PREDICTIVE MODEL FOR SCOUR DEPTH OF COASTAL STRUCTURE FAILURES DUE TO TSUNAMIS

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Post-tsunami field surveys carried out after the 2011 Great Eastern Japan Earthquake Tsunami revealed that scour around the landward side of concrete sea dikes and seawalls was the most dominant failure mechanism. To better understand this phenomenon, detailed scour data were collected and soil samples from the surveyed locations in Miyagi and Fukushima Prefectures of Japan were comprehensively analysed. Mathematical modeling technique was employed with various combinations of input variables considered in order to determine the effective variables needed to predict the representative scour depth at the leeward of a concrete sea dike or seawall and possible design of these coastal structures against tsunami impact. Parameters such as impact overflowing pressure, height of structure measured at the landward side, inundation height, inundation velocity, angle of landward slope, Darcy's coefficient of permeability and scour depth were found to be the effective parameters essential to generate proposed scour depth predictive model. The results indicate that the hydrodynamic parameters, soil properties and physical geometry of coastal structure play a crucial role in the scour process of such structures. In addition to that, numerical experiments were also performed in order to understand the characteristics of tsunami flow around a typical coastal dike, and to propose preliminary guidelines for structure resilience against future tsunamis.

Keywords: 2011 Great Eastern Japan Earthquake Tsunami; mathematical modeling; impact overflowing pressure; representative scour depth; scour depth predictive model

INTRODUCTION

Scour failure of coastal dikes and seawalls as a result of tsunami is a complex mechanism which has not been fully understood by the coastal researchers. It is one of the many failure patterns of coastal defense structures and poses one of the greatest threats to their structural performance. Yeh and Li (2008) reported about the scour depth created between breakwaters at Okushiri Port in Japan, by the 1993 Okushiri tsunami attack, and a large scour hole created at the entrance to Kasenuma Port, Japan by the 1960 Chilean tsunami. While many past scour research work have focused primarily around bridge structures (Breusers and Raudkivi 1991; Melville and Coleman 2000), and vertical cylinders (Sumer et al. 2001; Zhao et al. 2010), the need to study tsunami-induced scour around coastal structures such as seawalls and sea dikes, has been greatly influenced by the extensive damage caused by the 2011 Great Eastern Japan Earthquake Tsunami.

Kato et al. (2012) carried out an extensive field surveys and hydraulic model experiments on tsunami-induced dikes and estimated that 49.2% of the eight failure patterns studied was as a result of scouring at landward toe. Survey results that were carried out after the 2011 Tohoku tsunami attack revealed that the coastal defences might have been built to withstand storm surge conditions and not the high pressure associated with the tsunami bore. Numerous structures were partly or completely damaged at many locations in Miyagi and Fukushima prefectures of Japan. Scour holes were noticed at the leeward slope and artificial ponds were formed at the leeward of the damaged structures. The aftermath of tsunami damage to coastal defences is a proof that there is a need to improve coastal dikes against future tsunami risks.

The mechanisms of scour and coastal structure instability under tsunami-like loadings are not sufficiently understood. In this paper, a simple predictive scour depth model around seawalls and sea dikes, and numerical experiments performed to study the behaviour of tsunami flow around a coastal dike are presented.

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FIELD SURVEYS OF COASTAL STRUCTURE FAILURES

Detailed field surveys such as scour depth and extent, geographical information, tsunami deposit samples and linear measurements of damaged dike sections due to the 2011 Great Eastern Japan Earthquake Tsunami were carried out at five different locations along the coastline of Miyagi and Fukushima prefectures in Japan by the authors (Jayaratne et al. 2013). The inundation heights (h), measured at leeward of each dike were obtained from The 2011 Tohoku Earthquake Tsunami Joint Survey Group (2012). The field data was broadly analysed to reveal the variations among the hydraulic, geometrical and sediment parameters. The measured and estimated scour data were based upon the accessibility to the scour features in the field. Dimensions taken off the sea dikes and seawalls were used in the wave pressure calculations at all locations. The scour depth measurements (D_s), were the representative maximum values along the stretch of the coastal structures surveyed. Table 1 shows the longitude and latitude of locations surveyed while Figure 1 illustrates the location of map of cities surveyed in Miyagi and Fukushima prefectures in Japan by Jayaratne et al. (2013).

