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Assessment of hydrodynamic competence in extreme marine events through application of Boussinesq–Green–Naghdi models

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ABSTRACT

Here in present work, rotational Boussinesq–Green–Naghdi models were applied to assess the hydrodynamic intensity through the study of the boulder transport in east coast of Philippines during typhoon Haiyan and damage to coastal residences in New Jersey coast due to hurricane Sandy. The hydrodynamic forces were quantitatively analyzed and correlated to both boulder transport distance and the structural damage state in the two cases. The boulder transport was found initiated at vicinity of infragravity swash bores. Inertial force generated by the acceleration in front of the bore was found increasingly large as boulder sizes increased therefore far from negligible as in some other literatures. Besides, transport distances were highly sensitive to wave-heights and boulder sizes, so that onshore positions might be a viable approach of identifying rough magnitudes of paleostorm before other information is available. Fragility functions to predict the damage state of coastal residences due to runups was derived and preliminary validated. Water velocity and the shielding parameter were identified as major predictors of damage while free board and water depth are relatively insignificant. Due to the relative lack of wind damage observed, nearshore hydrodynamics featuring instantaneous nonhydrostatic impact might be the persistent cause of massive littoral processes and low-level structural failure in coastal regions during extreme marine events. Nonhydrostatic phase-resolving models such as Boussinesq-type models would be necessary complements for the intermediate-scale assessment of marine hazards in coastal ocean.

1. Introduction

Extreme marine hazard such as hurricane surge, tsunamis, and waves carrying tons of energy all the way from deep ocean to coast could entirely devastate coastal regions. Especially in coastal ocean, the nearshore environmental phenomena include waves, currents, surge, turbulence, and many other hydrodynamic processes and occasionally act simultaneously. Usually people focus on wind speeds, surge levels, and the inundation area in large scope. Much more detailed studies on waves and currents in coastal ocean are generally case specific and lag behind others [16]. However, due to the relative lack of wind damage observed, nearshore hydrodynamics featuring instantaneous nonhydrostatic impact might be the persistent cause of massive littoral processes and structural failure in coastal regions during extreme marine events.

As the modern computing power progressed, the numerical model has become a sophisticated approach for marine hazard assessment [26,36,38,51]. In large scope, depth-averaged models based on the shallow water equation are commonly adopted in the computation of long-period processes with relative small depth/length ratio (kh) such as hurricane surge and tsunamis. However, lack of higher order approximation for nonlinearity and nonhydrostatics leads to certain underestimate of maximum hydrodynamic intensity in nearshore regions like the surf zone when wave shoaling, breaking, eddies, and turbulence get involved [4,13,23,41,54,59,65]. Even phase-averaged linear wave models such as SWAN and STWAVE are regularly coupled into the circulation models to feed ad hoc radiation stress of waves, the complexity of nearshore hydrodynamics might still not be represented very well, which is totally acceptable for large-scale modeling of ocean dynamics. Currently there are straightforward formulas for surge and wave loads that are used for coastal protection design [1,2,11]. But, missing the effects of unsteady wave and surge processes leads

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to severe overestimate of wave loads near the shoreline and hinders investigations into the nonhydrostatic features.

Boussinesq-type models present a phase resolving approximation of nonlinear nearshore wave dynamics with good computational efficiency and range of validity, thus experienced significant progress in both theories and applications during past decades [8,14,31,33,37,39,52]. The model system uses perturbation expansion in two parameters: $\mu = kh$, a description of dispersion and $\delta = a/h$ representing nonlinearity [15,34,48]. The increase of accuracy depends on the truncations of either Taylor series or polynomial expression of the velocity. The resolving of the nonhydrostatic pressure and depth-varying velocities are realized by increasing the correction terms based on the hydrostatic pressure and depth-averaged velocities. Therefore researches made strenuous efforts to extend the Boussinesq theory into deeper water by increasing the formal expansions to higher order and adopting asymptotic rearrangement methods to improve the properties at given approximation order. However, most Boussinesq models features partial or full irrotationality assumption for orbital velocities, which is entirely violated in surf zone. Zhang et al. [61] developed Boussinesq–Green–Naghdi models that shows resemblance to both Boussinesq and Green–Naghdi systems [28]. Polynomial expansions and Boussinesq scaling were both applied to completely remove the irrotationality assumption while keeping the computational efficiency of Boussinesq-type models. The systems show excellent convergence toward exact solutions for dispersion, shoaling, and orbital velocities. Rotational surf zone flows may be modeled naturally.

