Applicability of silty material brought by black tsunami to estimation of inundation area

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ABSTRACT

Tsunami is said to be recurrent according to historical sources. Estimation of inundation area of paleotsunamis have been done by finding tsunami deposit in stratum by using sandy material in it as a clue. However, Black stream of 2011 Tohoku Earthquake left silty black tsunami deposit beyond the area where sandy material is found. It was expected that silty material as additional clue will bring better accuracy to estimation of inundation area. Formation of tsunami deposit during 2011 Tohoku Tsunami was numerically simulated. Soil core samples were obtained at Sendai Plain to find silty black tsunami deposit of AD 869 Jogan Tsunami. Silty material reached 90% of distance between the front edge of inundation area and the shorelines in the simulation result of 2011 Tohoku Tsunami. Silty black tsunami deposit of AD 869 Jogan Tsunami was found from all 18 soil core samples within inundation area of 2011 Tohoku Earthquake. Silty material was found in the simulation result at 15 out of 18 sampling points. Black tsunami deposit which contains rich amount of silty material can be another clue to estimate inundation area of paleotsunamis.

Keywords: Tsunami disaster, paleotsunami, inundation area, tsunami deposit

1 INTRODUCTION

Tsunami deposit came to be well known in the world after 2011 Tohoku Earthquake (Sugawara, 2014) because it widely appeared on the land surface after a tsunami with black color. It is known that large proportion of this tsunami deposit consists of silty material and clayey material (Shishikura et al., 2012).

Tsunami is a disaster which is known to be recurrent according to historical sources. 869 AD Jogan Tsunami is a paleotsunami and thought to be former case of 2011 Tohoku Tsunami. Tsunami deposit are usually found in stratum at inundation areas not only of recent tsunami but also of paleotsunamis. The above features make it possible to estimate inundation area of paleotsunamis by finding tsunami deposit in stratum.

Sandy material has been used as a clue to know whether a layer of stratum is tsunami deposit or not. However, sandy material extended only 2.8 km while tsunami inundated up to 4.5 km inland in 2011 Tohoku Tsunami (Goto et al., 2011a). Depending only on sandy material may result in underestimation of inundation area. Additional clue for estimation of inundation area is necessary to know exact magnitudes of paleotsunamis.

Formation of tsunami deposit is a phenomenon by multiphase flow of water and sediment. Surface flow of tsunami erodes sediment at seabed and land surface. Turbulence of tsunami is increased while it flows over seabed or land surface. Sediment particles are transported by tsunami while they are kept in tsunami by its turbulence. Flow velocity of tsunami becomes smaller as its wave front goes inland. Sediment particles settle on land surface or seabed when turbulence becomes calm as tsunami slows down.

Settling velocity depends on grain size and density of sediment particles. Smaller sediment particles such as silt and clay can stay in tsunami with small turbulence. Therefore, silty material and clayey material of sediment is expected to reach farther distance than sandy material does during tsunami.

The above trend is found in previous field surveys of 2011 Tohoku Tsunami (Fujiwara et al., 2011). Muddy material even extended to the inundation limit (Goto et al., 2011a). Hence, silty material and/or clayey material in tsunami deposit is promising clue which brings better accuracy in estimation of paleotsunamis.

However, not only paleotsunamis but also 2011 Tohoku tsunami is not understood in full detail. Tsunami has many parameters which are difficult to measure such as distribution of inundation depth, distribution of flow velocity, distribution of tsunami deposit, etc. (Sugawara, 2014). For this reason, numerical simulation of tsunami has been developed to estimate inundation depth and flow velocity, etc. This is later extended to handle formation of tsunami deposit.

Numerical simulation still has limited accuracy about distribution of tsunami deposit because of the above difficulties in measurements of tsunami disaster. Validation by using results from field survey about
thickness of tsunami deposit in inundation area gives better certainty to simulation results. Thickness of tsunami deposit can be obtained by soil core sampling.

In this paper, applicability of silty material in black tsunami deposit to estimation of paleotsunami is evaluated by using numerical simulation of 2011 Tohoku Tsunami and soil core sampling of 869 AD Jogan tsunami.

2 METHOD

2011 Tohoku Tsunami and formation of tsunami deposit during this event at Sendai Plain were numerically simulated. It was validated by two aspects: inundation area and grain size distribution of tsunami deposit at several points. Soil core samples obtained at inundation area of 2011 Tohoku Tsunami were observed to find black and silty material of AD 869 Jogan Tsunami, which is recognized as the former case.

2.1 Concept of this numerical model

During a tsunami event, leading waves and drawbacks with large wavelength are repeated. In a drawback, seabed surfaces because sea water leaves the shore. In a leading wave, water flow coming from the sea erodes the surfacing seabed and transports sediments to land surface. When a leading wave reaches maximum distance from the shorelines, it becomes slow letting sediment to sink. Sediment on land surface near the shorelines are washed away by the following drawback.