Table 1. Coordinates of locations surveyed.

Surveyed Location	Longitude	Latitude
Ishinomaki Port	141°18.312′	38°24.895
Iwanuma City	140°55.311′	38°03.224′
Watari Town	140°55.283′	38°02.262′
Yamamoto Town	140°54.930′	37°57.613′
Soma City	140°59.400′	37°46.165′

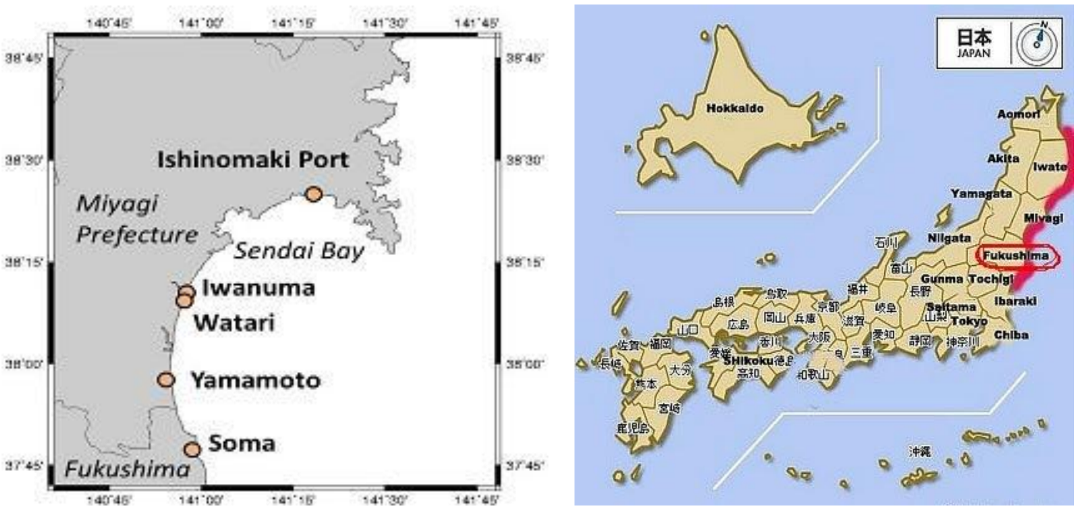

Figure 1. Location map of surveyed cities by Jayaratne et al. (2013).

Ishinomaki Port

Ishinomaki is one of the major cities in Miyagi Prefecture of Japan. According to the *2011 Tohoku Earthquake Tsunami Joint Survey Group (2012)*, it was among the cities most affected by the tsunami. Substantial scour depths were measured behind the 2.5 m high seawall (Fig. 2) protecting the hinterland. The walls were overtopped by the tsunami as the inundation height at the location was determined as 6.0 m (The 2011 Tohoku Earthquake Tsunami Joint survey Group, 2012). Representative tsunami deposit samples were also taken for particle size analysis. The degree of damage in the leeward slope and toe appeared to depend on the size and shape of structural elements (Jayaratne et al. 2013). The scour predictive model to be developed would be used to verify this claim.

Figure 2. Damaged seawall at Ishinomaki port.

Iwanuma City

Iwanuma city is located in Miyagi prefecture and founded in 1971. The leeward slope and toe of most sea dikes in this city completely collapsed due to the tsunami attack. The seaward slope was covered with tsunami deposit and vegetation layer at the time of survey. Maximum scour depth around dike toe was measured as 2.5 m and the soil samples were taken at this location in order to analyse the tsunami deposit conditions. It was clear from the original design of this structure that these dikes were built to protect against wave overtopping under storm surge conditions. A recurring formation of pool of water is also noticeable in this location (Fig. 3).

