Modelling of tsunami event caused by Great East Japan earthquake of 2011, including run-up at Fukushima nuclear plants

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Introduction

An analysis route using the three programs OKADA, TSUNWAVE and SWASH has been proposed for tsunami modelling work [7]. OKADA is used to generate the initial seafloor vertical displacement, TSUNWAVE to model wave propagation from the deformed seafloor to near-shore locations, and SWASH to model run-up for coastal land areas. The next stage is to test this analysis route using an actual large offshore earthquake event, the Great East Japan earthquake of March 11th 2011, also referred to in the literature as the Tohoku earthquake and the 'Off the Pacific coast of Tohoku' earthquake of 2011. In this document, the names Fukushima No 1 and Fukushima No 2 are used for the two nuclear power plants in the Fukushima region, these corresponding to the more frequently used names Fukushima Daiichi and Fukushima Daini (Daiichi and Daini mean No 1 and No 2 in Japanese).

An additional objective in the run-up analysis is to test whether it is adequate to use topographic data available in the public domain that is averaged out over a 3 arc second grid spacing, rather than it being necessary to use more detailed topographic data that might be provided by site drawings.

Generation phase

Numerous earthquake source models have been devised to represent the Great East Japan earthquake of 2011. The source selected for this study was devised by Fujii et al [1], and this has the arrangement of sub-faults and slip distribution shown in Figure 1 below.

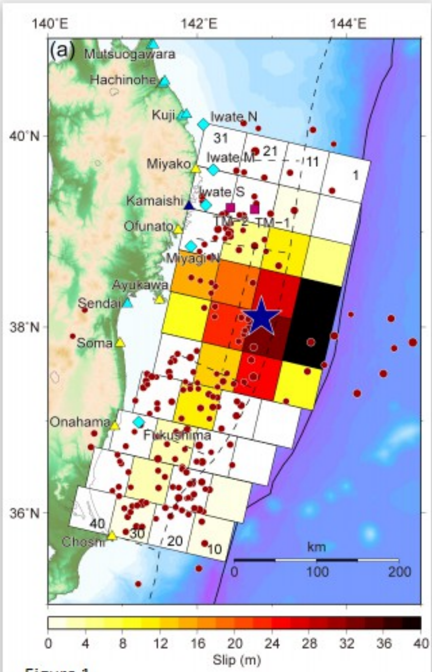


Figure 1

The source consists of forty sub-faults of size 50 km x 50 km, and all the sub-faults have a strike angle of 193°, dip angle of 14°, and rake angle of 81°. The best estimate slip, which acts in a direction along the dip plane at an angle of 112° measured clockwise from North, has a maximum value of 47.93 m and is zero for nineteen of the sub-faults. The eastern edge of the source coincides with the seafloor. The vertical displacement pattern of the seafloor calculated by the OKADA program for the Fujii et al source is shown in Figure 2. The contour plot is produced using the graphics capabilities of the R program, and includes part of the eastern coastline of Japan, together with an asterisk marking the location of the Fukushima No 1 plant. The maximum uplift calculated by OKADA is 12.996 m and the maximum subsidence is 2.15 m.

