Liquefaction Analysis of Sandy Ground due to Tsunami

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SUMMARY

The 2011 off the Pacific coast of Tohoku earthquake causes large scale of Tunami and the huge areas have been damaged. This is probably because of the huge force due to Tunami(JSCE investigation report, 2011). In addition, it is known that the high tidal wave causes the liquefaction in the sea bed(Oka et al. 1994). These studies are, however, dealing with the short period wave such as tidal one. For the tsunami, we need to study the effect of the wave with the longer period, i.e., 10-60 minutes. In the present study, we have studied the liquefaction potential and the change of the effective stress due to the change of the water pressure caused by tsunami by using a liquefaction simulation method.

Keywords: Tsunami, Liquefaction, Degradation of Ground, liquefaction analysis

1. INTRODUCTION

The 2011 off the Pacific coast Tohoku earthquake generated large scale of Tunami and the huge areas have been damaged. In Onagawa town of Miyagi prefecture, the reinforced concrete building has been damaged by pulling up the foundation pile. This is probably because of the huge force due to Tunami. In addition, it is known that the high tidal wave causes the liquefaction in the sea bed (Oka et al. 1994) (**Figure 1.1**). Sassa et al.(2001) studied the liquefaction of the sea bed and its propagation considering the fully liquefied soil as a viscous fluid. Then Liu et al.(2008) extended their theory considering the two-layer fluid model of liquefied fluid and the surrounding region. These studies are, however, dealing with the short period wave such as tidal one. For the tsunami, we need to study the effect of the wave with the longer period, i.e., 10-60 minutes. In the present study, we have studied the liquefaction potential and the change of the effective stress due to the change of the water pressure caused by tsunami by using a liquefaction simulation method.

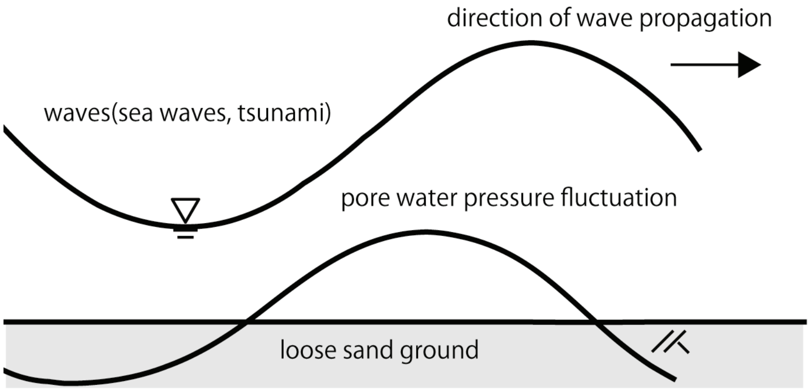

Figure 1.1. Submarine ground affected by waves

2. ANALYSIS METHOD

There are two reasons for the liquefaction of the sea bed. One is the principle stress rotation and the other is the compressibility of the pore water. The compressibility of the pore water leads to the retardation of the dissipation of the pore water pressure against the change of the applied water pressure on the sea bed surface. In the numerical analysis, we used the numerical code based on the elasto-plastic finite element method called "LIQCA2D". This method has been developed based on the u-p formulation by the research group including the authors of this paper and has been successfully applied to the liquefaction problems(Oka et al., 2009, 2011). In the numerical simulation of the propagation of tsunami, we used a leap-frog scheme with staggered grid for the finite difference method (Goto et al., 1997).

2.1. Stress variables for the mixture

The total stress tensor is assumed to be composed of two partial stresses for each phase.

$$\sigma_{ij} = \sigma_{ij}^{s} + \sigma_{ij}^{f} \tag{2.1}$$

where σ_{ij} is the total stress tensor, and σ_{ij}^{s}, σ_{ij}^{f}, and σ_{ij}^{a} are the partial stress tensors for solid, liquid, and gas, respectively. The partial stress tensors for unsaturated soil can be given as follows:

$$\sigma_{ij}^{f} = -nS_r p^f \delta_{ij} \tag{2.2}$$

$$\sigma_{ij}^{s} = \sigma'_{ij} - (1-n) p^f \delta_{ij} \tag{2.3}$$

where σ'_{ij} is the effective stress tensor, p^f is the pore water pressure, respectively, n is the porosity. Using Eqs. (2.1), (2.2) and (2.3), we have the total stress tensor as

