Major Inundation and Erosion Disasters in China' s Coastal Zone and Mitigation Strategies (Postprint)

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Abstract

China is a major maritime nation possessing a mainland coastline of 18,000 kilometers, characterized by high coastal population density, dense distribution of critical infrastructure, and abundant marine resources. Simultaneously, China' s coastal zones are frequently impacted by major natural disasters, resulting in direct annual economic losses of approximately 18.8 billion yuan and an average of 256 fatalities per year (1989-2015). Among these, storm surges and typhoon-generated waves induced by typhoons constitute the primary disaster-causing factors. With the intensification of global climate change and sea level rise, disaster conditions in China' s coastal zones may continue to exacerbate, posing severe threats to the lives and property safety of coastal populations and constraining the sustainable development of coastal zone economies. Based on the latest Chinese marine disaster data (1989-2015) and advanced foreign coastal zone disaster prevention and mitigation technologies, this article discusses the current status of major marine disasters striking China' s coastal zones, quantitatively analyzes and evaluates the impacts of these major disasters on China' s coastal economy and human life safety, and finally proposes several countermeasures and recommendations for enhancing disaster prevention and mitigation along China' s coast.

Full Text

Special Topic: Coastal Science and Sustainable Development

Coastal Inundation and Erosion Hazards along the Coast of China and Mitigation Strategies

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Abstract

China is a major maritime nation with an 18,000 km-long mainland coastline, characterized by high population density, dense distribution of critical infrastructure, and abundant marine resources. However, China' s coastal zones are frequently struck by major natural disasters, causing average annual direct economic losses of approximately RMB 18.8 billion and 256 fatalities (1989–2015). Typhoon-induced storm surges and typhoon-generated large waves are the primary disaster-causing factors. With intensifying global climate change and sea level rise, coastal disasters in China may continue to worsen, posing severe threats to the lives and property of coastal residents and constraining the sustainable development of coastal economies. Based on the latest China marine disaster data (1989–2015) and advanced international coastal disaster prevention and mitigation technologies, this paper discusses the current status of major marine disasters affecting China' s coastal zones, quantitatively analyzes and assesses the impacts of these disasters on China' s coastal economy and human safety, and finally proposes several countermeasures and recommendations for improving disaster prevention and mitigation along China' s coast.

Keywords: storm surge, inundation, erosion, coastal hazards, sea level rise
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China possesses an 18,000 km-long mainland coastline and 14,000 km of island coastlines. Along China' s mainland coastal zone, more than 70% of the nation' s large and medium-sized cities are concentrated, including 15 cities with populations exceeding one million. The coastal economic zone, which accounts for only 13% of the country' s land area, supports 42% of the national population and generates over 60% of China' s gross domestic product [1]. Meanwhile, China' s coastal zones have long suffered from various natural disasters (such as typhoons, storm surges, typhoon-generated large waves, coastal erosion, green tides, ice disasters, etc.), causing direct economic losses of approximately RMB 18.8 billion per year and 256 casualties (including missing persons) annually (1989-2015 *China Marine Disaster Bulletin*). Storm surges and storm-generated large waves are the primary disaster-causing factors in China' s coastal zones. With the rapid development of large, medium, and small cities along the coast and the rapid increase in infrastructure, the losses caused by storm surges and other major coastal disasters will become increasingly severe, becoming a major obstacle to the development of China' s coastal cities.

1 Current Status of Major Natural Disasters in China' s Coastal Zones

China has approximately 3 million km² of jurisdictional sea area. Marine industries and marine-related industries can be divided into three major categories: primary marine industries, marine scientific research, education, management services, and marine-related industries. The latest data from the *2015 China Marine Economic Statistics Bulletin* presents the proportional distribution of different marine industries (Figure 1 [Figure 1: see original paper]), where items 3–14 belong to the primary marine industries category, with a total value of approximately RMB 6.47 trillion, accounting for about 10% of China' s GDP in 2015.