Two modes are considered to achieve the above concept for transportation of tsunami deposit: bed load and suspended load. Sediment consists of multiple grain size. Sediment is assumed to be non-cohesive. No debris made by tsunami disaster is considered.

2.2 Numerical model for water flow

This numerical model starts from conservation of mass as follows.

$$ \nabla \cdot (\rho_w \mathbf{v}_w) - M_w = \frac{\partial (\rho_w S_w)}{\partial t} $$

where, $\mathbf{v}_w$ is flow velocity (m/s), $S_w$ is saturation ratio at a computational cell (-), $M_w$ is mass source term of water (kg/m³/s), $\rho_w$ is density of water (kg/m³), $t$ is time (s). Problem domain is spatially discretized by set of computational cells. $S_w$ indicates how much volume is occupied by water in each computational cell. Water depth $h$ can be given by the following equation.

$$ h = S_w H $$

where, $H$ is height of a computational cell.

Flow of water over land surface is assumed to be open channel flow. When water depth is enough shallow compared to width of a channel, distribution of horizontal flow velocity along vertical direction can be assumed to be uniform (depth-averaged). In this situation, shallow water equations can be applied. Driving force of water flow consists of gradients of topography and water depth. Combination of both gradients brings better accuracy of simulation where a slope contains non-uniform distribution of angle and/or non-negligible gradient of water depth. Hindrance to water flow is friction between the bottom and water. Friction is calculated by using Manning formula to reflect different friction according to usage of land. Difference of friction is represented by changing Manning’s Roughness Coefficient $n$ (m⁻¹/₃/s).

The above considerations lead to an equation for conservation of momentum with many terms. It takes unpractical duration of computational time. Terms with small (<1%) contribution were removed according to a sensitivity analysis on the equation for conservation of momentum.

With diffusive wave approximation, conservation of momentum is described as follows.

$$ v_x = -\frac{R_s^2}{n} \left( \frac{\partial \xi}{\partial x} - \frac{\partial h}{\partial x} \cos^2 \theta \right) \left| \text{sgn} \left( \frac{\partial \xi}{\partial x} - \frac{\partial h}{\partial x} \cos^2 \theta \right) \right| $$

where, $v_x$ is depth-averaged flow velocity in x-direction (m/s), $R_s$ is hydraulic radius (m), $\xi$ is height of an open channel (m), $x$ is coordinate in x-direction (-), $\theta$ is slope angle in x-direction (-).

2.3 Numerical model for bed load

Bed load is assumed to begin moving when dimensionless tractive force exceeds dimensionless critical tractive force.

Dimensionless tractive force is calculated by the following equation.

$$ \tau^* = \frac{\tau_0}{(\rho_s - \rho_w) g D} $$

where, $\tau^*$ dimensionless tractive force (Pa), $\tau_0$ is bottom shear stress (Pa/m²), $\rho_s$ is density of sediment particle, $g$ is gravitational acceleration (m²/s²), $D$ is grain size (m).

Bottom shear stress is described as follows.

$$ \tau_0 = \rho_w g \frac{g - n^2}{R_s^2} U^2 $$

where, $U$ is depth-averaged flow velocity.

Dimensionless critical tractive force $\tau_{c*}^*$ (-) is calculated for each grain size by using Egiazaroff’s equation (Egiazaroff, 1965).

Bed load transport rate is also calculated for each grain size by Ashida-Michigami equation (Ashida and Michigami, 1972) as follows.

$$ \frac{q_{Bi}}{q_{Bi}} \equiv \frac{q_{Bi}}{\sqrt{\left( \frac{\rho_s - 1}{\rho_w} \right) g D_i D_i}} $$

$$ q_{Bi} = 17 \left( \frac{\tau_{c*}}{\tau_{ci}} \right)^2 \left( 1 - \frac{\tau_{c*}}{\tau_{ci}} \right) \left( 1 - \frac{\tau_{c*}}{\tau_{ci}} \right) $$

where, $D_i$ is grain size (m), $q_{Bi}$ is dimensionless bed load transport rate (-) for grain size $D_i$, $\tau_{Bi}$ is bed load transport rate (m³/s/m), $\tau_{ci}$ is dimensionless tractive
force (-) for grain size $D_i$, $\tau_{ci}^*$ is dimensionless critical tractive force (-) for grain size $D_i$. When sediment consists of multiple grain size, proportion of amount for one grain size to amount for all grain size must be multiplied to right hand side of Eq. 7.

### 2.4 Numerical model for suspended load

Generation rate of suspended load from bed to water is evaluated by balance between sinking and rising of sediment. Transportation of suspended load by water flow is represented by advection-diffusion equation.

