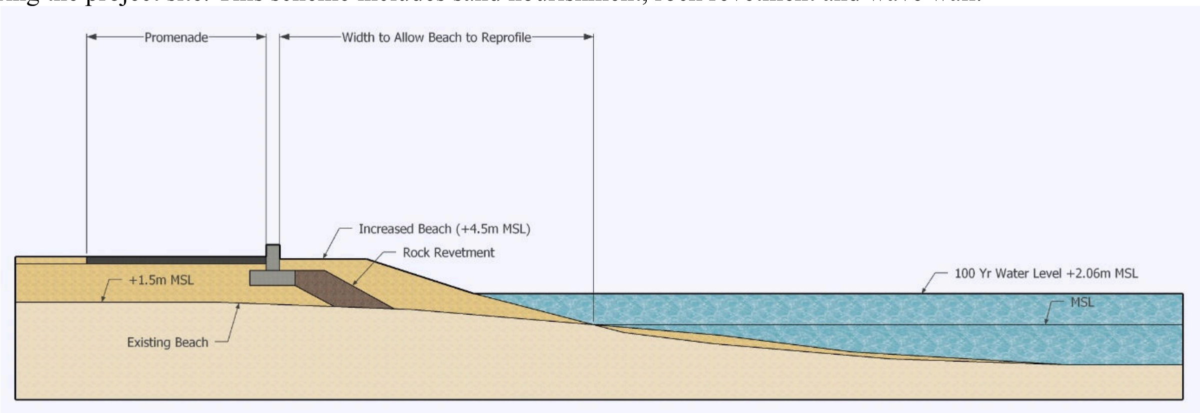


**Fig. 15** An example of the conceptual flood mitigation options

## 9. OPTIMISATION OF FLOOD MITIGATION OPTIONS

The next step will be optimising the conceptual flood mitigation options. This involves finalising the location, length and height of the flood defences. It requires various numerical modelling studies including sediment transport modelling. The sediment transport modelling includes the modelling of cross-shore profile changes and shoreline morphology. Finally, robustness of the preferred layout needs to be examined to investigate the stability of the scheme through sensitivity runs. Such stability tests (sensitivity runs) involve changes in sediment size and impacts of climate change (such as changes in wave direction, sea level rise and storm directions) and long-term performance of the scheme. Laboratory scale physical model tests are required to examine the stability of an important flood defence scheme that protects key infrastructures (such as major cities, nuclear installations and major industries or facilities).

## 10. SUMMARY AND FINDINGS

This paper describes flood risk assessment, deriving of input conditions, overtopping (run-up) modelling, modelling of inland flood inundation, development of conceptual flood mitigation options and finally optimisation of flood mitigation options. Flooding from both cyclones and tsunamis was considered in the study.

It was found that the project site is subjected to flooding from cyclones and tsunamis. Cyclone Gonu was found to be the worst condition for the site. Cyclone waves and surge at the project site were derived using the MIKE21 Spectral Wave model and the MIKE21 Flow Model respectively. Overtopping modelling was carried out using the Amazon model. The existing beach level was initially used in Amazon and then the beach crest level was gradually raised to stop overtopping. The present day water level as well as sea level rises over the next 50 years and 100 years were considered in the study. The design standard was 1 in 100 year. The inland flood inundation modelling was carried out using the MIKE21 Flow Model.

Maximum flood levels from cyclones and tsunamis were predicted using the MIKE21 Flow Model. Then conceptual flood mitigation options were developed to prevent flood water entering the project site.

The methodology described in this paper for inland flood inundation modelling study and development of flood mitigation options adopted by Royal HaskoningDHV could also be applied to similar projects around the world.

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