様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

平成 ３０ 年　４ 月 ２４ 日現在

機関番号： １１３０１
研究種目： 基盤研究(C)（一般）
研究期間： 2015～2017
課題番号： １５Ｋ０６２２４
研究課題名（和文） Boussinesq-type Modeling of Destructive Surf Beat over a Fringing Reef during Typhoon Haiyan

研究課題名（英文） Boussinesq-type Modeling of Destructive Surf Beat over a Fringing Reef during Typhoon Haiyan

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交付決定額（研究期間全体）：（直接経費）　3,500,000円

研究成果の概要（和文）：本研究では，高潮・高波による浸水に関する様々なシナリオについて詳細な検討を行った．その結果，特に沖合での波の状態，局所地形，潮位変化が重要であることがわかった．長周期波は，強い砕波が生じる場所で発生する傾向がある．そうした場所は海岸侵食も強い．潮位の変化は，砕波帯のプロセスを変化させる．波の遡上は，通常は高潮位時に最も高くなる傾向にあるが，長周期波はむしろ潮位が低い時に大きくなる傾向がある．潮位が低い状態において，砕波はより急激に発生する．これにより，長周期波のエネルギーが増大し，土砂移動を引き起こすと考えられる．

研究成果の概要（英文）：The research for this study has lead to a detailed investigation of coastal flooding from a variety of different scenarios. We have analysed the importance of offshore wave conditions, local bathymetry, and tidal fluctuations. Infragravity wave hotspots tend to form in areas with intense wave breaking. These are also areas where coastal erosion can be high -given that the surf and swash zone is composed of erodible material. Tidal fluctuations can modulate the surf zone processes. Though wave runup is usually highest at high water levels, infragravity waves can be highest at low to intermediate water levels. This has to do with the intensity of wave breaking. Under some low to intermediate water levels, wave breaking happens more abruptly than during high water stage. This can lead to higher levels of infragravity wave energy, which is the driving component for sediment transport. flooding and shoreline changes.

研究分野： Coastal Engineering

キーワード： Typhoon　swell　infragravity wave　surf beat　beach erosion　numerical modeling　Sendai Port　Boussinesq equation

1. 研究開始当初の目的

The town of Hernani, Eastern Samar, in the Philippines is a fishing and agricultural community protected from the open Pacific Ocean by a wide fringing reef (Figs. 1 & 2). The tsunami-like wave that struck the town during Typhoon Haiyan on November 8, 2013 (Fig. 3) astonished both villagers and disaster managers, as the coast near Hernani is sheltered by a broad coral reef, which was expected to serve as a reliable wave defense. The event has been a mystery because the destructive bore lasted for a few minutes, much longer than what would correspond to storm-induced ocean wind waves, which generally have periods of less than 20 seconds.

Media have reported this event as a meteotsunami or as storm surge, albeit storm surge refers to the elevated still water level due to barometric-, wind-, and breaking-wave-induced setup, but not wave-induced oscillations. A meteotsunami can only form when the forward propagation speed of a storm is close to the free long wave speed of the ocean over which it propagates. The forward propagation speed of Typhoon Haiyan was at most 14 m/s, which would have required a water body on the order of 20 m deep for the storm to have been able to keep up with the free long wave generated; the propagation speed of a free long wave is $c=(gh)^{1/2}$, where g is the acceleration due to gravity and h is the water depth. However, the water depth offshore of Hernani quickly drops to hundreds of meters (Fig. 2), precluding the possibility of a meteotsunami at this location.

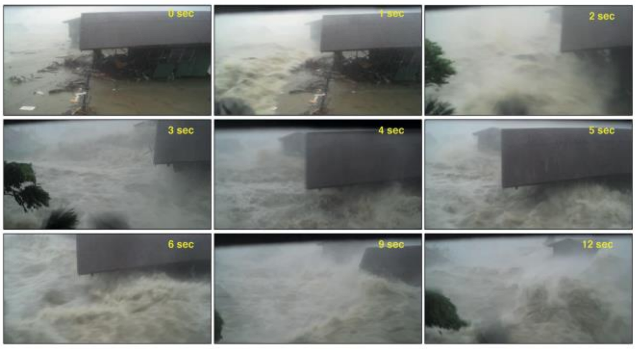

Fig. 3: Tsunami-like bore destroying residential home in Hernani. The house is located in 3.4 m elevation behind a seawall. The village is protected by a wide fringing reef (see Fig. 1). Permission granted by Plan International[4].

Based on the authors' own interviews on site, local residents believed that the typhoon triggered a landslide, which caused a near-field tsunami. However, no tsunami-genic earthquake or landslide seismicity was reported. Furthermore, a similar tsunami-like flood was reported to have occurred during the October 12, 1897 typhoon, underscoring the likelihood that the bore was a direct consequence of the typhoon, and not a tsunami that happened to occur simultaneously.

