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Development of a warning model for coastal freak wave occurrences using an artificial neural network

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ABSTRACT

The potential for coastal freak waves (CFWs) represents a threat to people living in coastal areas. CFWs are generated via the evolution of a wave and its interactions with coastal structures or rocks; however, the exact mechanism of their formation is not clear. Here, a data-driven warning model based on an artificial neural network (ANN) is proposed to predict the possibility of CFW occurrence. Seven parameters (significant wave height, peak period, wind speed, wave groupiness factor, Benjamin Feir Index (BFI), kurtosis, and wind-wave direction misalignment) collected prior to the occurrence of the CFW are used to develop the model. The buoy data associated with 40 known CFW events are used for model training, and the data associated with 23 such events are used for validation. The use of data obtained during the 6-h period prior to CFW occurrence combined with the same amount of non-CFW data is shown to produce the best model. Two validations using media-published and camera-recorded CFW events show that the accuracy rate (ACR) exceeds 90% and the recall rate (RCR) exceeds 87%, demonstrating the accuracy of the proposed model. This warning model has been implemented in operational runs since 2016.

1. Introduction

An oceanic freak wave is a suddenly appearing, unexpected wave in the open sea. Such waves can cause shipwrecks. Hazardous waves of this type may also occur in coastal areas, where they can be disastrous for those on the shore, including individuals who may be fishing at breakwaters or along rocky shores. The coastal freak wave (CFW) is a phenomenon in which a large amount of splash water is generated due to the interaction between shoaling waves and coastal structures such as breakwaters, armor blocks and rocks. A CFW may occur even when the sea is calm and in the absence of significant preceding phenomena. In Taiwan, especially along its northeastern coast, people are frequently hit by these unpredictable CFWs. Local media and fishermen in Taiwan call this type of dangerous wave a "mad-dog wave", a term that emphasizes its unpredictability. A photograph of a typical CFW is shown in Fig. 1.

An oceanic freak wave is common defined by two quantitative criteria ($H > 2H_s$ or $\eta_c > 1.25H_s$), where H is the individual wave height, H_s is the significant wave height, and η_c is the height from the mean sea level to the wave crest over a time series of finite duration 20 min. They were proposed by Dysthe et al. (2008) used for typical wave conditions for North Sea. Wave-wave interaction has been proven to be one of the mechanisms for the occurrence of oceanic freak waves (Janssen, 2003; Dysthe et al., 2008; Kharif et al., 2009). However, a quantitative definition of a CFW is still lacking because this type of wave involves complicated interactions among waves, structures and people.

Academic articles on CFW are rare compared to studies of oceanic freak waves (Mori et al., 2002; Guedes Soares et al., 2004; Dysthe et al., 2008; Kharif et al., 2009; Veltcheva and Guedes Soares, 2012, 2016; Mori, 2012; Cavaleri et al., 2012; Fedele et al., 2016). One of the reasons for this is that CFWs are not easily recorded by scientific instruments. However, CFWs have been reported worldwide (Didenkulova et al., 2006; Kharif et al., 2009; Didenkulova and Andersen, 2010; Nikolkina and Didenkulova, 2011). Chien et al. (2002) assumed that the freak waves that occur in the coastal ocean and at the coast are both CFWs, which is not entirely consistent with the definition of CFW employed in this study. Those authors studied 140 accidents associated with CFWs reported in Taiwanese newspapers from 1949 to 1999. These events caused 35 shipwrecks and left more than 500 persons injured or dead. Tsai et al. (2004) suggested that the generation of CFWs is associated with typhoons and winter monsoons, and they found that the presence of grouping waves is highly correlated with the occurrence of CFWs. Moreover, they observed three successive waves

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Fig. 1. An actual photo of a typical coastal freak wave.

with similar periods when CFWs occur. Some researchers (Zhao et al., 2014; Deng et al., 2016; Tang et al., 2016; Qin et al., 2017) have begun to consider the impacts of these rare but extreme waves on coastal and ocean construction. The mechanism of CFW occurrence is still unclear, and human activities in coastal areas still carry inherent risks. This paper describes the development of an early warning model that can be used to mitigate threats due to such dangerous waves.

Because the mechanism of CFWs is not yet understood, deterministic predictions are not possible in this phase; hence, a stochastic approach is employed in this study. An artificial neural network (ANN) is used to develop a CFW warning model. An ANN is a type of data mining technique that is designed to mimic biological structures and features. The greatest benefit of an ANN is its ability to organize fuzzy information associated with complicated interrelations or unclear functional relations. ANNs are frequently used to address complicated problems of coastal engineering such as tide level forecasting and compensation, storm surge forecasting, typhoon wave height prediction, etc. (Deo et al., 1999, 2001; Tsai and Lee, 1999; Lee, 2006; Makarynska and Makarynskyy, 2008; de Oliveira et al., 2009; Deo, 2010; Chang et al., 2011; Bernier and Thompson, 2015; Hashemi et al., 2016). Thus, the use of an ANN to develop an early warning model to mitigate the risks associated with natural hazards is not a novel concept. For example, an early warning system for earthquakes was developed by Böse et al. (2008); their results provided highly accurate predictions of real earthquake events. An early warning system for tsunamis has also been established using an ANN (Romano et al., 2009; Mase et al., 2011); this ANN-based warning system not only forecasts the occurrence of a tsunami but also predicts the tsunami's level and arrival time. In addition, Chang et al. (2007) and Kung et al. (2012) built an ANN-based warning system for debris flow; their results show a 70% accuracy rate for the debris flow warning system. Thirumalaiah and Deo (1998) and Sunkpho and Ootamakorn (2011) used an ANN to predict floods in urban areas. López et al. (2012) connected such a warning system to personal communication devices to communicate flood warnings as rapidly as possible. These previous studies show that ANNs are widely used to establish warning systems, especially for potential natural disasters. This paper describes the development of an early warning model for CFWs using an artificial neural network; the physical mechanisms underlying CFWs are not discussed.

2. ANN model

2.1. Artificial neural network

ANNs were inspired by biological systems and are designed to mimic the structure and function of the human brain. Much like a human brain, an ANN is able to learn and generalize from experience. The structure of a typical ANN is shown in Fig. 2. An ANN is composed of a number of interconnected computational elements called neurons or nodes. Each node receives an input signal from an input layer, and this signal is then multiplied by a given weight, summed, and fed into the next node with this added bias. The signal is then passed on to the hidden-layer nodes, which provide an output signal through a (generally) nonlinear transfer function. The concept of artificial neurons was first introduced by McCulloch and Pitts (1943). However, the presentation of a back-propagation algorithm by Rumelhart et al. (1986) made possible numerous applications of this concept. Currently, a major application of ANNs is forecasting. Several distinctive features of ANNs make them valuable and attractive for forecasting tasks. Zhang et al. (1998) noted some advantages of ANNs. Compared with traditional statistical methods, an ANN is a data-driven self-adaptive method. Hence, ANNs are well suited for application to problems that involve abundant descriptive data or observations but whose solutions require knowledge that is difficult to quantify. An ANN can often correctly infer the unseen component of a problem after learning from the data even if the input data contain noisy information. In addition, ANNs