Conservation of mass for suspended load is described as follows.

$$\nabla \cdot (\rho_{s,i} \mathbf{v}_w) + \nabla \cdot \left[ \varepsilon_{i} \nabla \rho_{s,i} \right] + M_{s,i} = \frac{\partial (\rho_{s,i} S_{w} C_i)}{\partial t} \quad (8)$$

where, $\rho_{s,i}$ is density of sediment particle (kg/m$^3$) for grain size $D_i$, $C_i$ is volumetric concentration of sediment in water (m$^3$/m$^3$) for grain size $D_i$, $M_{s,i}$ is mass source term of sediment (kg/m$^3$/s) for grain size $D_i$, $\varepsilon_{i}$ is eddy diffusion coefficient (m$^2$/s) for grain size $D_i$. Sinking and rising is included in mass source term.

Eddy diffusion coefficient is calculated as follows.

$$\varepsilon = \frac{1}{6} \kappa u^* h \quad (9)$$

where, $\varepsilon$ is eddy diffusion coefficient (m$^2$/s), $\kappa$ is von Kármán constant, $u^*$ is friction velocity.

Mass source term can be evaluated when the concentration of suspended sediment with depth is given. It can be obtained by Rouse Profile of suspended sediment or the Lane-Kalinske model (Lane and Kalinske, 1941). Settling velocity of sediment is calculated by Rubey’s equation (Rubey, 1933a). Generation flux of suspended load is calculated by formula of Itakura and Kishi (Itakura and Kishi, 1980).

### 2.5 Deformation of topography

Changing in elevation of topography is calculated concerning bed load and rising and sinking of suspended load.

### 2.6 Numerical simulation of 2011 Tohoku tsunami

Problem domain of this simulation was Sendai Plain and Gulf of Sendai between lower reaches of Nanakita River and Abukumagawa River (Fig. 1). Topography of land surface is based on Fundamental Geospatial Data (5 m or 10 m grid elevation) by Geospatial Information Authority of Japan (GSI). Topography of seabed is based on J-EGG500 (JODC-Expert Grid data for Geography -500m) by Japan Oceanographic Data Center (JODC). Topography of riverbed is based on basic maintenance plans for major rivers. They are combined into one topography (Fig. 1).

Boundary condition of flow rate is given to the boundary where is river. Flow rate of rivers are obtained from Water Information System by Ministry of Land, Infrastructure, Transport and Tourism of Japan. Boundary condition of water level is given to the problem domain where is underwater when the water level is minimum during drawbacks. Tsunami waveform at Soma and Iwaki of 2011 Tohoku Tsunami was used as fluctuating water level of boundary. Transportation of water and sediment is calculated at problem domain where the above boundary condition is not given.

Sediment was set to consist of four grain sizes (0.55, 0.15, 0.05, 0.001 mm) based on results of field survey by National Institute of Advanced Industrial Science and Technology (AIST) at several locations (Fig. 1, S085, S087~S090). Thickness of sediment exchange layer was set to 1 m.

### 2.7 Observation of soil core sample

Percussion type sampler is used to obtain soil core sample. Drilling depth was up to 3 m. 5 sampling locations (Fig. 1) were chosen where traces of AD 869 Jogan Tsunami are thick (Sawai et al., 2008). 18 soil cores were taken. They were cut in half along a plane passing through its central axis to observe stratum.

### 3 RESULTS

#### 3.1 Validation by inundation area

Inundation area in the simulation (Fig. 2) was in a good agreement with 1:100,000 Tsunami flood area overview map (Sendai Area) by GSI (Fig. 2). Maximum distance between the shorelines and the front edge of the inundation area was up to 5 km.
3.2 Distribution of tsunami deposit in simulation

Silty material of tsunami deposit (0.05 mm) reached about 4.5 km from the shorelines (Fig. 3). It was not found within about 1.5 km from the shorelines.

Sandy material of tsunami deposit (0.55 or 0.15 mm) reached about 3–4 km from the shorelines (Fig. 4, Fig. 5). It was not found within about 0.5–0.75 km from the shorelines. This result is consistent with previous field survey (Goto et al., 2011a).

Contrary to the above coarser material of tsunami deposit, clayey material (0.001 mm) was not found on land surface.

Grain size became smaller as the distance from the shorelines gets larger. Thickness of tsunami deposit tends to be thinner in every grain size as it reaches farther distance. These behaviors also match with previous field surveys (Fujiwara et al., 2011, Goto et al., 2011a).

3.3 Validation by grain size distribution

Silt and clay were dominant at S085, S088, and S089 in the soil samples and the simulation result (Fig. 3–5).

Fine sand, silt, and clay had a rate of about 27% for each at S087 in the soil sample. This was not reproduced in the simulation result because there was almost no silt.