This paper presents the assessment of hydrodynamic intensity through applications of the Boussinesq–Green–Naghdi model in two catastrophic marine hazards. The hydrodynamic forces was quantitatively analyzed and correlated to both boulder transport distance and the structural damage state in the two cases. The mechanism of nonhydrostatic features in front of the infragravity swash bore and after onshore runup is discussed respectively in the two cases. Onshore movement of the boulder was simulated and validated by the field data. Components of the force on the boulder were computed and analyzed in details. Hydrodynamic intensity was correlated to the verified damage in the field survey with a proportional expectation. An assessment method of damage to coastal residences was derived and parameterized using Backwards Multiple Regression techniques. Present work confines itself to the study of wave loads in intermediate-scale regions during extreme marine events. More works in large scope are introduced briefly, but will be fully discussed elsewhere.

2. Nonhydrostatic phase-resolving model

Boussinesq–Green–Naghdi wave model [60,61] applied in present work is dimensionless using Boussinesq scaling for nondimensional variables which are defined as

$$
\begin{aligned}
&(x,y)=k_0(x^*,y^*), && z=h_0^{-1}z^*, && t=k_0(g_0h_0)^{\frac{1}{2}}t^*,\\
&h=h_0^{-1}h^*, && \eta=(h_0)^{-1}\eta^* && P=(\rho^*g_0h_0)^{-1}P^*,\\
&g=g_0^{-1}g^*, && (u,v)=(g_0h_0)^{-1/2}(u^*,v^*), && w=(k_0h_0)^{-1}(g_0h_0)^{-1/2}w^*\\
&\nu_t=h_0^{-1}(g_0h_0)^{-1/2}(k_0h_0)^{-1}\nu_t^* && \tau_{\mathbf{xz}}=g_0^{-1}k_0^{-1}h_0^{-2}\tau_{\mathbf{x}z}^* && \tau_{\mathbf{xx}}=g_0^{-1}k_0^{-2}h_0^{-3}\tau_{\mathbf{xx}}^*
\end{aligned}
\tag{2.1}
$$

where the superscript * indicates dimensional variables. Polynomial expansion for the horizontal and vertical velocity is assumed

$$\mathbf{u}=\sum_{n=0}^{N}\mu^{\beta_n}\mathbf{u}_n(\mathbf{x})f_n(q) \tag{2.2}$$

$$w=\sum_{n=0}^{N}\mu^{\beta_n}[-(\nabla\cdot\mathbf{u}_n)(h+\eta)g_n+(\mathbf{u}_n\cdot\nabla(h+\eta))r_n-(\mathbf{u}_n\cdot\nabla h)f_n] \tag{2.3}$$

where $\beta_n = n$ when n is even; $\beta_n = n+1$ when n is odd. The horizontal coefficients, $\mathbf{u}(\mathbf{x}) = (u(x, y), v(x, y))$ with $q = (z+h)/(h+\eta)$. The polynomial basis functions $f_n = \sum_{m=0}^{n} a_{nm}q^m$, where a_{nm} are real constants with $a_{nn} \neq 0$. The model equations consist of the vertically integrated mass equation and horizontal momentum equations which are integrated in a weighted residual sense using the $N+1$ basis functions from the bed to the free surface.

$$\frac{\partial\eta}{\partial t}+\nabla\cdot\int_{-h}^{\eta}\mathbf{u}\,dz=0 \tag{2.4}$$

$$\int_{-h}^{\eta}f_m\left(\frac{\partial\mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}+w\frac{\partial\mathbf{u}}{\partial z}+\nabla P-\mu^2\nabla\cdot\tau_{\mathbf{xx}}-\frac{\partial}{\partial z}\tau_{z\mathbf{x}}\right)dz=0,\ \ m=0,1,\ldots,N, \tag{2.5}$$

where μ is a dimensionless is a measure of dispersion. Boussinesq equations attempt to go to as high a value as possible to increase the range of application. The nonhydrostatic pressure is similar to most Boussinesq theory and results in mixed space-time derivatives are like typical Boussinesq models.