$$\sigma'_{ij} = \sigma_{ij} + p^f \delta_{ij} \tag{2.4}$$

2.2. Constitutive equations for solid and fluid

The constitutive equation for soil skeleton is given based on the elasto-plasticity theory (Oka et al., 1999) as

$$d\sigma'_{ij} = D_{ijkl}^{EP} d\varepsilon_{kl}^{s} \tag{2.5}$$

where D_{ijkl}^{EP} is an elasto-platic modulus, $d\sigma'_{ij}$ is the effective stress increment and $d\varepsilon_{kl}^{s}$ is the strain increment of soil skeleton. For the pore water, the material is elastic fluid as

$$p^f = -K^f \varepsilon_{ii}^{f} \tag{2.6}$$

where K^f is the volumetric elastic coefficient of the pore water, ε_{ii}^{f} is the volumetric strain of liquid.

2.3. Equation of motion and continuity equation

The equations of motion for the whole mixture are defined as

$$\bar{\rho}\ddot{u}_i^{s} = \frac{\partial \sigma_{ij}}{\partial x_j} + \bar{\rho} b_i \tag{2.7}$$

where $\bar{\rho}$ is the mass density of the mixture, $\ddot{u}_i^{s}$ is the acceleration vector of the solid phase, b_i is the body force vector and σ_{ij} is the total stress tensor.

Incorporating the constitutive equation for pore water, $p^f = -K^f \varepsilon_{ii}^f$ (K^f : volumetric elastic coefficient of liquid, ε_{ii}^f : volumetric strain of liquid) into the above equation leads to the following continuity equation for the liquid phases:

$$-\frac{\partial}{\partial x_i}\left[\frac{k^f}{\gamma_w}\left(\rho^f \ddot{u}_i^s + \frac{\partial p^f}{\partial x_i} - \rho^f b_i\right)\right] + \dot{\varepsilon}_{ii}^s + \frac{n}{K^f}\dot{p}_r^f = 0 \tag{2.8}$$

where γ_w is the unit weight of water and k^f is the permeability coefficient.

2.4. Compressibility of the pore water

Following Okusa(1976), we use a relationship between saturation S_r and volumetric elastic modulus K^f of the water as

$$m_w = m_{w0}S_r + \frac{1-S_r}{P_{mg}} = \frac{1}{K^f} \tag{2.9}$$

where K^f =5880kPa for the saturation of 98%, m_w is compressibility of water considering a air bubble, m_{v0} is a value of m_w when saturation is 100% , P_{mg} is an absolute pore pressure.

3. RESPONSE OF SAND GROUND DUE TO TSUNAMI INUNDATION DEPTH CHANGE

3.1. Analysis Conditions

We assume a ground model at Gobo city of Wakayama prefecture in Japan where the huge tsunami is assumed by the expected Tokai-Tounankai-Nankai earthquake. The ground model is shown in **Figure 3.1.** with a loose sandy layer followed by the impermeable clay layer. Several ground are used with different N1 value (converted N value; Japan Road Association, 2009). N1 =5 is the most loose sandy soil. The material parameters are listed in **Table 3.1.** The liquefaction strength curve is shown in **Figure 3.2.** The soil parameters have been determined by fitting the liquefaction strength curve shown in **Figure 3.2.**