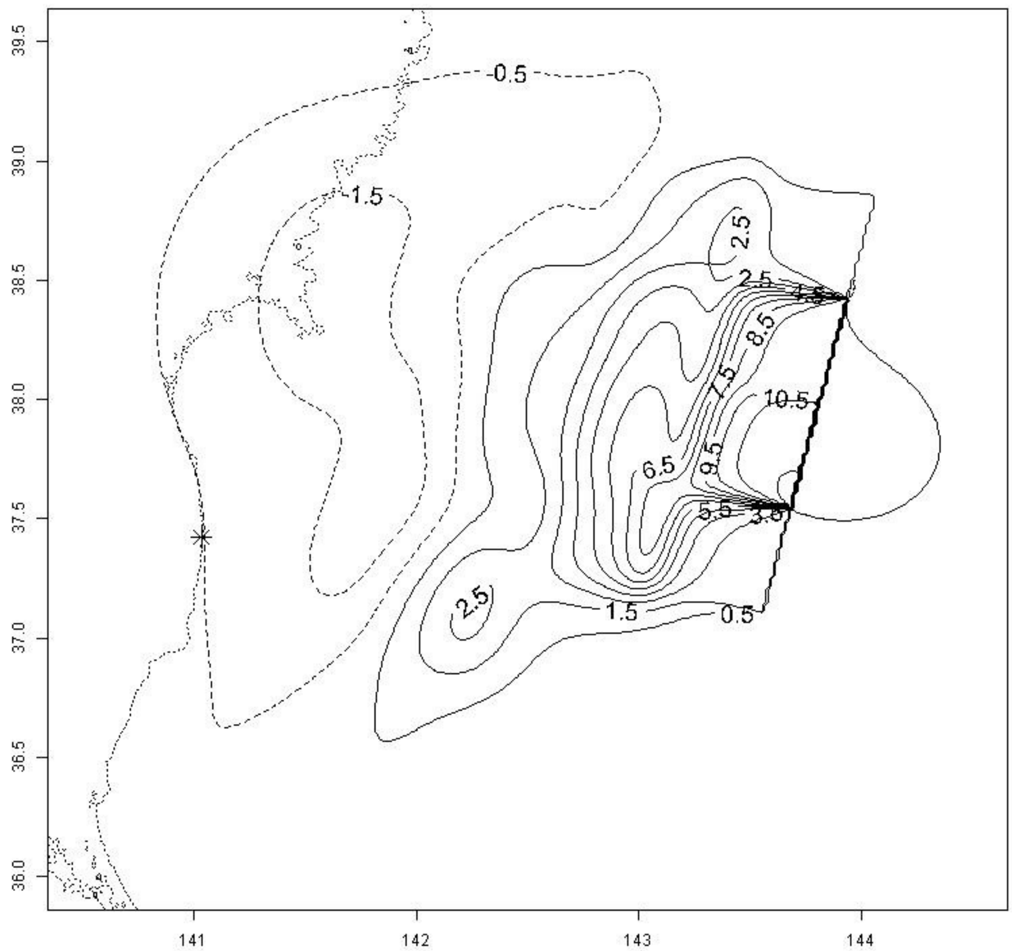


Figure 2

The vertical displacement pattern is assumed in the propagation analysis to occur instantaneously at the start time of the earthquake, 2:46 pm JST (Japan Standard Time). Conceivably there could be some variation in the displacement pattern over the strong motion duration of the earthquake event. An interesting feature of the Great East Japan earthquake was that ground subsidence at the Fukushima nuclear plants appears to have begun a significant time before the earthquake's main vibratory strong ground motion started. In Figure 3 below, the observed tide level at Onahama, a port about 30 miles south of the Fukushima nuclear plants, started to deviate from the astronomical tide level at about 2:00 pm JST, and this apparent rise in the tide level can be attributed to ground subsidence.

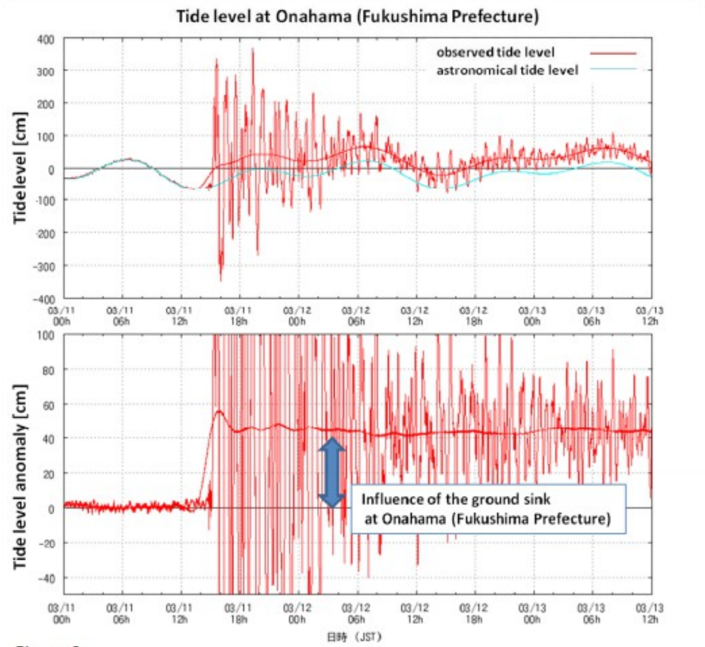


Figure 3

Propagation phase

The propagation analysis phase was carried out using the program TSUNWAVE. Bathymetric and topographic data for the Japan region were downloaded from the NOAA "GEODAS Grid Translator - Design-a-Grid" webpage. The grid data selected was ETOPO1 (1 arc minute x 1 arc minute) in the latitude range 32°N to 46°N and longitude range 138°E to 148°E. This results in a computational model with 505,441 grid cells.

To check that TSUNWAVE performs a satisfactory propagation analysis for tsunami waves, wave height time history results from the model were output at six locations corresponding to the positions of various GPS buoys which are moored at a distance of 10 to 20 km from the Japanese coastline. The measured time history data for the GPS buoys was obtained by digitising graphs available in [2].

The comparison of TSUNWAVE results with measured data for the six GPS buoys is shown in Figures 4a to 4f, and is reasonably good. The time axis in the graphs represents elapsed time in minutes since the start time of the earthquake event at 2:46 pm JST.

