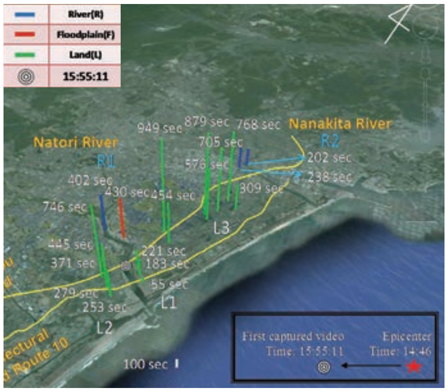

Figure 1: The arrival time at each point is given with the base time beginning at 15:55:11

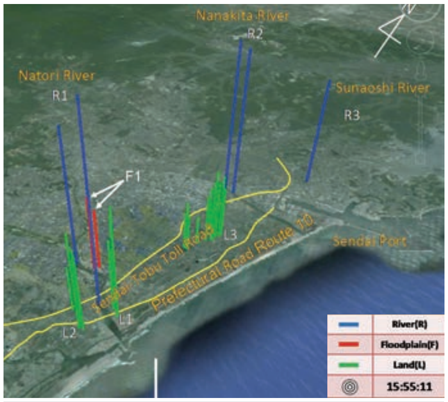

Figure 2: Tsunami celerity, showing that the tsunami travels faster up river than on land

THE PERFECT BORE

Rivers are natural breaches in coastlines, giving a natural path for tsunami waters to flood inland areas. River mouths are often more vulnerable to tsunami than other coastal areas protected by natural dunes, rock promontories and coastal structures. They are difficult to protect, but their critical funneling role is acknowledged in the extent of the inundations, sometimes further aided by the river discharge.

At the river mouth, the leading edge of the tsunami forms a series of waves propagating upriver. This phenomenon is called 'shio-tsunami' (bore), 'kaisho' (tsunami-induced bore) or simply 'tsunami'. After breaking, a tsunami propagating in shallow-waters is led by a bore. The tsunami-induced bore may propagate far upstream. Evidence of this was seen during the Great North East Japan Tsunami. In these rivers and shallow-water bays, the propagation of the bores is associated with strong mixing and massive sedimentary processes upriver.

The transformation of the tsunami into a bore, the location of the bore inception and the upstream propagation of the bore front may be predicted using straightforward shallow water equations.

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The celerity computation based on the equation above does not require the actual time to be in the video. Therefore the recordings at L4, which were omitted from the arrival time analysis, can be used to assess the tsunami celerity. Figure 2 shows the celerity magnitude at several locations based on the video analysis. It clearly shows the celerity differences at each location with different topology and land cover. The video recordings at R2 were obtained from two sources. Nevertheless the analysis results between these videos show no major differences in the celerity magnitude. The average celerity value at R2 is 24.5km/h with a non-biased standard deviation of 0.9km/h. The videos at L2 and L4 were also collected from more than one source. However, they were at different points on land and do not represent the same point. Hence there is no similarity in the result, which may be due to different land cover, topology or other factors.

The result reveals that the tsunami behaved differently in the river and on land; the celerity on land was much lower. In addition the celerity magnitude in the river gradually decreased more slowly than on the land. The celerity in the downstream and upstream areas of the Natori River (R1) shows no major reduction in magnitude although the propagation distance was approximately 3km. This corresponds well with the arrival time analysis, which shows that the arrival time in the river was faster than on the land. Overall, celerity in rivers behaves similarly, with minor differences. The river discharge, size, normal water depth and meanders are some of the factors that may cause these minor differences.

Tsunami trends and course prediction

The video recordings at the Natori River (upstream R1) reveal interesting information about the tsunami propagation in the river. The celerity at R1 is higher than the celerity on the floodplain (F1), which also agrees with the arrival time analysis presented previously. At F1 the river embankment is straight instead of following the curve of the main river. Due to the river meanders, the tsunami intrusion flowed along the curved main channel (A) as well as on the floodplain (B). Due to the difference in roughness (or terrain), a higher magnitude of celerity was found upstream at R1 (21.6km/h) than at F1 (10.7km/h), although R1 is further upstream from the river mouth (4.5km) than F1 (3.7km).

Tsunami propagation over land is affected by the land cover. The flow speed is highly related to surface roughness. In addition flow resistance from debris may have considerable influence on tsunami propagation on land. L4, around Sendai Airport was mostly open and covered with asphalt. Therefore this location had a smooth surface and a lower degree of debris than other locations. These conditions lead to lower flow resistance as reflected in the result from the celerity analysis in Figure 2. Overall the celerity at L4 is higher than at other land locations.

The tsunami celerity was much reduced after flowing over Route 10 at L1. The celerity magnitude before the tsunami reached the road was 15.6km/h. This value was greatly reduced to 9.3km/h after passing the road. This agrees well with the previous analysis of the arrival time.

The video recordings of a tsunami may hold a lot of information about the propagation process. The arrival time, as well as the celerity, of the Great North East Japan Tsunami of 2011 around the Sendai Plain was successfully assessed using video recordings.

Further analysis reveals interesting information about the tsunami propagation process. Propagation in a river is much faster and with higher celerity than propagation on land. In addition the tsunami in a river propagates along the main channel. It was also confirmed that the tsunami propagation on land is highly related to type of land cover. ∎

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