Figure 3. Damaged structure at Iwanuma city.

Watari Town

Watari town is located on the southern part of Miyagi Prefecture, close to Abukuma. A rubble mound revetment was placed in front of the sea and a 4.6 m curved seawall at 13.43 m from the leeward slope of the revetment. The curved seawall, though erected to protect against storm surges caused by the typhoons, was unable to perform its intended function as maximum scour depth of 4.06 m was measured and massive destruction to the seaward slope and seawall at this location was observed. The overtopping tsunami wave caused scouring at the back of the dike. This undermined their structural integrity and lead to the exposure of the central sand and gravel core, which was then easily eroded and caused the subsequent collapse of the structure. The aftermath of the event caused the formation of pool of water behind the seawall (Fig. 4), similar to the damaged structure at Soma city.

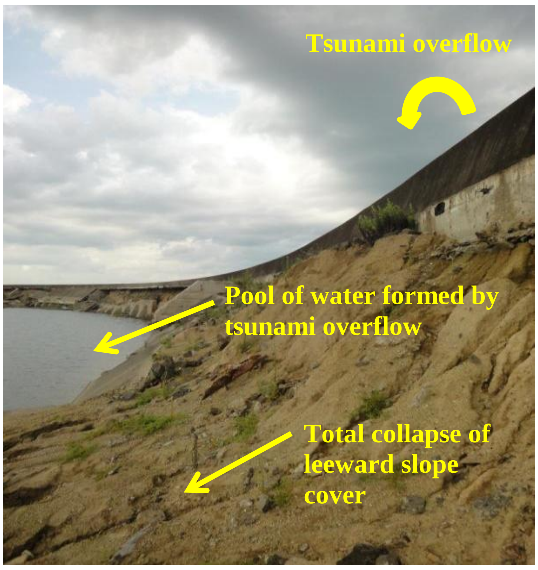

Figure 4. Damaged structure at Watari town.

Soma City

Soma city is situated in the north-eastern part of Fukushima prefecture and has a port that is situated in its northern part. An enormous damage to sea dike and large scour depths were observed at this location due to tsunami wave run-up. The large surge and impact forces generated by the tsunami flow created large pool of water after the event. Only four maximum scour depth measurements were taken due to the difficulty of accessing the damaged areas. A lot of damage to the toe of the dike was prevalent and concrete slab sections on the leeward slope were greatly ripped apart in most locations as seen in Fig. 5.

Figure 5. Damaged structure at Soma city.

PREDICTIVE MODEL FOR REPRESENTIVE SCOUR DEPTH

A new scour depth predictive model was developed using the impact overflowing wave pressure (P_{om}) model of Mizutani and Imamura (2001) and inundation flow velocity (U) model of Matsutomi et al. (2010) to propose an appropriate geometry that will improve the structural stability of concrete dikes and seawalls under tsunami attack. This proposed model was combined with other vital non-dimensional terms (geometrical and sediment properties) using Buckingham pi theorem and coefficients were calibrated with tsunami field data gathered by the authors in 2011 and 2012. The results of particle size distribution curves at each surveyed locations (grain diameter, D_{10} and Darcy's coefficient of permeability, k) were embed as boundary conditions in the formulation.

Grain Size Analysis

The particle size distribution curve as shown in Fig. 6 reveals that the soil grains are predominantly single-sized sand because the particle size ranges from 0.063-2.0 mm. Since the samples are uniformly graded, the Darcy's coefficient of permeability (k) which is a measure of the ease with which water can flow through the voids of soil particles could depend on the void size, which is related to particle size. The empirical relationship of coefficient of permeability for clean filtered sand is given by Hazen (1892: cited by Powrie 2004) as in Eq. (1).

$$k\ (\mathrm{m/s}) = 0.01D^2_{10} \qquad (1)$$

The coefficient of permeability (k) of the soil grains behind the coastal structures were derived using particle size analysis in order to set the boundary condition for the proposed model and thus preserve its applicability. The deduced values of coefficient of permeability for tested soils fall in the range of 0.000144 and 0.00114.