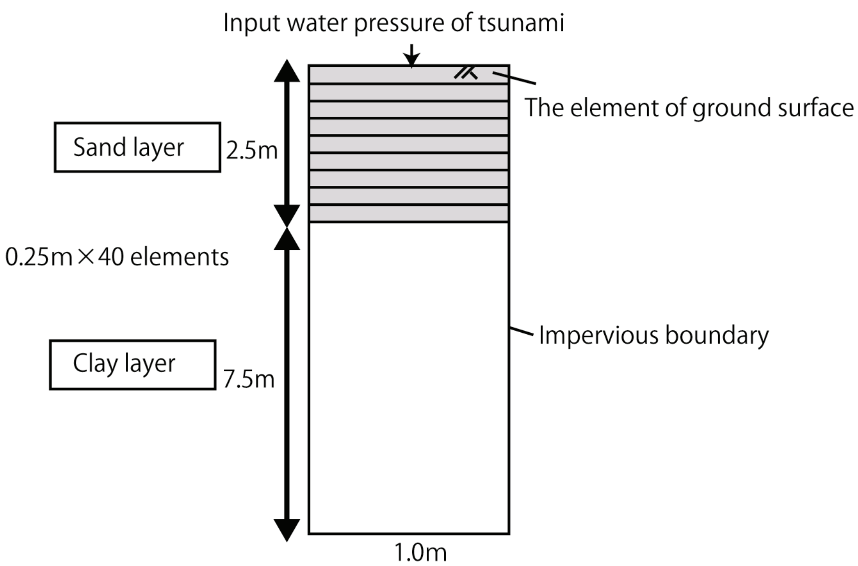

Figure 3.1. Ground model

The tsunami inundation depth change as the input data of this analysis is shown as a broken line in **Figure 3.4.**.This wave profile has been computed at the distant of 1.0km on the land area in **Figure 3.3.** by the tsunami inundation simulation. The sine wave has been imputed from a left hand side boundary shown in **Figure 3.3.**. We used a sine wave for simplicity and the amplitude is 5.0m and the period is 20 minutes.

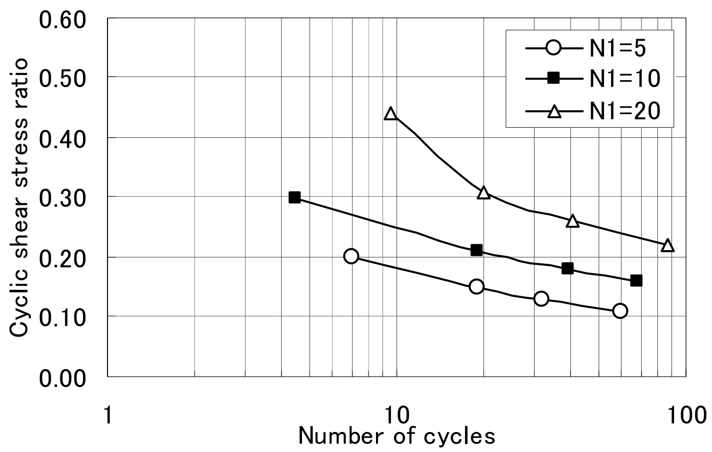

Figure 3.2. Simulated liquefaction strength curve

Table 3.1. Material parameters for sandy soil

Parameters	N1=5	N1=10	N1=20
Initial void ratio e_0	0.800	0.800	0.800
Compression index λ	0.025	0.025	0.025
Swelling index κ	0.0025	0.0025	0.0025
Int.shearcoefficient ratio G_0/σ'_{m0}	374.0	594.0	943.0
Permeability k (m/s)	1.0×10-5	1.0×10-5	1.0×10-5
Density ρ (t/m^3)	2.0	2.0	2.0
Stress ratio at PT M_m^*	0.91	0.91	0.91
Stress ratio at failure M_f^*	1.13	1.13	1.34
Hardening parameter B_0^*	2000	2500	5000
Hardening parameter B_1^*	110	59	46
Hardening parameter C_f	0	0	0
Elastic modulus of water K_f (kPa)	2.0×105	2.0×105	2.0×105
Quasi-OCR OCR*	1.0	1.2	1.5
Dilatancy parameters D_0^* ,n	1.0, 2.0	1.0, 3.0	1.0, 3.0
Plastic ref. strain γ_{ref}^{P*}	0.0035	0.0035	0.0035
Elastic ref. strain γ_{ref}^{E*}	0.005	0.005	0.005