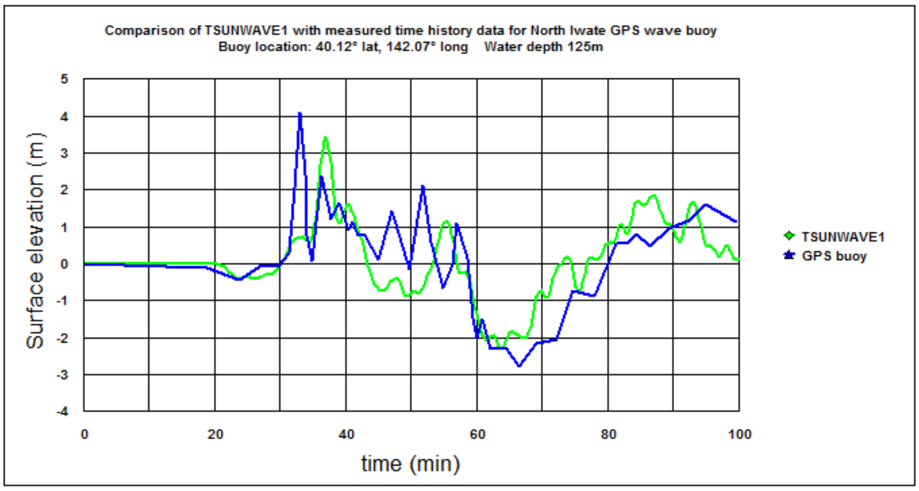


Figure 4a

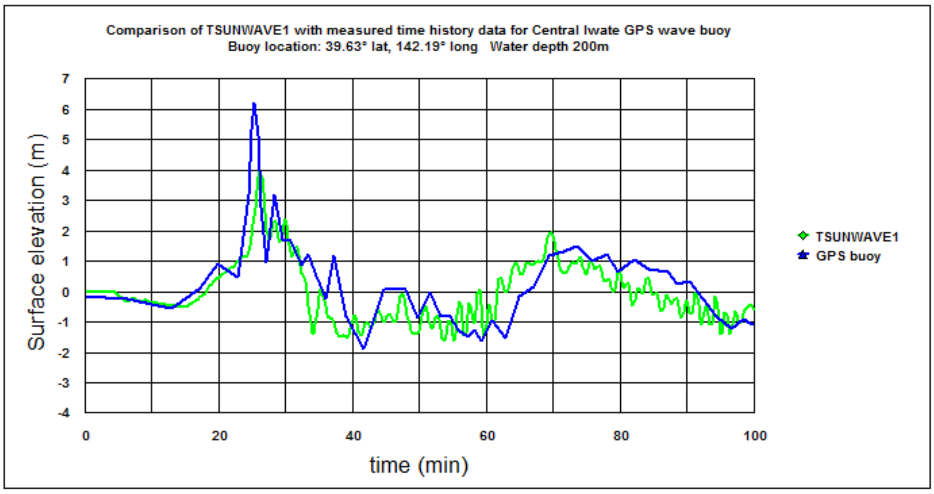


Figure 4b

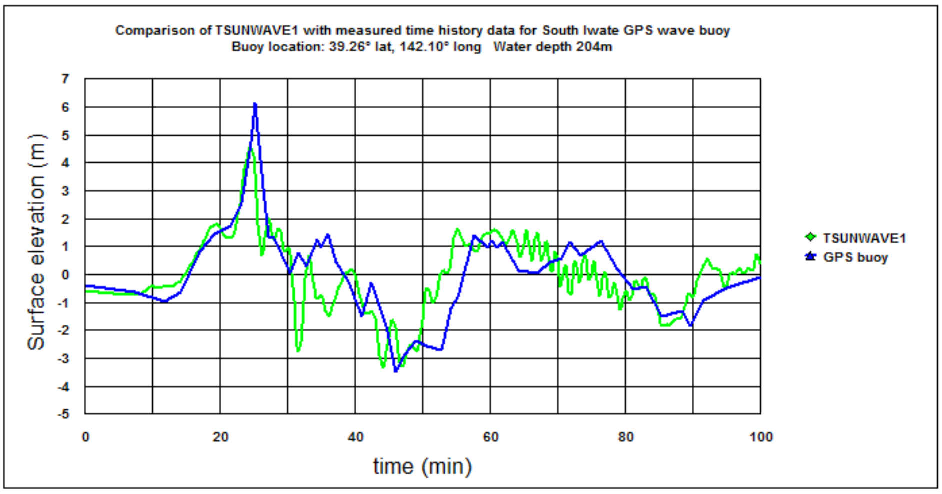


Figure 4c

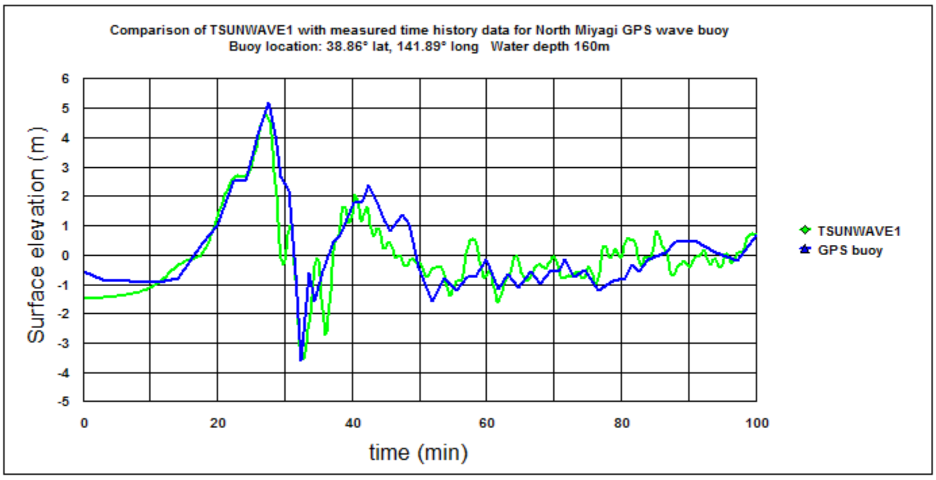


Figure 4d

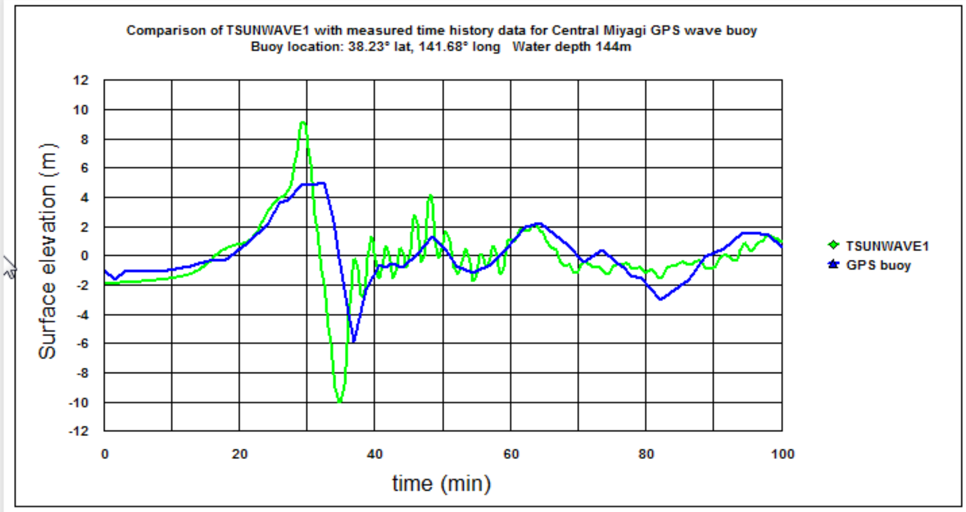


Figure 4e

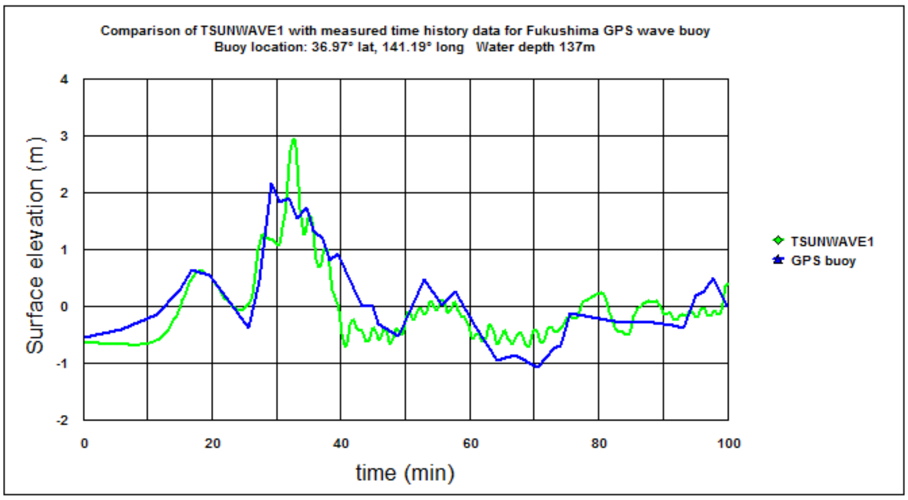


Figure 4f

For a run-up analysis for the Fukushima nuclear plants, it would be desirable to generate wave height time histories that are only a few km distant from the coastline. A measured wave height recording is available, up to the time when the gauge failed (corresponding to the wave height exceeding the gauge limit of 7.5 m), for a location about 1.5 km offshore from the Fukushima No 1 plant. Using information given in TEPCO presentation slides in [3], the location of the seafloor-mounted gauge was estimated as being at 37.4177° latitude and 141.5173° longitude.

The time history obtained from the TSUNWAVE analysis is compared in Figure 5a with both the gauge recording and Japanese analysis results for this location, digitised from graphs in [2]. The Japanese analysis is based on a different earthquake source described as JNES. The pronounced trough in the TSUNWAVE wave height time history at this location is probably associated with the Fujii et al source, as this feature is also noticeable in Figure 4e for the Central Miyagi GPS buoy location. The comparison of time histories in Figure 5a suggests that TSUNWAVE is producing reasonably satisfactory results in a water depth of only 14m using the ETOPO1 grid.