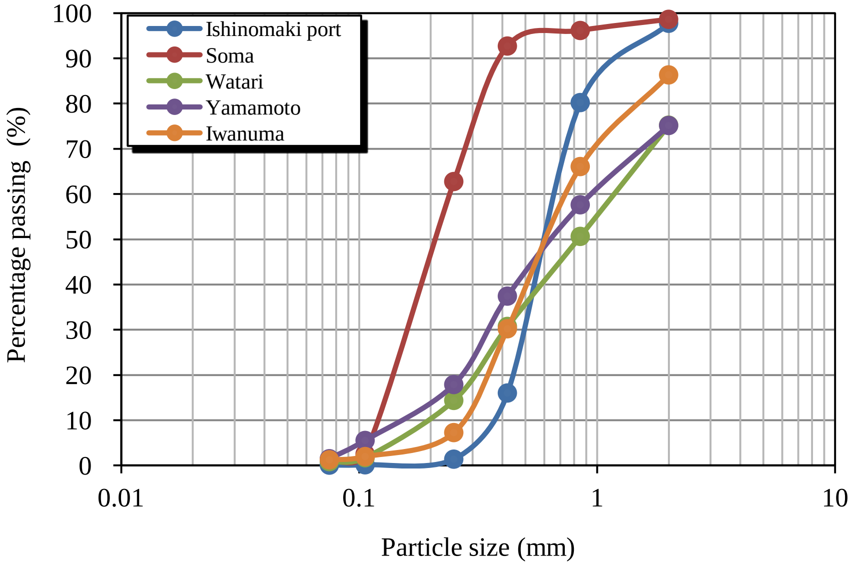

Figure 6. Particle size distribution curves for tsunami deposit samples.

Predictive Model

Figure 7 is generated on the assumption that by applying the Buckingham pi theorem, relative impact overflowing wave pressure is related to the relative scour depth (D_s) at damaged structures. It can be observed from the trend of the data that a decreasing exponential function seems to exist between the relative scour and the inverse of relative impact overflowing pressure. The average error of the function was reduced using the Solver tool in MS spreadsheet application package to 0.05.

The final model that incorporates measurable *in-situ* quantities is developed as:

$$\frac{D_s}{H_{d2}} = \lambda\left(exp - \left(\frac{\sqrt{H_{d2}}}{2\lambda\sqrt{h}\,sin\theta_2}\right)^4\right) \Bigg\} \begin{array}{l} h > 0 \\ 10^{-4} < k < 10^{-3} \end{array} \qquad (2)$$

where; H_{d2}=height of coastal structure measured from the leeward toe, h=inundation height, θ_2=angle of leeward slope, =scour coefficient (=0.85) and g=gravitational acceleration.

The following deductions can be made from the scour predictive model:

- High impact overflowing wave pressure will generate a high relative scour depth.
- For given angle of landward slope, higher sea dike will minimise scour.
- The higher the inundation height, which is a function of flow velocity, the higher the possible scour depth. It agrees with the general fact that high flow velocity will cause high shear stress which in turn will cause scour.
- Higher sea dike and seawall with mild landward slope tends to decrease scour depth.