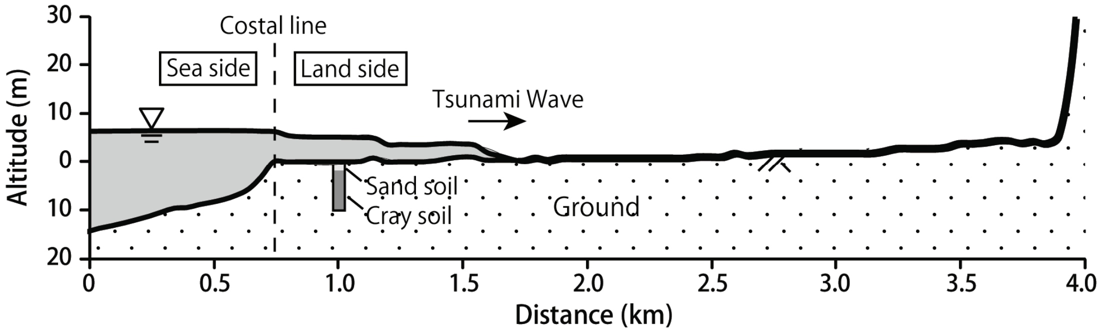

Figure 3.3. Topographic model

3.2. Numerical Results

From the analysis, we have obtained a time profile of the effective stress decreasing ratio (ESDR) in **Figure 3.4.** at depths of 1m and 2.5m. The ratio is defined as

$$ESDR = 1 - \frac{\sigma'_m}{\sigma'_{m0}} \tag{3.1}$$

where σ'_{mo} is the initial value of the mean effective stress. ESDR indicates the degree of liquefaction.

From **Figure 3.4.**, we can see that the effective stress increases due to the increase of the water depth associated with the progress of tsunami at 1 stage illustrated as ① shown in **Figure 3.4.** The at the second stage as ② shown in the figure, The effective stress decreases associated by the seepage flow induced by the gradient of the pore water pressure even at a depth of 2.5m .Then the effective stress gradually decreases but almost become constant.

Table 3.2. shows the maximum value of ESDR for different N1 value. This table indicates that the relatively loose sandy soil, i.e., N1 is less than 10, the ground deteriorates below at a depth of 1m.

4. SENSITIVITY ANALYSIS OF TSUNAMI INUNDATION HEIGHT AND PERIOD

In this chapter, we will examine the effect of tsunami waveform on the soil deterioration.

4.1. Analysis Conditions

We assume that the ground is loose sandy ground of N1=5 and the change of water depth associated with the tsunami wave is modeled by the simple sine wave. In particular effects of the period T and the inundation depth H are studied as:
H(m)=5.0,10.0,15.0,20.0 and 30.0, and T(sec)= 5,10,20,30,40,50 and 60.

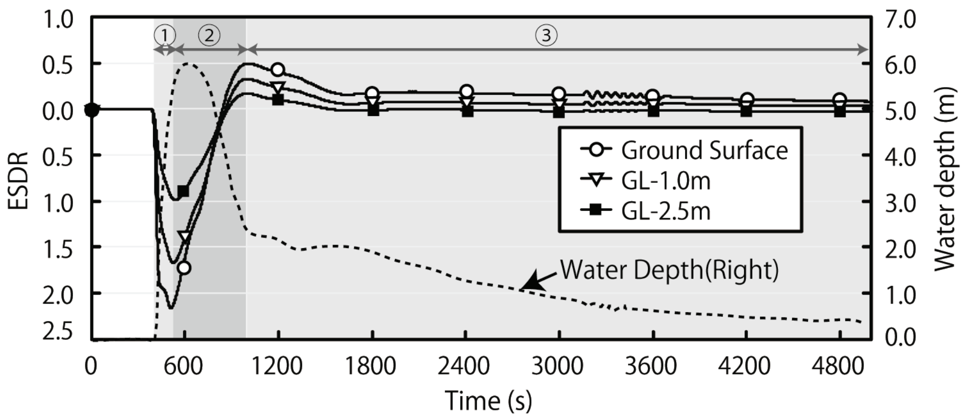

Figure 3.4. ESDR at depths of 1m and 2m of the ground (N1=5)

Table 3.2. Maximum value of ESDR for the ground with several N1 value

Material parameters	N1=5	N1=10	N1=20
The element of ground surface	0.44	0.44	0.29
The element of GL.-1.0m	0.36	0.33	0.22
The element of GL.-2.5m	0.23	0.20	0.15

4.2. Numerical Results

The model ground is presented in **Figure 4.1.**. A relationship between the maximum value of ESDR and the inundation depth H is shown in **Figure 4.2.**.

From this figure it is seen that ESDR depends on the inundation depth at all depths. Near the surface, the maximum value is large, i.e., at a depth of 1m the ground is fully liquefied for the inundation depth of 30m. But at the larger depth, the maximum value is not so large, i.e., soil is not deteriorated.