China's coastal zones have long suffered from various marine disasters, primarily including storm surges, large ocean waves, sea ice, red tides, and green tides, with sea level change, coastal erosion, seawater intrusion, and soil salinization also occurring to varying degrees. Based on the latest marine disaster data from the 2015 *China Marine Disaster Bulletin*, the direct economic losses caused by various marine disasters in China totaled approximately RMB 7.3 billion, with 30 fatalities (including missing persons). Storm surge disasters accounted for 99.8% of these losses, while the marine disaster causing the most deaths was large ocean waves, accounting for 77% of total fatalities. Based on analysis of the latest disaster data from the *China Marine Disaster Bulletin* (1989–2015), major marine disasters in China' s coastal zones caused average annual direct economic losses of approximately RMB 18.8 billion and 256 fatalities per year, with over 1,200 deaths in the worst year (Figure 2 [Figure 2: see original paper]), and maximum annual economic losses exceeding RMB 44.6 billion, adjusted for annual inflation (Figure 3 [Figure 3: see original paper]).

During the period 2001–2015, the degree of damage and casualties from various marine disasters varied significantly across China' s coastal provinces (Figure 4 [Figure 4: see original paper]). The five provinces with the most severe average annual economic losses were Guangdong (RMB 5.2 billion/year), Fujian (RMB 2.4 billion/year), Zhejiang (RMB 1.8 billion/year), Shandong (RMB 1.4 billion/year), and Jiangsu (RMB 1.0 billion/year). The five provinces with the highest average annual casualties were Guangdong (25 persons/year), Zhejiang (18 persons/year), Hainan (13 persons/year), Fujian (12 persons/year), and Jiangsu (11 persons/year). This is primarily because the spatial distribution of large ocean waves gradually weakens from south to north; consequently, Hainan, Guangdong, Fujian, Zhejiang, and Jiangsu are the five coastal provinces with the most casualties caused by wave disasters.

During the same period, the spatial distribution intensity of direct economic losses and casualties caused by major marine disasters in China' s coastal zones also varied (Figure 5 [Figure 5: see original paper]). The natural disaster causing the most casualties was large ocean waves (65.3%), followed by the combination of storm surges and waves (34.3%), with estuarine bores causing the fewest (0.3%). However, the disaster causing the greatest direct economic losses was storm surges (83%), with all other disasters accounting for only 17% of total economic losses (sea ice, *Enteromorpha*, red tides, large waves, green tides, oil spills). Therefore, storm surges and large ocean waves are the most important disaster factors or hazard agents causing direct economic losses and casualties in China' s coastal zones.

In summary, typhoon-induced storm surges and large ocean waves are the primary disasters causing casualties and direct economic losses along China' s coast, with Hainan, Guangdong, Fujian, Zhejiang, and Jiangsu being the five most severely affected coastal provinces among China' s 11 coastal provinces.

2 Research Status and Progress of Major Coastal Disasters

Based on existing China marine disaster observation data (1986–2015), natural disasters in China' s coastal zones are typically dominated by storm surges, large ocean waves, sea ice, red tides, and green tides, with sea level change, coastal erosion, seawater intrusion, and soil salinization also occurring to varying degrees. Typhoon-induced storm surges and large ocean waves are the two most important factors causing disasters in China' s coastal zones (Figure 5). The focus of this section is on storm surges and large ocean waves that cause coastal inundation and erosion disasters.

2.1 Storm Surge Disasters

Storm tide is formed by the superposition of storm surge and astronomical tide. Storm surge consists of two components: water level increase/decrease generated by storm winds and water level increase caused by the storm' s low-pressure center. The spatial extent of storm surge impacts generally ranges from tens to thousands of kilometers of coastline, with temporal scales of several hours to several days. Storm surge magnitude depends primarily on storm characteristics (such as storm intensity, radius of maximum wind speed, central pressure difference, movement speed and direction), coastal/estuarine geometry of the affected area, and onshore and seabed topography. Historical storm surge disasters have caused enormous economic losses and heavy casualties in coastal and island nations: for example, storm surges in Bangladesh caused 300,000 deaths in 1970 and 140,000 deaths in 1991; Hurricane Katrina in the United States in 2005 resulted in 1,863 deaths and 705 missing persons; and three catastrophic storm surge disasters with over 1,000 deaths each occurred in China' s coastal regions between 1949 and 1995 (Figure 2).

Since the 1950s, European and American countries have initiated numerical forecasting research on storm surges. For example, in 1995, American countries developed the Tropical Storm Disaster Analysis System TAOS (The Arbiter Of

Storms), which simulates the entire process of hazard factors including strong winds, rainfall, storm surges, and waves to produce storm surge disaster maps and vulnerability level maps, primarily applied to practical uses such as evacuation planning, coastal planning, and disaster prevention and mitigation. The U.S. National Hurricane Center (NHC) primarily provides storm surge risk assessments for local government decision-making departments, insurance companies, and coastal communities. Based on research of historical typical marine disaster cases and comprehensive consideration of storm surge hazard factors and the distribution of coastal exposure elements, Japan has developed distribution maps of maximum coastal inundation areas and maximum inundation depths, mainly applied to marine disaster prevention and mitigation in Japanese coastal communities.