$$
\begin{aligned}
P(z)=&\mu^2\int_z^{\eta}\frac{\partial w}{\partial t}\,dz+\mu^2\int_z^{\eta}\mathbf{u}\cdot\nabla w,\,dz+\mu^2\int_z^{\eta}w\frac{\partial w}{\partial z}dz\\
&-\mu^2\int_z^{\eta}\left(\nabla\cdot\tau_{z\mathbf{x}}+\frac{\partial}{\partial z}\tau_{zz}\right),dz+g(\eta-z)
\end{aligned}
\tag{2.6}
$$

After substitution and integration, these give the coupled momentum equations for different levels of approximation. At $O(\mu^2)$,

$$\eta_{,t}+\nabla\cdot\left(\mathbf{u}_0(\eta+h)+\mu^2\sum_{n=1}^{2}\mathbf{u}_n(\eta+h)g_n|_{q=1}\right)=0, \tag{2.7}$$

$$
\begin{aligned}
&\mathbf{u}_{0,t}(\eta+h)g_m|_{q=1}+\mathbf{u}_0\cdot\nabla\mathbf{u}_0(\eta+h)g_m|_{q=1}+g\nabla\eta(\eta+h)g_m|_{q=1}\\
&+\mu^2\sum_{n=1}^{2}(\mathbf{u}_{n,t}(\eta+h)\phi_{mn}-\mathbf{u}_n\eta_{,t}\varepsilon_{mn})|_{q=1}\\
&-\mu^2\left[\frac{1}{2}\nabla(\nabla\cdot\mathbf{u}_{0,t})(\eta+h)^3(g_m-\nu_m)+(\nabla\cdot\mathbf{u}_{0,t})(\eta+h)^2\nabla(\eta+h)g_m\right.\\
&+\nabla(\mathbf{u}_{0,t}\cdot\nabla h)(\eta+h)^2(g_m-S_m)+\mathbf{u}_{0,t}\cdot\nabla h\nabla\eta(\eta+h)g_m\\
&\left.-(\nabla\cdot\mathbf{u}_{0,t})(\eta+h)^2\nabla hS_m\right]|_{q=1}\\
&+\mu^2\sum_{n=1}^{2}[(\mathbf{u}_n\cdot\nabla\mathbf{u}_0+\mathbf{u}_0\cdot\nabla\mathbf{u}_n)(\eta+h)\phi_{mn}-\mathbf{u}_n\nabla\cdot(\mathbf{u}_0(\eta+h))\varepsilon_{mn}]|_{q=1}\\
&+\mu^2(\eta+h)^2[(\nabla\cdot\mathbf{u}_0)^2-\mathbf{u}_0\cdot\nabla(\nabla\cdot\mathbf{u}_0)](\nabla\eta g_m+\nabla h(g_m-S_m))|_{q=1}\\
&+\frac{\mu^2}{2}(\eta+h)^3\nabla[(\nabla\cdot\mathbf{u}_0)^2-\mathbf{u}_0\cdot\nabla(\nabla\cdot\mathbf{u}_0)](g_m-\nu_m)|_{q=1}\\
&-\mu^2(\eta+h)\nabla\eta\mathbf{u}_0\cdot\nabla(\mathbf{u}_0\cdot\nabla h)g_m|_{q=1}\\
&-\mu^2(\eta+h)^2\nabla(\mathbf{u}_0\cdot\nabla(\mathbf{u}_0\cdot\nabla h))(g_m-S_m)|_{q=1}\\
&=\int_{-h}^{\eta}f_m\frac{\partial\tau_{\mathbf{x}z}}{\partial z}dz+\int_{-h}^{\eta}\mu^2f_m\nabla\cdot\tau_{\mathbf{xx}}\,dz,\ \ m=0,1,2
\end{aligned}
\tag{2.8}
$$

where g_m and S_m are integral functions of f_n, e.g. $g_n \equiv \int_0^q f_n(q)dq$, with many other functions defined (subsection, Integral Functions). Unlike standard Boussinesq expansions, rotational processes are included and evolve naturally once turbulent stresses τ_{ij} are solved properly:

$$\mu^2\nabla\cdot\tau_{\mathbf{xx}}=\mu^2\nabla\cdot[\nu_t(\nabla\mathbf{u}+(\nabla\mathbf{u})^T)] \tag{2.9}$$