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Letter

# On the magnetic anomaly at Easter Island during the 2010 Chile tsunami

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ABSTRACT

A magnetic anomaly was recorded at Easter Island on 27 February 2010 during the Chile tsunami event. The physics of the magnetic anomaly is analyzed using kinematic dynamo theory. Using a single wave model, the space and time behavior of the magnetic field is given. By joint analysis of the magnetic observations, tide gauge data and numerical results of the global tsunami propagation, we show the close resemblance between the predicted spatial and temporal magnetic distributions and the field data, indicating the magnetic anomaly at Easter Island was actually induced by the motion of seawater under tsunami waves. Similarity between the field magnetic data at Easter Island during 2010 Chile tsunami and sea surface level is verified with realistic tsunami propagating model.



2010 Chile earthquake occurred off the coast of central Chile on February 27, 2010, at 06:34 UTC, having a magnitude of 8.8 on the moment magnitude scale. Large tsunami was generated and propagated across the south Pacific ocean. A tiny magnetic signal oscillation was captured by the magnetic station named IPM after UTC 11:30 am when the tsunami wave passed through Easter Island as shown in Fig. 1. The occurrence of oscillation of magnetic field is coincident with the arriving time of tsunami wave, which suggests the tight connection between the seawater's motion and variation of magnetic field variation.

Magnetic anomaly induced by seawater's motion is recognized and known in very early days [1–3]. Seawater is an electrically conducting media which generates small electromagnetic fields as it flows through the Earth's main magnetic field. Gravity surface water wave is a common flow form in ocean. Around $O(0.1)$–$O(1)$ nT magnetic field can be generated by the Kelvin waves after submarine and surface ship at cruise speed [4,5]. Electromagnetic fields tend to enhance when wave periods and lengths increase. Waves of period 16–17 s and amplitude of 1 m can induce magnetic anomaly of 1 nT. Swells of period 10–20 s can induced a magnetic field of $10^3$–$10^4$ times of the one's induced by wind waves of 5 s. Typical tide flow can induce magnetic field of 20–30 nT. For some internal wave in tropical area, measured magnetic fields value may reach 100 nT [6]. Tyler [7] compared and found similarities between the results of a numerical prediction of lunar $M_2$ tide (i.e. twice tide cycles in one day) and scalar magnetic records measured by satellite CHAMP. It has been shown for the first time that the ocean flow makes a substantial contribution to the geomagnetic field at satellite altitude. For the magnetic anomaly induced by 2010 Chile tsunami, it is the first time that field magnetic data induced by seawater's motion under tsunami was captured. However, the shifted sea surface record at Deep-ocean Assessment and Reporting of Tsunamis (DART) 51406 with a time lag were imperfectly used to verify the existence of the similarity due to the lack of accurate seismic data [8,9].

Employing global tsunami transport modeling, at now we can simulate the sea surface elevation during the 2010 tsunami event accurately. We start with modeling the sea surface elevation during the selected tsunami events, employing the phase resolved global tsunami propagation equations. A benchmarked numerical package GeoClaw [10], an adaptive numerical solver of nonlinear shallow water equations in spherical coordinates, was used to simulate the 2010 Chile tsunami propagation across the south Pacific ocean, which has been successfully used on 2004 Sumatra tsunami and 2012 Tohoku tsunami [11]. ETOPO 2-min global dataset at the National Geophysical Data Center (NGDC) is used for the bathymetry in offshore region at a resolution of 10 min in latitude and longitude, and 1-min dataset is used near the epicenter. Initial sea surface deformation was computed by applying Okada's

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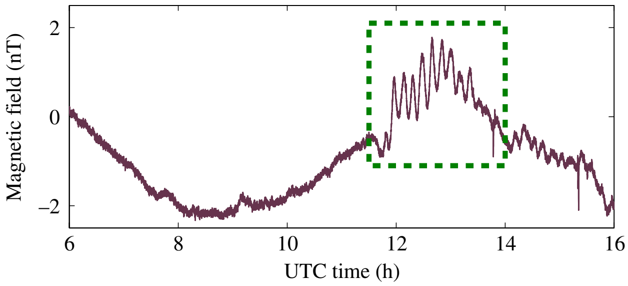


**Fig. 1.** Vertical component of total main magnetic field at IPM during February 27, 2010 Chile tsunami event. Mean value of -19 000 nT has been subtracted. Magnetic gauge station IPM is operated by the Bureau Central de Magnetisme Terrestre, France, locates at (−27.200° S, −109.420° W).

formulas for 180 sub-fault using the fault parameter [12]. With the refined adaptive mesh, good agreements at DART 32412 and 51406 are obtained as shown in Fig. 2. Although there is no DART data at Easter Island, we have confidence that the numerical results of GeoClaw could predict reliable sea surface elevation since the position IPM locates between DART 32412 and 51406 along the tsunami's path. On a mild slope bathymetry, leading waves from shoaling of a transient wave usually appear like a capital letter N or M [13,14]. In the same situation, numerical wave gauges from GeoClaw record similar tsunami shapes as shown in Fig. 2 when the tsunami approaching Easter Island. However, a single wave profile was captured by DART buoy, where the water is deep and there is no wave shoaling effects. Snapshots of sea surface elevation during the tsunami event are given in Fig. 3.