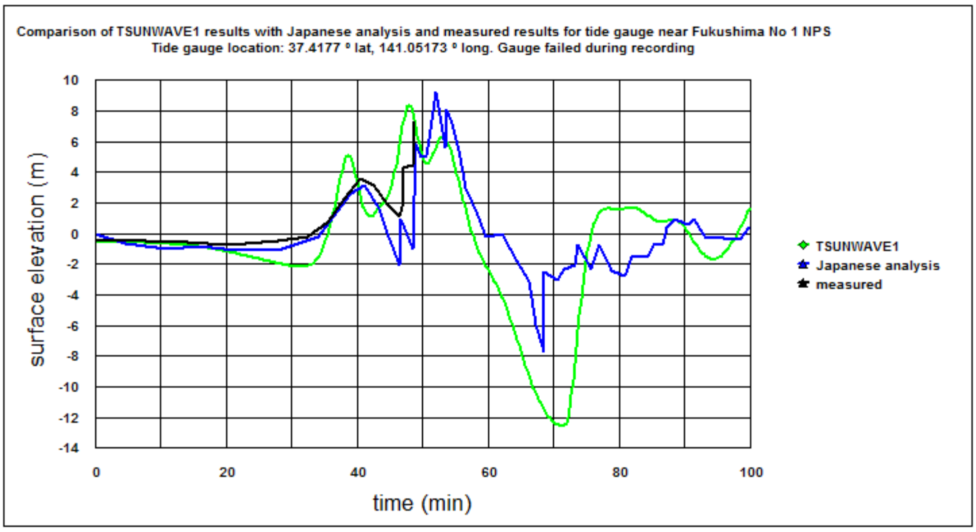


Figure 5a

Another wave height time history was calculated by TSUNWAVE at the nominal latitude of the Fukushima No 2 plant as shown in Figure 5b. This time history is similar to that calculated at the latitude of the tide gauge close to the No 1 plant.

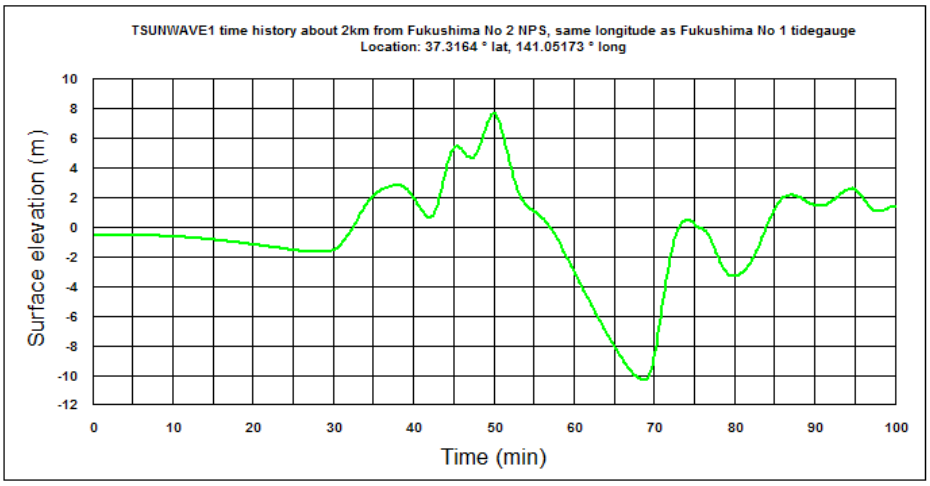


Figure 5b

Figures 5a and 5b represent the input wave height time histories used later in the run-up analyses for the nuclear plants. The input direction of the tsunami wave at the location of the nuclear plants was estimated using a wave height contour plot produced by TSUNWAVE as being at an angle of about 300° measured clockwise from north, which is mainly in the east to west direction.

Inundation phase

Layout of plants

The overall layout of the Fukushima nuclear plant sites is shown in Figures 6 and 7. As the detailed topography of the sites was not known, it was preferred, at least initially, to carry out a transect or 1HD analysis (one horizontal dimension), where the transect is taken as being the 37.423° latitude line for the Fukushima No 1 plant and the 37.3164° latitude line for the No 2 plant, and the tsunami wave is assumed to be travelling in the east to west direction. These two latitude angles, marked on Figures 6 and 7, were supplied by the Google search engine as being the nominal latitude angles for the two nuclear plants.

As-built heights of the harbour walls at the time of the tsunami event are available for most of the walls for the No 1 plant (the heights are included in Figure 6 taken originally from [4]), but no information was available for the harbour walls of the No 2 plant. In the case of the No 2 plant, inundation was limited just to the south side of unit 1, which implies that there was a wall sufficiently tall enough to hold back the tsunami in front of most of the four units of the plant. For the No 1 plant, inundation occurred at all six units of the plant. The substantially taller wall provided in front of units 5 and 6 of the No 1 plant actually failed during the tsunami, but units 5 and 6 were not operating at the time.