Europe, America, and Australia have established several mature storm surge numerical models, such as the U.S. SLOSH, British STWS and SEA, Dutch DELFT3D, Australian GCO2D/3DM, and Danish MIKE-12, which have been applied in different regions worldwide. Storm surge-prone areas such as India, Japan, and Bangladesh frequently use SLOSH. Figure 6 [Figure 6: see original paper] shows an application case of the SLOSH model combined with LiDAR elevation data and 3D satellite imagery [2], simulating the maximum water depth distribution that might inundate the campus of Old Dominion University (ODU) in the United States, with the highest model resolution precise to the scale of individual buildings.

Since the 1970s, China has begun developing storm surge numerical models, particularly with strong support from major national science and technology programs during the Seventh, Eighth, Tenth, and Eleventh Five-Year Plan periods, establishing an operational storm surge numerical forecasting system for China. In recent years, the National Marine Forecast Center, in collaboration with domestic research institutions, has developed the CTS model for typhoon storm surge forecasting and the CES model for extratropical storm surge forecasting. Storm surge forecasting now covers 11 coastal provinces and autonomous regions nationwide, with regional marine forecasting networks established successively in the Bohai Sea, East China Sea, and South China Sea. However, severe shortages of coastal topographic elevation and nearshore bathymetric data directly affect the accuracy of storm surge model calculations in China' s coastal zones.

2.2 Storm Waves, Wave Setup, and Wave Runup

Among China' s coastal provinces (Figure 5), the marine disaster causing the most casualties is typhoon-induced large ocean waves (65.3%), followed by the combination of storm surges and waves (34.3%). However, the marine disaster causing the greatest direct economic losses is storm surges (83%), with all other disasters accounting for only 17% of total economic losses. Typhoon-induced large ocean waves constitute another important factor causing coastal inundation and erosion disasters. The primary mechanisms through which storm waves cause coastal inundation are wave setup and wave runup. Wave setup is the phenomenon of water surface elevation caused by wave breaking, which increases as water depth decreases [3]. The physical implication of coastal wave setup is that the shoreline position under large waves is higher than that under small waves and is also pushed landward by a certain distance, intensifying the interaction between large waves and beaches/dunes. Wave runup refers to the height that waves rush up above the shoreline, representing a physical process where wave kinetic energy is converted to wave potential energy as waves climb up the beach [3].

Numerous field data from abroad have demonstrated that storm wave setup and runup are important factors causing inundation and erosion of sandy coasts, while storm surge is another element causing inundation and erosion of sandy coasts. Analysis based on coastal hazard data from New South Wales, Australia, revealed that maximum nearshore storm surge is approximately 0.4 m, whereas wave runup is 5–10 times that of storm surge, with wave runup reaching 20–30 m on steep rocky coasts. In wide and deep estuaries, wave-induced setup is generally negligible [4], whereas in narrow and shallow estuaries, waves cause estuarine water level rise through a "wave pumping" effect.

2.3 Coastal Erosion Disasters

Coastal erosion disasters are widespread along China' s 18,000+ km mainland coastline and 14,000+ km of island coastlines, with almost all open muddy coasts and approximately 70% of sandy coasts suffering from erosion to varying degrees [5]. Coastal erosion in China has caused serious economic losses; for example, coastal inundation and erosion disasters on March 3–5, 2007, resulted in 7 deaths along the coast of Shandong Province and economic losses as high as RMB 2.1 billion (Figure 7 [Figure 7: see original paper]). China' s coastal beaches face serious problems of erosion, narrowing beach surfaces, and steepening beach faces.

