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Research article

Effective tree distribution and stand structures in a forest for tsunami mitigation considering the different tree-breaking patterns of tree species

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ABSTRACT

The effectiveness of coastal forests to mitigate a tsunami has received increased attention. However, many trees are broken, overturned, or washed out in large tsunami events like the 2011 Great East Japan tsunami (GEJT). For quantitatively estimating the advantages and disadvantages of a coastal forest, it is important to reproduce the forest breakage, especially paying attention to the production of driftwood and the trapping ability of standing trees. The objective of this study was to analyze the tree-breaking mode in detail, considering the stand structure of trees, to demonstrate an energy reduction even when trees are broken, and to utilize the information about the breaking pattern to design and manage a coastal forest properly. In this regard, one location, Misawa, the forest of which was affected by the GEJT, was selected for model validation, and coastal forests in two locations, Shiranuka Town and Taiki Town, in Hokkaido, Japan, were selected because a large tsunami is expected to occur there in the future. A numerical simulation of two tsunami magnitudes at the two Hokkaido sites demonstrated that a tree whose crown is far from the ground tends to be broken at the tree trunk. Dahurian larch (*Larix gmelinii*) and Daimyo oak (*Quercus dentata*) tend to be overturned and broken at the tree trunk, respectively. However, the tendency changed with the tsunami magnitude. In addition, even when trees with a dense crown were overturned, they contributed to tsunami resistance to some extent. The fluid force was reduced not only with the forest thickness but also with the tree species and the destruction mode. To maintain the fluid-force reduction and to reduce secondary damage by driftwood, mixed planting is recommended in which tree stand structures are different and large diameter trees at the landward side of forest are planted to trap the driftwood produced from the sea side.

1. Introduction

The 2011 Great East Japan tsunami (GEJT) largely exceeded the designed level of coastal defense. The tsunami extensively destroyed parts of sea walls (tsunami gates, large embankments) (Tappin et al., 2012) and coastal forests (Tanaka et al., 2013), and thus caused catastrophic damage to people and buildings in the Tohoku and Kanto regions of Japan (Udo et al., 2012; Suppasri et al., 2013). After the GEJT, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan classified tsunamis into two types, i.e., Level 1 (L1) and Level 2 (L2). L1 tsunamis are thought to recur at a period of around 100 years, while L2 tsunamis recur over hundreds to a thousand years. The goal of the coastal defense for a L2 tsunami is changed from 'disaster prevention' to 'disaster mitigation'. The method is also changed from 'line defense' to 'compound or hybrid defense' (Strusińska-Correia, 2017; MLIT, 2015; Usman et al., 2014). One of the important lessons of the GEJT is that a coastal forest was not negligible in mitigation of the fluid force of an overtopping tsunami current (Tanaka et al., 2014). The remaining forest also acted to mitigate the tsunami by trapping floating debris (Tanaka, 2012; Pasha and Tanaka, 2016), although the coastal forest was largely destroyed.

Many previous studies recognized again the effectiveness of coastal vegetation for mitigation of water-born disasters like a tsunami by post-disaster surveys after the 1998 Papua New Guinea tsunami (Dengler and Preuss, 2003), 2004 Indian Ocean tsunami (Danielsen et al., 2005; Mascarenhas and Jayakumar, 2008; Tanaka et al., 2007), and the GEJT (Nandasena et al., 2012; Tanaka, 2012; Tanaka et al., 2014), although the effectiveness and limitations had already been discussed in Shuto (1987). Attempts to evaluate the effectiveness of a coastal forest were also conducted by numerical simulations with changing tsunami and