As shown in Fig. 2, the numerical model nearly perfectly captures the period and amplitude of the first wave at site DART 51406. The simulated tsunami arrived approximately 6 min before the observed tsunami. Such a phase shift has been previously discussed and corresponds to the dispersive effects of natural tsunami waves. However, the nonlinear shallow-water equations used in present simulations neglect dispersive effects and therefore over-predict the phase speed. From the linear frequency dispersion relation, the phase speed of tsunami waves can be estimated by

$$C_0 = \sqrt{gh}\left(1 - \frac{1}{2}k^2h^2 + O(k^4h^4)\right). \tag{1}$$

By estimating the average ocean depth as 4000 m and the leading wavelength as 200 km, we obtain a correction due to dispersive effects of $\frac{1}{2}k^2h^2 \approx 0.01$. This correction would result in approximately a 1% change in the arrival time of the leading wave; for present study, this corresponds to a 6-min difference, which nearly equals the time lag in Fig. 2 for DART 51406.

At DART 32412, the main feature of the sea surface elevation is captured. The slight discrepancy is attributed to the interaction of large-scale resonance from the coast to the edge of the continental shelf. With validation using data from the two DART gauges, the numerical tsunami propagation model provides a reliable sea surface elevation for the leading wave near Easter Island. The trailing tsunami waves near Easter Island, however, cannot be well predicted by nonlinear shallow-water equations due to the weak dispersive properties. Therefore, the magnetic field induced by the trailing waves is excluded from our analysis.

Generation of magnetic field by a conductive fluid's motion is known as the dynamo problem. The complete dynamo problem consists of the equations of motion and Maxwell equations, which are coupled by the action of the Lorentz forces. Due to the tiny magnetic strength caused by seawater's motion, the Lorentz forces exerted on seawater can be neglected, which lead to an equilibrium magnetic field. Therefore the hydrodynamic problem and dynamo problem are decoupled. Using kinematic dynamo

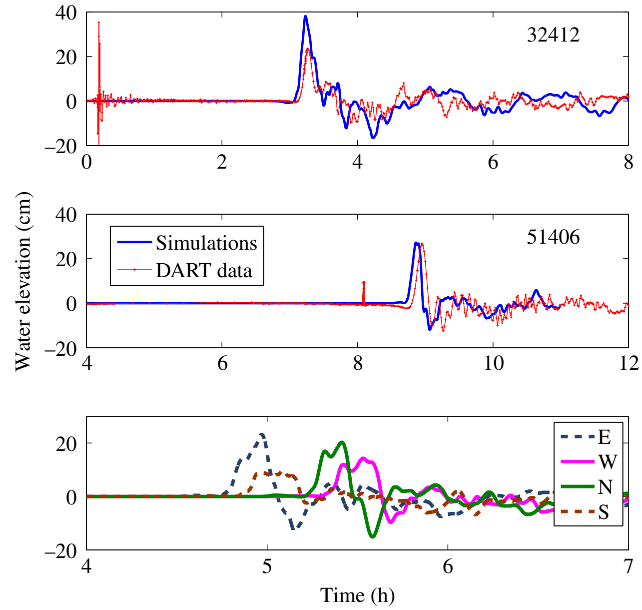


**Fig. 2.** Sea surface elevation during February 27, 2010 Chile tsunami event. DART 51406 and 32412 are two buoys for real time tsunami monitoring systems operated by National Oceanic and Atmospheric Administration (NOAA) center for tsunami research. Sea surface elevations at four numerical wave gauges around Easter Island, wherein E, W, N and S are abbreviation of each directions. These four positions are two degrees away from Easter Island.

theory, the induced magnetic field could be predicted when the seawater velocity is known.

Harmonic solutions of linear kinematic dynamo problem for linear progressive waves were obtained by many works [2,3]. Focusing in the tsunami induced magnetic field, two kinds of one dimensional simplified models are derived: the first one is based on the projection of Maxwell equation at vertical direction [15]; taken the dispersive effects into account an elaborated model was proposed recently [9]. The attenuation of the induced magnetic field could be well predicted by these two models for long waves. At sea surface, both of these two models reduce to a simple formulae: the induced magnetic field linearly depends on the sea surface elevation. The other relative parameters include the local main magnetic field, the local water depth and conductivity of the seawater.

When considering the induced magnetic field at the sea surface only, the dispersive model and long-wave approximation reduce to the same expression for long waves:

$$B^{(z)} = F^{(z)}\frac{C_0}{C_0 + iC_d}\frac{\zeta}{h}. \tag{2}$$

Here, $h$ is the local water depth and $\zeta$ is the sea surface elevation obtained from the numerical simulations with nonlinear shallow water equations. At a distance of two degrees from Easter Island, the average water depth is taken as $h = 3000$ m. $F^{(z)}$ is the vertical component of the magnetic field of Earth. The value of $F^{(z)} = 19600$ nT at Earth's surface at station IPM on Easter Island is used in this analysis, although it may vary slowly over a timescale of several hours or even over periods of months or years. $C_0 = \sqrt{gh}$ is the phase speed of the tsunami, and $C_d = 2K/h$ is the lateral diffusion speed of the magnetic field, where $K = (\mu\sigma)^{-1}$ can be interpreted as a diffusion coefficient determined by the permeability of free space, $\mu = 4\pi \times 10^{-7}$ N/A$^2$, and the electrical conductivity of seawater, $\sigma = 4$ S/m. Consequently, we set $K = 10^7/(16\pi)$ A$^2$m/(NS) in the following analysis. With these parameters, we can easily calculate the vertical magnetic field $B^{(z)}$ (e.g. the results shown in Fig. 4) from the sea surface elevation $\zeta$ by multiplying a coefficient of 4.1 at Easter Island.