Domestic and international scholars have conducted extensive research on beach "equilibrium profiles." A beach equilibrium profile represents a statistically meaningful relatively stable beach state resulting from long-term and sufficient interaction between marine dynamic systems and beaches; absolutely ideal equilibrium beach profiles rarely exist in nature. Larson and Kraus [6] conducted experiments and proposed empirical profiles based on Dean' s [7] coastal equilibrium profile model, and simultaneously proposed the storm erosion beach model SBeach. In recent years, Roelvink et al. [8, 9] improved and refined SBeach, developing a new generation coastal storm erosion model XBeach. The coastal erosion model for sea level rise was first proposed by Bruun [10], also known as the "Bruun Rule." Larson et al. [11] established the long-term coastal evolution model GENESIS for numerically simulating long-term shoreline evolution processes. You et al. [12] developed a storm erosion model that is also applicable for simulating the effects of sea level rise on sandy coast erosion, as well as the impacts of other slowly changing coastal dynamic factors on shoreline evolution.

Several internationally commonly used coastal sediment transport mathematical models simulate coastal sediment erosion/accretion problems at different time scales: for example, Delft-3D or MIKE-21 simulate short-term coastal sediment transport physical processes (time scale: seconds to days); XBeach estimates beach erosion caused by coastal storms (time scale: hours to days); and GENESIS predicts long-term shoreline evolution processes (seasons to decades).

Since existing coastal erosion models cannot yet accurately predict long-term evolution of coastal zones, significant differences remain between model calculation results and actual observation data. Therefore, in practical engineering applications, coastal erosion disaster assessment is typically also based on long-term beach profile observation data (such as long-term 3D aerial imagery, coastal elevation profiles, and other historical data). Figure 8 [Figure 8: see original paper] illustrates a calculation case for different erosion zones at Kingscliff Beach in New South Wales, Australia, where the seaward area beyond the green line represents zones currently suffering from beach erosion disasters; the seaward area beyond the blue line represents coastal zones that may be eroded between now and 2050; and the seaward area beyond the red line represents coastal zones that may be eroded between now and 2100.

3 Conclusions and Recommendations

Based on analysis of the latest China marine disaster data from 2001–2015, the marine disaster causing the most deaths in China' s coastal zones is typhoon-generated large waves (65.4%), followed by the combination of storm surges and large waves (34.3%). The coastal provinces with the highest average annual casualties are Guangdong, Zhejiang, Hainan, Fujian, and Jiangsu. The marine disaster causing the greatest direct economic losses is storm surges (83%). The major coastal provinces with the largest average annual direct economic losses are Guangdong, Fujian, Zhejiang, Shandong, Jiangsu, and Hainan. Considering that economic losses and casualties from disasters are also related to factors such as population density, economic development level, topography, and disaster prevention and mitigation capacity in the affected areas, Hainan, Guangdong, Fujian, Zhejiang, Jiangsu, and Shandong are the six most severely affected coastal provinces in China.

Although early warning and disaster defense work for storm surge disasters in China' s coastal zones has been greatly improved, and storm surge forecasting now covers 11 coastal provinces and autonomous regions, the accuracy of existing storm surge models is severely limited due to the lack of extensive and high-quality coastal topographic elevation and nearshore bathymetric data. The importance of typhoon-generated wave runup for coastal inundation in China has not received sufficient attention.

Nearly all open muddy coasts and approximately 70% of sandy coasts in China' s coastal zones suffer from erosion to varying degrees, yet research on coastal erosion in China has been minimal, with a lack of long-term coastal erosion data.

To address these challenges, several measures are recommended. First, improve existing data collection methods and systems for major disasters in China’ s coastal zones, rationally deploy data collection areas or stations, systematically collect disaster data and related marine dynamic data, and establish a large-scale, internet-based, GIS-format database for disasters in China’s coastal zones and estuaries to achieve data sharing. Second, great importance must be attached to the significant impacts of typhoon-generated wave runup on coastal inundation in China, and research in this field is urgently needed. According to wave runup data collected from the coast of New South Wales, Australia, maximum nearshore storm surge is approximately 0.4 m, whereas maximum wave runup on sandy beaches is about 2–4 m, and wave runup on steep rocky coasts reaches 20–30 m. Third, internationally accepted mathematical models should be applied to establish a numerical modeling system for disaster early warning and forecasting in China’ s coastal zones, enabling real-time prediction of the spatial and temporal variations of major disasters. Simultaneously, an ARGO observation system for China’s coast should be established to record and observe the occurrence processes of coastal disasters in real time and to verify and correct the modeling system. Finally, scientific management and planning of coastal zone utilization and development in China should be implemented. For areas where coastal inundation and erosion disasters occur frequently, construction of large-scale infrastructure and residential communities should be avoided whenever possible; indiscriminate large-scale extraction of beach sand, land reclamation, and construction of large coastal structures should also be avoided.

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