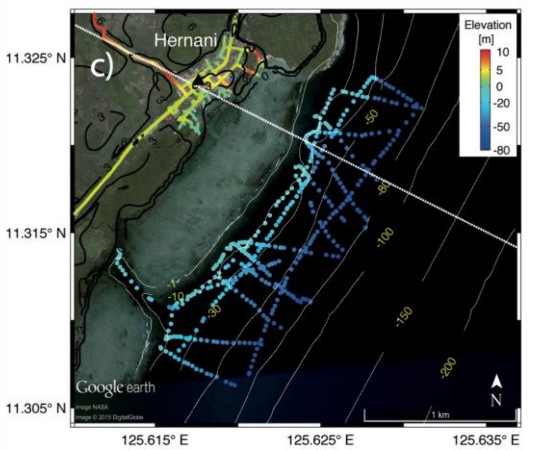

Fig. 1: Location of Hernani in Eastern Samar. The dots denote data points gathered during topographic and bathymetric surveys.

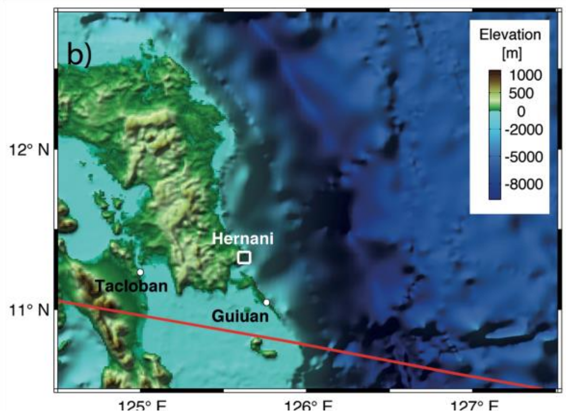

Fig. 2: Bathymetry and topography of Eastern Samar. The red line denotes the track of Typhoon Haiyan.

The grave significance of the damage in Hernani is that the mechanism, which caused the destruction, is unaccounted for in coastal hazard assessment, evacuation planning, or structural building codes. In the deep water offshore of Hernani, wind-driven setup is no larger than a few 10's of centimeters, similar in size to the setup caused by the barometric pressure drop. This is in contrast to the situation of the city of Tacloban (Fig. 2), which is located at the end of a shallow bay with a maximum water depth of 50 m. The strong winds from Typhoon Haiyan, together with a local basin and shelf seiche, pushed enough water onshore to cause up to 6 m of storm surge to flood the city of Tacloban. In addition, the wind-generated waves on top of this surge also destroyed buildings along the shoreline. Storm surge and damage of the type seen in Tacloban was predicted with great accuracy, as similar wind-driven surges have been studied for decades, with some outstanding examples being Hurricane Katrina in the US, the Bhola cyclone in Bangladesh, and the Ise-Bay typhoon in Japan. Each of these events affected low-lying land at the head of a shallow bay, similar to the setting of Tacloban. Wind-driven storm surge is well understood because of its frequent occurrence and large geographic extent. Furthermore, the physics of wind-driven storm surge is a simple balance between pressure gradient and parameterized wind stress, allowing it to be calculated with depth-averaged hydrostatic approximations of the Navier-Stokes equations.

The physics responsible for damage in Hernani, however, is different, as it was caused by individual waves.

Previously, Nakaza & Hino[1] observed a similar wave phenomenon in Okinawa, which they investigated with a small-scale laboratory experiment. Nwogu and Demirbilek[2] utilized a phase-resolving Boussinesq wave model to analyze a similar set of laboratory experiments. The fundamental dynamics involved in this phenomenon are multiple:

1. The presence of alternating large and small incident wave groups (also called sets) causes the wave setup on the beach to vary in time, resulting in surf beat with an infragravity period on the order of minutes. The minimum wave envelope (group) return period is a function of the shape of the wave spectrum.
2. In the frequency domain, surf beat energy may overlap with the natural quarter-wave oscillator frequency of the reef, and is thus amplified due to resonance.
3. As the surf beat propagates over the reef, it steepens nonlinearly and forms a bore[1].
4. Individual incoming ocean waves also propagate on top of the wave setup and runup on land as shorter bores.

2. 研究の目的

Typhoons, hurricanes, and cyclones pose a constant threat to coastal communities and infrastructure throughout the world, including Japan. In 2013, Typhoon Haiyan revealed a counter-intuitive storm wave phenomenon, which destroyed an entire village. The natural resonance of surf beat (infra-gravity waves) over a coral reef produced unexpected tsunami-like bores. Previously unaccounted for, active emergency management plans do not address this type of wave hazard. Proper assessment of such disaster waves requires site-specific investigations with a new generation of numerical models. This study analyzed the processes that can lead to destructive infra-gravity waves in tropical and extra-tropical areas.