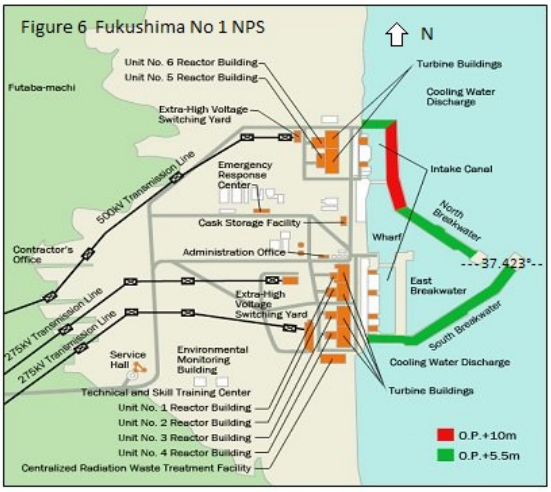
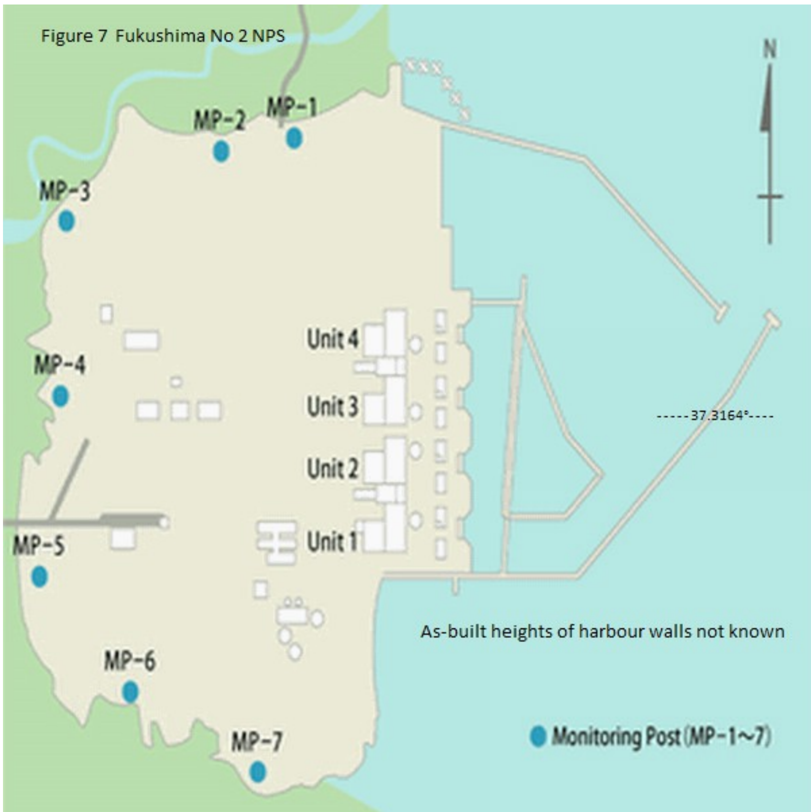


Figure 6 Fukushima No 1 NPS



Determination of transect data

To carry out the inundation analysis, more detailed bathymetric and topographic data is required than provided by the NOAA ETOPO1 grid that was used for the propagation analysis. More detailed bathymetric data, which can be freely downloaded for Japan's coastal areas, is provided by JODC (Japan Oceanographic Data Centre) as the J-EGG500 grid, which has a 500 m spacing for depth values. More detailed topographic data, which can be freely downloaded for Japan and most of the world, is provided by NASA as SRTM3 data (Shuttle Radar Topography Mission), which gives average land elevation values for 3 arc second x 3 arc second grid cells. The J-EGG500 depth data and SRTM3 elevation data is supplied rounded off to the nearest metre.

The combined J-EGG500 and STRM3 grid data is irregularly spaced and this was interpolated to produce regularly spaced depth and elevation values along the transect lines. The calculated transect data for the No 1 and No 2 plants are shown in Figures 8 and 9. The elevation values in the graphs are relative to MSL (mean sea level). The elevation values above sea level include a representation of heights of the power plant buildings rather than being just for bare ground. The harbour areas are not well represented in the transect data, as the SRTM3 data averages out the harbour wall heights over a 3" x 3" region, and there are no J-EGG500 data points for the water inside the harbour areas.