Coarse sand and fine sand were dominant at S090 in the soil sample. The simulation result was different from this because silt was dominant at S090. From above, grain size distribution of tsunami deposit was successfully simulated at 3 out of 5 locations (Fig. 3–5).

3.5 Tsunami deposit of AD 869 Jogan Tsunami

Soil layers which are expected to be AD 869 Jogan tsunami were found in soil cores between depth range from 16 cm to 53 cm. They had thickness of 3–25 cm (Fig. 6).

AI-1, AI-1’, AI-1”, AI-2, UM-1, UM-2, UM-2’, and YT-2’ cores had a layer of Jogan Tsunami (Fig. 6). Two area of black and greyish brown was observed. It consists of multiple grain size up to fine sand. At AI points, thickness of tsunami deposit in the simulation result was very thin. At UM points, tsunami deposit in the simulation result was almost silt. At YT-2’’, Grain size configuration were similar to the simulation result of 2011 Tohoku Tsunami.

AH-2’, AH-2’’, NT-1, NT-2, NT-2’, and YT-1, cores had a layer of Jogan Tsunami (Fig. 6). Distorted striped pattern of black and greyish brown was observed. The layers consist of multiple grain size up to fine sand. Grain size configuration were similar to the simulation result of 2011 Tohoku Tsunami.

AH-1, AH-2, and YT-2” cores had a layer of Jogan Tsunami (Fig. 6). The layers were black and consist of silt and clay. The soil layers had more silt than the simulation result of 2011 Tohoku Tsunami.

Fig. 3. Distribution of silty material (0.05 mm) by numerical simulation. Area with red circle is lower than surrounding land.

Fig. 2. Inundation area by simulation (left) and 1:100,000 Tsunami flood area overview map (Sendai Area) by GSI.
YT-2 and YT-2’ core had two layers of Jogan Tsunami (Fig. 6). Upper layers were black and silty. Lower layers were distorted stripe of black and greyish brown. It consists of multiple grain size up to fine sand or coarse sand. Grain size configuration of lower layer is similar to the simulation result of 2011 Tohoku Tsunami.

Black layer of tsunami deposit was found from 5 core samples and were silty. It also appeared in the rest 14 samples as one component of stripe pattern consists of two colors.

4 DISCUSSION

4.1 Applicability of silty material of black tsunami deposit to estimation of inundation area

Silty material of tsunami deposit reached up to 90% of the distance between the shorelines and the front edge of inundation area in the simulation result of 2011 Tohoku Tsunami. Silty black layer in tsunami deposit of AD 869 Jogan Tsunami appeared in 18 out of 18 soil core samples taken from inundation area of 2011 Tohoku Tsunami. In the simulation result, silty material was found at 15 out of 18 points of soil core sampling. The simulation result is consistent with soil core samples. AD 869 Jogan Tsunami is said to be former case of 2011 Tohoku Tsunami according to historical sources. Therefore, it can be said that silty black tsunami deposit is promising additional clue to know the inundation area of paleotsunamis.

4.2 Where to look for silty black tsunami deposit of paleotsunamis

According to the simulation result, silty material of tsunami deposit with thickness more than 50 cm was found mostly at canals, ponds, and place which has lower elevation than surrounding land such as south to UM and NT.
west to NT. This is thought to be a result of general rule of sediment transportation and slow settling velocity of silty material. When tsunami goes into those places, it becomes difficult to stay flowing and finally stops. This makes silty material to settle on land. The above sedimentation seems to be also happening with less scale at rice paddies around UM because they are designed to keep water inside.

Silty tsunami deposit was not found within 1.5 km from the shorelines. Within this area, both leading waves and drawbacks are fast. This erodes silty material at the bottom and do not let it settle down on land.

According to the above sedimentation behavior, a place which is far from shorelines by at least 1.5 km and lower than surrounding land can be good location to find silty black tsunami deposit of paleotsunamis.

4.3 Behavior of clayey material
Clay (0.001 mm) has very slow settling velocity of about 10^{-5} m/s. It cannot settle on land surface even in slow flow of tsunami. One possible situation for clay to settle on land surface is to be kept in places lower than surrounding land. This behavior is expected to be represented in simulation by concerning underseepage and volatilization.

5 CONCLUSIONS
Applicability of silty black tsunami deposit to estimation of paleotsunamis was evaluated. Numerical simulation of 2011 Tohoku tsunami was done and validated by inundation area and grain size distribution of tsunami deposit. Silty material of tsunami deposit reached farther distance than sandy material in the simulation of 2011 Tohoku Tsunami. Silty black tsunami deposit of AD869 Jogan Tsunami was found within inundation area of 2011 Tohoku Tsunami. Silty black tsunami deposit is promising additional clue to estimate paleotsunamis with better accuracy.

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