In **Figure 4.3.**, a relationship between the period of wave and the maximum value of ESDR. Maximum value of ESDR becomes large with increase of the period but becomes constant over the period of 20 minutes.

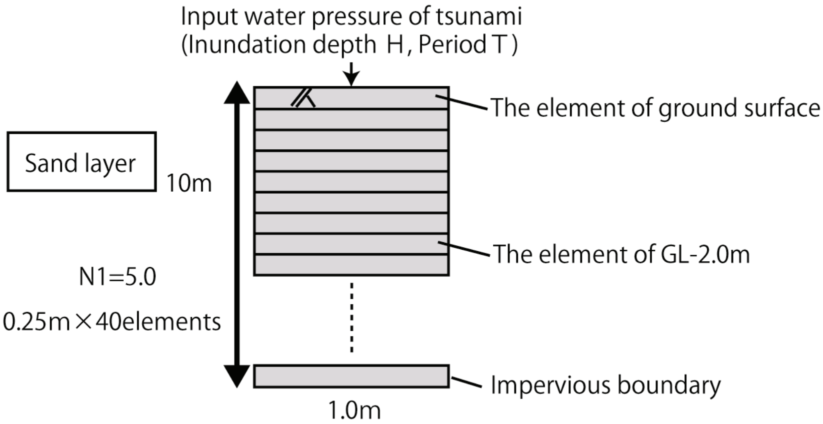

Figure 4.1. Analysis model

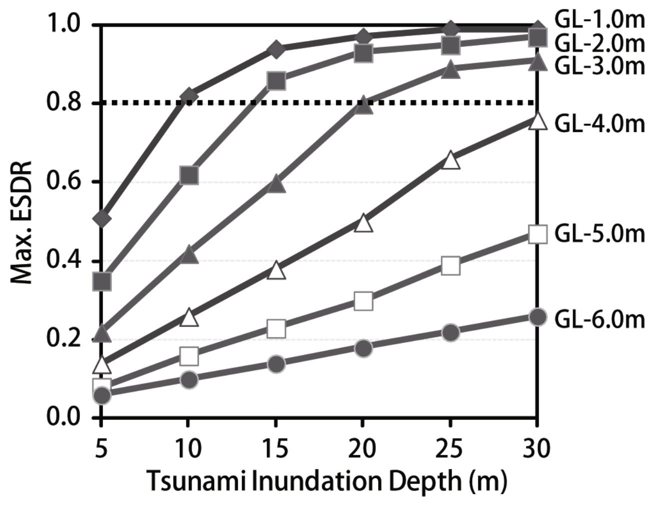

Figure 4.2. The relation between the maximum value of effective stress decreasing ratio and the tsunami inundation depth

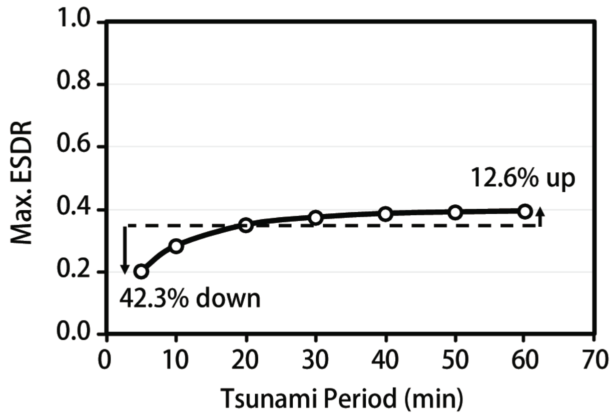

Figure 4.3. The relation between the maximum value of effective stress decreasing ratio and the tsunami period (H=5m, GL-2.0m element)

5. CONCLUSION

The following conclusions have been obtained from the present study.

1) The large scale of tsunami induced by huge earthquake such as the 2011 Tohoku earthquake in Japan may cause a deterioration of ground through the compressibility of the pore water.

2) Near the ground surface, the effective stress decreases at a level of 44% of the initial effective stress and this effect propagates downward. For the analysis conditions taken in this paper, it is probable that the relatively loose sandy soil, in which the converted N value (N1) is less than 10, the ground deteriorates below at a depth of 1m.

3) The soil deterioration increases in proportional to the amplitude of the tsunami and the effect becomes larger for the wave with the longer period although it becomes saturated over 20 minutes.

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