3. 研究の方法

(1) Field Surveys

Land surface and coral reef elevations were measured from May 25-27, 2014 via walking and driving surveys with two Ashtech ProMark 100 DGPS units, in base/rover differential configuration, and post-processed for vertical accuracy with GNSS Solutions software. The water depth seaward of the coral reef was measured from a hired fishing canoe, using a Hondex PS-7 handheld digital sounder, which has an operational range up to 80 m. Sounder readings were photographed with a Canon PowerShot D20 GPS camera to record location of each measurement. All elevation and depth measurements were referenced to MSL using the TPXO global tide model.

(2) DELFT-3D/SWAN

The Delft-3D/SWAN model was run using domain decomposition. The large domain (125°<east longitude<130°, 10°<north latitude<15°) had a resolution of 0.01°(about 1 km), and the small domain (125.59°<east longitude<125.66°, 11.29°<north latitude<11.36°) had a resolution of 0.0004°(about 40 m). Coarse bathymetry data was taken from GEBCO and topography from SRTM. Within the region of the field survey of Fig. 1, the bathymetry and topography were interpolated from surveyed data. Tides were included using the Global Tide database TPXO as a boundary condition to the hydrodynamic model. Bed roughness was parameterized with a uniform Manning’s n of 0.025 $s/m^{1/3}$. The Delft-3D model was run with a uniform time step of 6 sec, while SWAN was run in stationary mode at 15-minute intervals (a test was run in non-stationary mode, but results did not differ noticeably from stationary mode).

(3) BOSZ Wave Model

The wavemaker source function used in *BOSZ* (*B*oussinesq *O*cean & *S*urf *Z*one model) is based on an internal source function. To ensure uniform wave energy distribution over the portion of the BOSZ 2-dimensional computational domain of uniform 150 m water depth, all three open-ocean facing domain boundaries contain wave generating source functions. Wave shadowing due to the directionality of the spectral components is only visible in very limited regions along the Northern and Southern boundary. For the 1-dimensional analyses, the components from the 2-dimensional wave spectrum are collapsed into a one directional distribution of the wave energy over all frequency bins.

The resulting time series were used as a boundary condition for the phase-resolving depth-averaged BOSZ model, which was then used to evaluate the effects of surf beat and resonance over the reef in 2 dimensions (plan view) as well as along a 1-dimensional transect passing through the house seen washed away in Gensis' film[4].

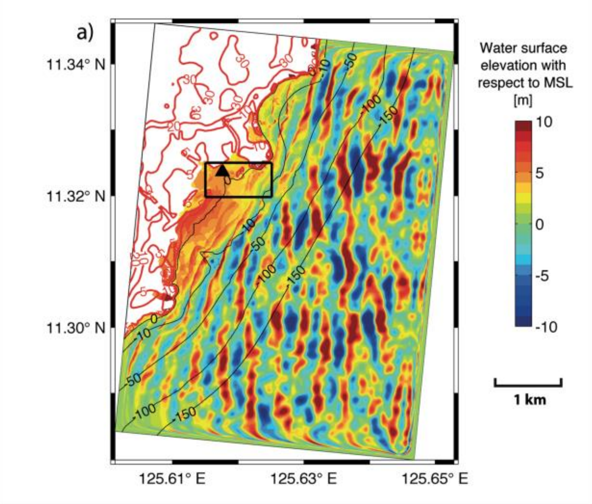

Fig. 4: BOSZ Boussinesq wave model. 2D Computational domain with free surface elevation after 1h of computation. BOSZ computes wave inundation of the village.

To recreate the tsunami-like wave which struck Hernani, the offshore SWAN wave spectrum was input to a 2-dimensional (plan view) BOSZ[3] Boussinesq phase-resolving model. The model run was conducted with a uniform 5 m by 5 m resolution over a domain extending 5 km in the east-west direction, 6.9 km north-south, and rotated 5° clockwise to allow input of waves at the peak direction as output by SWAN (Fig. 4).

Due to constraints in computational resources, only one 2-dimensional computation was run, using real bathymetry for Fig. 4. Other cases were calculated using 1-dimensional setups with 5-m resolution. For each bathymetry, 1-dimensional BOSZ model runs were evaluated with 10 different random phase seeds and then ensemble-averaged to produce robust frequency spectra (Fig. 5).

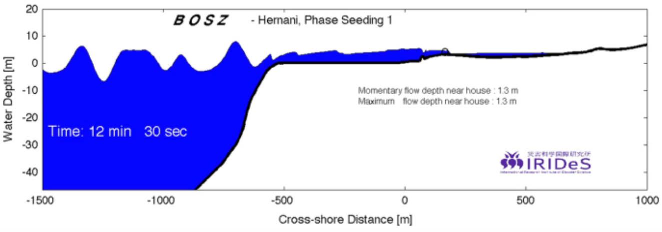

Fig. 5: BOSZ Boussinesq wave model. 1D Computational domain with free surface elevation. Surf beat amplification over reef.