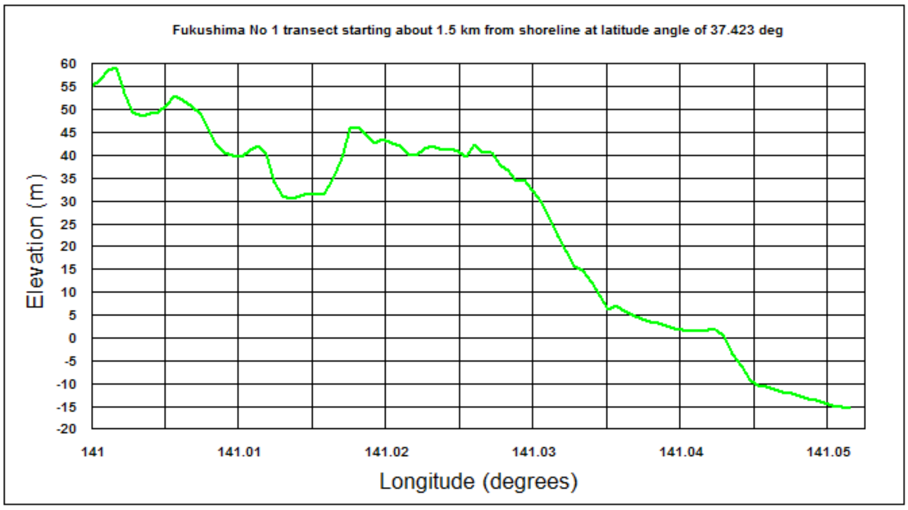


Figure 8

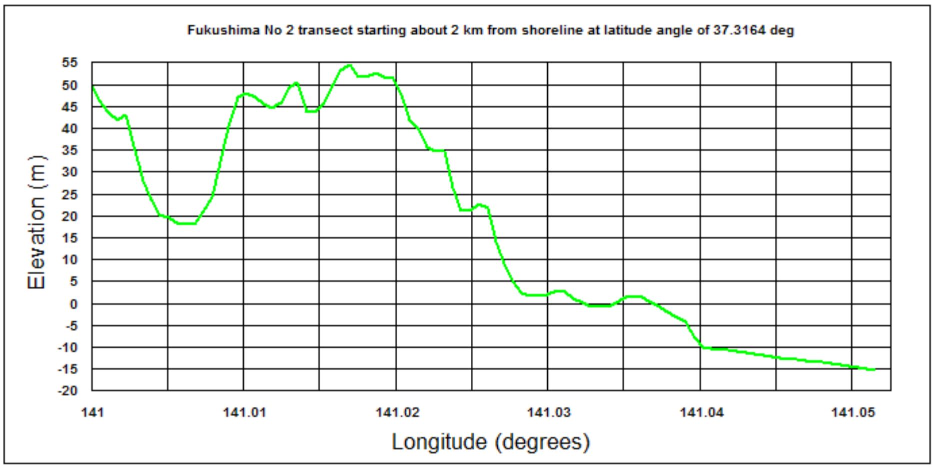


Figure 9

The astronomical tide level at the time of arrival of the tsunami at the nuclear plants was only -0.34 m and this would be counteracted by the tide level appearing to rise due to ground subsidence at the plants of 0.5 m. Therefore it is appropriate to ignore the effect of tide conditions in the run-up analysis.

Comparison of run-up analysis results with TEPCO measured data

SWASH (version 2.00) was used to calculate the amount of run-up at the Fukushima No 1 and No 2 plants. Flood depth time histories were also calculated by SWASH at locations on the transect corresponding to the main power plant site levels, which are shown in Figures 10 and 11. For the No 1 plant, units 1 to 4 are located at the +10m OP level, with units 5 and 6 located at the higher +13m OP level. For the No 2 plant, all units (1 to 4) are located at the +12m OP level. The site level acronym 'OP' refers to 'Onahama Peil', which is a datum understood to correspond to a low tide condition at the main port of Onahama (located about 30 miles south of the nuclear plants).

'Peil' is a Dutch word that has been adopted in Japan which means 'datum'. Mean sea level at the Fukushima plants has been taken to correspond to +0.8m OP.

The SWASH analysis used a 1HD computational grid with a 5 m spacing and adopted a bottom friction value (in Manning's n value form) of 0.03. Manning's n values for tsunami run-up for various coastal terrain conditions are provided in a table in [5]. The terrain condition assumed to be applicable to a nuclear plant was "Average for developed areas (lawn grass up to 5 cm high, gravel, presence of some buildings, houses and other obstructions)", which has an n value range of 0.03 to 0.035. The SWASH analysis was non-hydrostatic and wave breaking effects are automatically included.

Figures 10 and 11 indicate that at the +10m OP, +12m OP and +13m OP site levels, where most of the safety-related buildings are located, the flood depth time histories consist of a small number of surges of tsunami flood water which build up and decay over a duration of about 2 to 4 minutes, and there are intervals where the flood water is not present.