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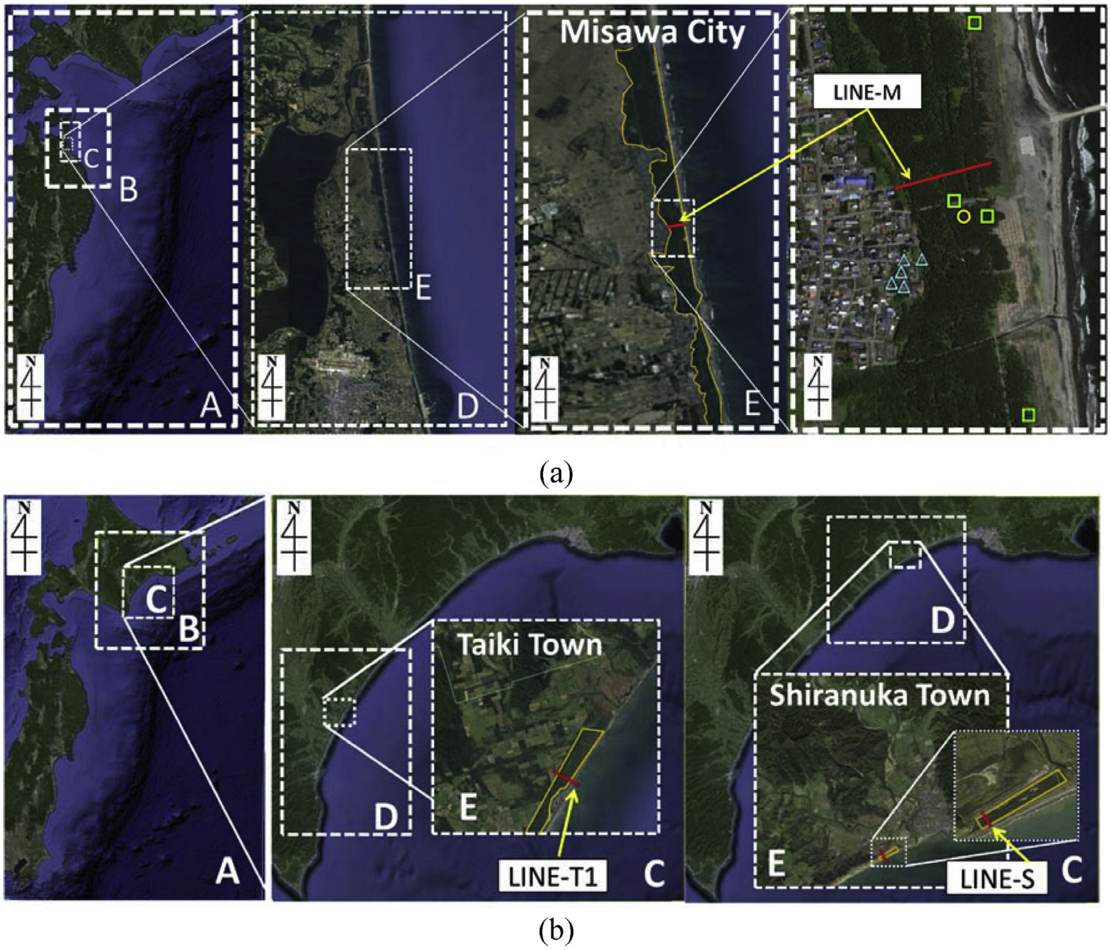

Fig. 1. Definition of the grid system. A: Linear long-wave equations were used, B–D: non-linear long-wave equations were used. E: non-linear long-wave equations with a turbulence model were used. Orange line shows the forest area, and red line shows the line analyzed in detail. Open plots show the locations of tsunami inundation depths obtained by post-tsunami surveys of the 2011 Great East Japanese tsunami. Square: TETJSG (2012), circle: this study (inside forest), triangle: this study (behind forest). (a) Misawa, (b) Shiranuka and Taiki. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

forest characteristics (Hiraishi and Harada, 2003; Harada and Imamura, 2006; Nandasena et al., 2008). The effectiveness of vegetation in not only tsunami but storm surge mitigation was also reported in Vietnam (Mazda et al., 1997) and Bangladesh (Tanaka, 2008). On the other hand, limitations of the tsunami mitigation ability of a coastal forest were also discussed concerning the destruction of the coastal forest itself (Tanaka et al., 2007), the production of driftwood (Dengler and Preuss, 2003; Cochard et al., 2008), channeling of the flow by a gap in a coastal forest (Thuy et al., 2009; Nandasena et al., 2012; Tanaka, 2009; Samarakoon et al., 2013b), and formation of a dangerous zone behind the forest (Iimura and Tanaka, 2013).

Not only field surveys but also physical experiments and/or numerical simulations indicated the effectiveness of vegetation for decreasing the run-up heights of a tsunami (Irtem et al., 2009; Ismail et al., 2012), and reflection and transmission of a solitary wave (Huang et al., 2011). Most of the experiments were conducted using only a simplified tree model (circular cylinders) as the physical model of a coastal forest, although a post-tsunami survey after the GEJT demonstrated the importance of the tree crown by showing the difference in damage depending on whether the tsunami height exceeded the crown height or not (Sato et al., 2012).

When a large tsunami attacks a coastal forest, many of the coastal trees are broken or overturned. To estimate the effectiveness, it is important to reproduce the tree breakage numerically. Although previous studies indicated the importance of considering the tree stand structure, including crown height, and two important breaking modes (Tanaka et al., 2013, 2015), not many studies paid attention to the crown structure of real trees.

Moreover, Tanaka and Ogino (2017) directly compared the advantage (reduction of fluid force) with the disadvantages (production of driftwood and secondary damage due to the impact force on buildings) at their study site and concluded that the impact force of driftwood was smaller than the reduction of the tsunami fluid force. Tanaka and Onai (2017) further demonstrated that the shielding effect by trapping was large and continued far inland, and that some houses remained standing just behind the forest because the remaining standing trees trapped driftwood. From that point of view, it is very important to quantitatively estimate the effects of the arrangement of a coastal forest because a coastal forest has quite different effects regarding whether it can withstand and trap driftwood or not. A large tsunami can destroy trees by many modes (Tanaka and Yagisawa, 2009), although most are bent (Tanaka et al., 2011, 2013). Thus, tsunami mitigation effects and limitations (destruction and production of driftwoods) should be clarified for the proper establishment and management of a coastal forest for tsunami risk reduction.

Therefore, the specific objective of this study was to 1) develop a model that can analyze the tree-breaking mode in detail considering the stand structure of the trees (i.e., tree height, crown height, projected area of crown and trunk, and drag characteristics of leaves), 2) establish an effective coastal forest structure that produces less driftwood and