4. 研究成果

(1) Surf beat depending on reef dimensions

To determine the relative contribution of offshore wave groups and reef resonance to amplification of the surf beat, BOSZ was evaluated in 1-dimension along the transect shown in Fig. 1. Fig. 6 shows that for the actual bathymetry (reef) case, most of the water level variance on the beach is at *f*=0.0035 Hz (frequency *f* is the inverse of period *T*), which is close to the theoretical wave group return frequency of *f*=0.004 Hz. The hypothetical case of no reef represents the bathymetry of the channel surveyed in Fig. 1, where freshwater river outflow prevented the reef from growing. For this no-reef case, a peak in variance exists near the wave group return frequency, but it is much smaller than in the real reef case. In contrast, the no-reef case has a gradual wave breaking zone, resulting in less energy available for transfer from gravity to infragravity frequencies.

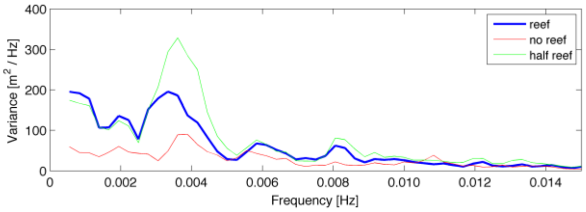

Fig. 6: Variance spectra from 1D BOSZ computations at the location of the destroyed house. The presence of the reef supports IG wave energy. The surf beat would have amplified even more if the reef were half as wide.

Interestingly, *the wave that struck Hernani was not a worst-case scenario*: if a similar storm to Typhoon Haiyan were to strike a city fronted by a narrower reef with an equally steep reef face, resonance would become significant, causing an even larger surf beat and subsequently more intense flooding. This is illustrated by the case of a reef with only half the cross-shore length of the real reef. The resonant frequency of this half reef is 0.0042 Hz, which is close to the wave group return frequency and results in stronger amplification of that peak than occurs in the real reef case (green line in Fig. 6).

The effect of the presence of the reef on damage onshore was further investigated using 1-dimensional BOSZ simulations. Storms of various intensities were modeled by scaling down the central pressure and maximum wind speed of Typhoon Haiyan. For each hypothetical storm, hydrodynamic force *F* on buildings near the beach was approximated with a drag law. Fig. 7 shows the spectra of *F* (proportional to hu^2, where h is water depth and u is flow speed) on the beach for the real reef and no-reef cases. For storms of up to about 50% the strength of Typhoon Haiyan, the reef protects the shore from incident waves. During larger storms, however, it exacerbates damage due to enhanced hydrodynamic force at infragravity frequencies.

(2) Further implications and take-home message

The tsunami-like wave, which struck Hernani was the result of abrupt breaking of waves over the steep reef face generating an energetic surf beat. Had the surf beat been in resonance with the reef flat, the wave would have been even larger. Results show that reefs protect the shoreline during moderate storms, but can exacerbate damage during strong storms like Haiyan. This phenomenon was successfully reproduced by a phase-resolving wave model, indicating the necessity for adoption of such models in coastal hazard assessment of reef-protected areas around the world.

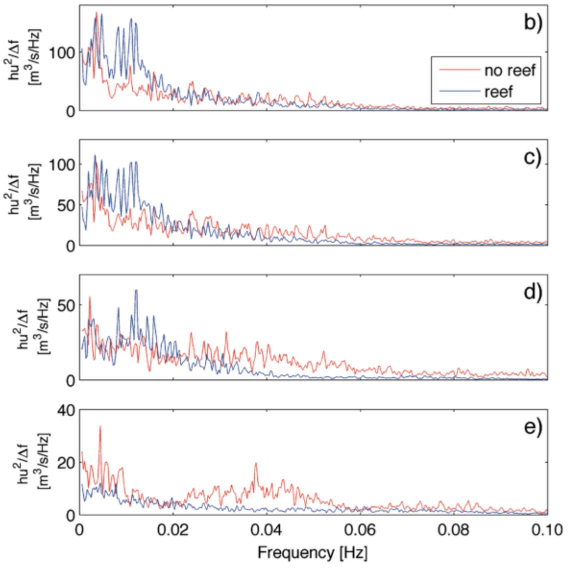

Fig. 7: Variance spectra from 1D BOSZ computations different storm intensities. Compared to a no-reef-case, the reef in front of Hernani does not protect from IG waves anymore for storms of half the intensity of Typhoon Haiyan and larger.
Under extreme wave conditions, fringing reefs do NOT always protect coastal communities!

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