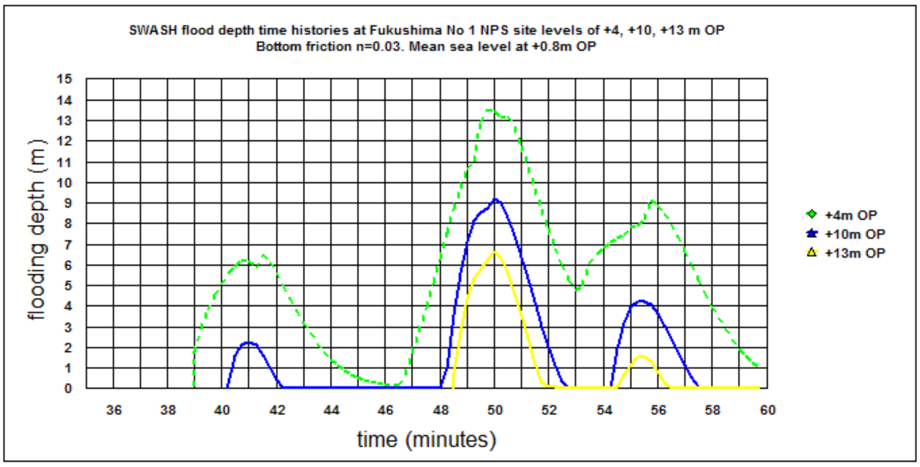


Figure 10

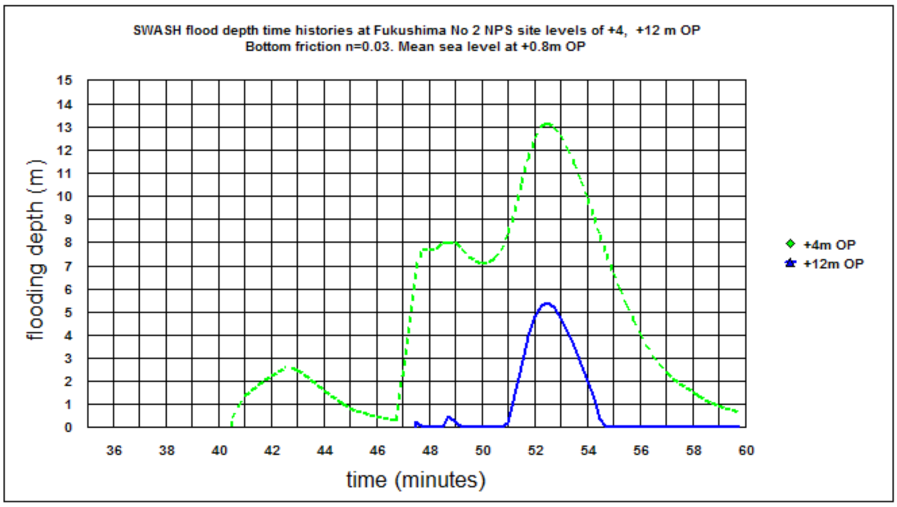


Figure 11

Measured inundation or flood heights and flood depths for the No 1 and No 2 plants are provided in TEPCO's accident analysis report [6]. A measured run-up height range for the No 1 plant is also available in [3]. TEPCO's measured data is based on identifying water marks left on buildings, equipment and sloping ground by the tsunami flood water.

Inundation or flood height refers to the height of tsunami flood water above some datum where the flood water is in contact with a building. Flood depth corresponds to the inundation or flood height minus the ground level for the building. Run-up height is the maximum height above some datum that tsunami flood water reaches before retreating due to gravity.

Table 1 below compares peak flood depths calculated by SWASH in Figures 10 and 11 at the main site levels with TEPCO measured results. Inundation heights (relative to the OP datum) can be obtained by adding the flood depth to the site level.

Plant	Main site level	SWASH peak flood depth	TEPCO measured peak flood depth	TEPCO measured flood depth range
No 1	+10m OP	9.20m	7m	Generally 1.5 to 5.5m, some local areas 6 to 7m
No 1	+13m OP	6.65m	1.5m	Generally 0 to 1.5m
No 2	+12m OP	5.38m	4m	Generally 0 to 2.5m, some local areas 3 to 4m

Table 1 Comparison of flood depths

Table 2 below compares the run-up height (relative to the OP datum) calculated by SWASH for the No 1 and No 2 plants with TEPCO measured results. For the No 2 plant, run-up data appeared not to be available and the measured run-up heights were taken to be the same as measured inundation heights.

Plant	SWASH run-up height	TEPCO measured peak run-up height	TEPCO measured run-up height range
No 1	+20.22m OP	+18m OP	+14 to +18m OP
No 2	+16.47m OP	+16m OP*	+12 to +16m OP*
Table 2 Comparison of run-up heights		* inundation height	

The SWASH 1HD run-up analysis results show conservative agreement with TEPCO's peak measured results for the No 1 and No 2 plant sites. The SWASH peak flood depth result at the +13m OP level for the No 1 plant is substantially higher than the measured peak flood depth, and this discrepancy might possibly be attributed to the +10m OP harbour wall provided in front of units 5 and 6 restraining the flow of tsunami flood water at this part of the site to some extent before the wall failed.

Conclusions

1 The analysis route proposed for tsunami modelling work, which consists of using the three programs OKADA, TSUNWAVE and SWASH, has been tested using the Great East Japan earthquake event of 2011 and appears to give satisfactory results.

2 The study lends support to the idea that tsunami run-up analysis for a nuclear power plant can be carried out using fairly coarse public domain topographic data like NASA's SRTM3 data. It might have been expected that it would be necessary to model the flow paths of tsunami flood water in the street-size gaps between buildings, which would require access to site drawings.

References

[1] Fujii Y, Satake K, Shin'ichi S, Shinohara M, Kanazawa T "Tsunami source of the 2011 off the pacific coast of Tohoku earthquake", Earth Planets Space 63 pp815-820, Sept 2011

[2] “Additional Report of Japanese Government to IAEA - Accident at TEPCO's Fukushima Nuclear Power Stations”, Chapter 2 II.1 “Tohoku District-Off Pacific Ocean Earthquake and Resulting Tsunamis”, 15 September 2011

[3] TEPCO presentation slide document "Tsunami survey results in the NPS and reproduction analysis using tsunami inversion", Tomoyuki Tani, July 2012

[4] "Special report on the nuclear accident at the Fukushima Daiichi nuclear power station", INPO 11-005, Nov 2011

[5] Bretschneider C L, Wybro P G, "Tsunami inundation prediction", Proceedings of 15th Coastal Engineering Conference, 1976

[6] "Fukushima Nuclear Accident Analysis Report", Tokyo Electric Power Company, June 2012

[7] Gardner D J, “Development of tsunami modelling analysis route”, Jan 2015