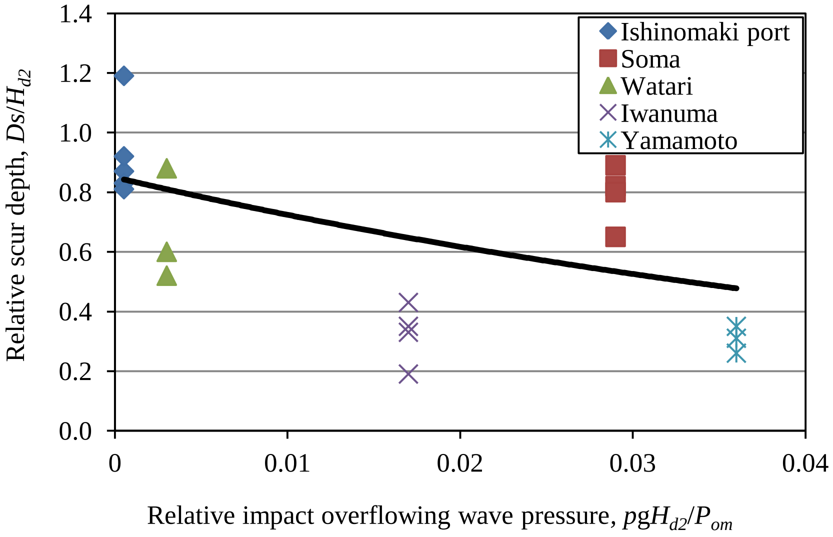

Figure 7. Relative scour depth vs. Relative impact overflowing wave pressure.

NUMERICAL EXPERIMENTS

A one phase (liquid-phase) Large Eddy Simulation (LES) model of Mikami and Shibayama (2013) was applied to simulate the estimated wave overflowing pressures and inundation flow velocities at the leeward slope and toe of the structures. The governing equations are the spatial filtered Navier-Stokes equations along with the continuity equation. The Cubic Interpolated Pseudo-particle (CIP) method is employed to solve the governing equations and the Successive Over-Relaxation method is employed to solve the pressure equation. The free surface position is calculated using the density function method. The Smagorinsky (1963) model was used to estimate the Sub Grid Scale (SGS) stresses acting on the fluid flow.

Figure 8 depicts the time variation of pressure, vorticity and velocity around a typical coastal dike in Soma city, produced at a laboratory scale. When t=1.0 s tsunami wave approaches the seaward toe of the structure and at t=2.0 s large pressures such as 3.0 KN/m^2 are generated at the seaward slope and toe, and subsequently at the leeward toe. An air entrapment is noticed on the seaward slope, between wave wall and leeward toe from the numerical model results. The pressure at the leeward slope and its toe reduces as time increases from t=2.0 s to t=3.0 s and further reduces from t=3.0 s to t=4.0 s. Large velocities are developed on the leeward slope when t=2.0 s as the flow is subjected to super critical condition. The maximum velocities generated under such flow conditions are in the range of 1.5 m/s. Numerical results also revealed two distinctive types of tsunami wave phases such as impact and overtopping phases which create massive pressures and velocities either on seaward slope/toe and leeward slope/toe.

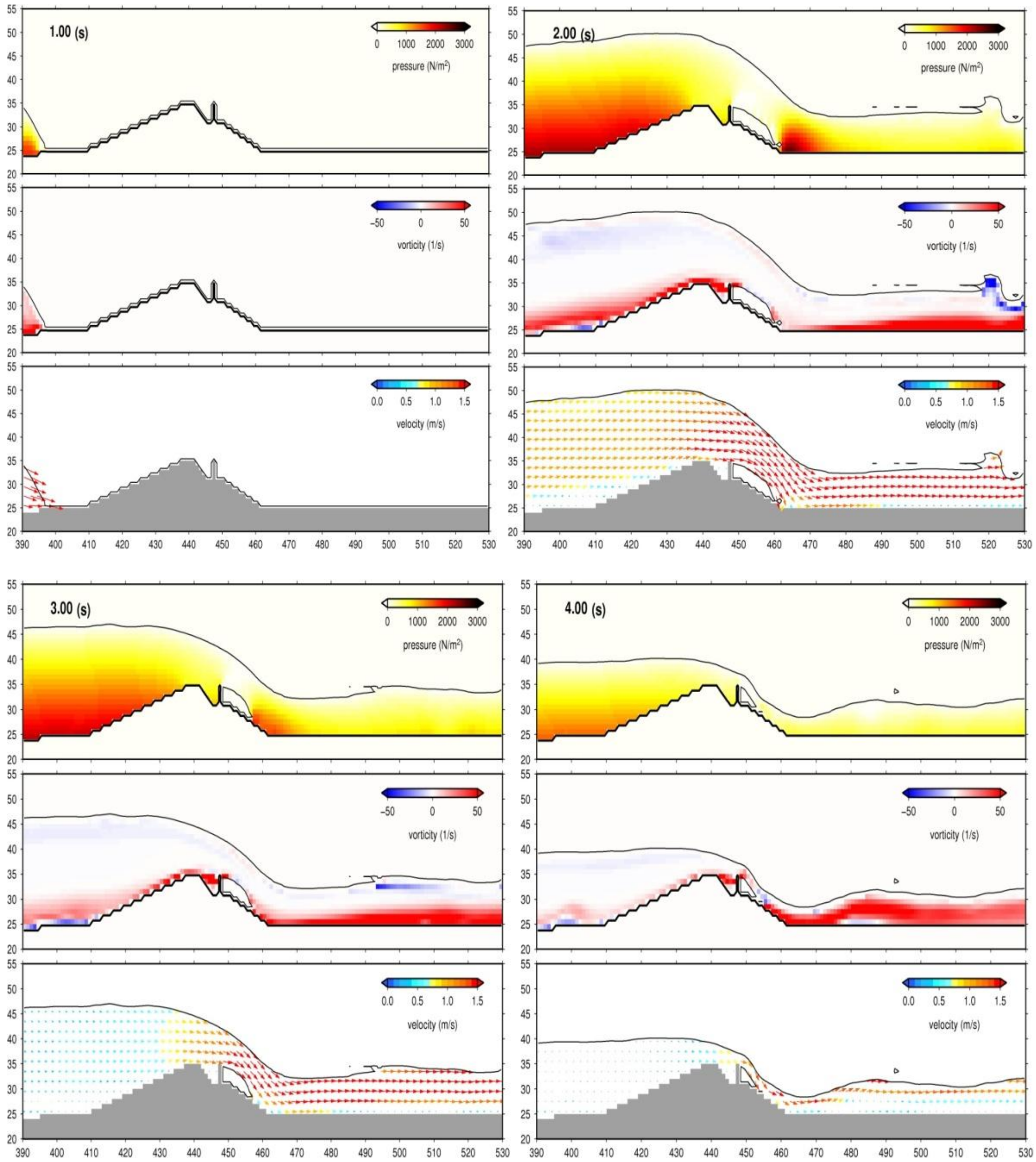

Figure 8. Calculated numerical results of pressure, vorticity and velocity fields around a sea dike at Soma city (t=1.0, 2.0, 3.0, 4.0 s).

CONCLUSIONS

The complexity of tsunami flow conditions and their relationship with scour failure mechanism of sea dikes and seawalls is evident. Tsunami scour profiles and depths are known to be dependent on the soil, water and structure interaction. A simple mathematical model for representative scour depth at the leeward toe of coastal structures is developed in terms of measurable parameters for a given tsunami event. The model allows for variation of physical geometry of sea dikes and seawalls in order to determine best possible tolerable design, which can ultimately be used to improve coastal structure design. It shows that soil permeability, angle of landward slope, height of sea dike measured from landward side, inundation height which is a function of inundation flow velocity strongly determine scour depth.

Numerical analysis was performed in order to understand the characteristics of tsunami flow around coastal dikes during the 2011 Great Eastern Japan Earthquake Tsunami. A dam break flow was used to simulate an overtopping flow in the numerical model. Based on the numerical results, the pressures acting on a coastal dike and the velocity field around it show that two distinctive phases can be identified, namely an impact and an overtopping phase.

Based on the field survey observations, deductions from scour predictive model and numerical analysis, it is suggested to extend and strengthen the toe of the landward side of the coastal dikes and seawalls in Miyagi and Fukushima prefectures of Japan. However, detailed analysis (e.g. laboratory experiments and further numerical modelling) is required in order to come up with definite parametric values of geometry of the structure to resist future tsunami attack.

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