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STUDY ON SCOUR BY TSUNAMIS
－EXAMPLES OF PORT AND HARBOR STRUCTURES－

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This paper examines the possibility of applying a simple model based on existing knowledge to the phenomenon of scouring of port and harbor structures by tsunamis, considering, in particular, scouring of the armor stones, etc. of breakwaters and the backfill ground behind seawalls by tsunami flows.

Key Words :*Scouring, Tsunami, Breakwater, Buckfill ground behind seawalls, Coastal engineering*

1. INTRODUCTION

Tsunamis caused by large-scale earthquake are considered imminent in Japan, and damage to port and harbor structures by tsunami flows is possible. At present, however, there are few examples of concrete study of these possibilities. Therefore, this paper describes the results of a study of the possibility of damage to port and harbor structures using a simple model. More precisely, the studied phenomena in this study are scouring of the armor stones, etc. on the front side of breakwaters and scouring of the backfill ground behind seawalls.

2. STUDY OF SCATTERING OF BREAKWATER ARMOR STONES

This chapter examines the possibility of scattering of the armor stones, etc. of caisson-type composite breakwaters by tsunamis, considering the outer (open sea) side and inner (harbor) side separately.

The objects of this study were the outer harbor breakwater and Miho breakwater at the Port of Shimizu, where a tsunami caused by a Tokai earthquake is feared. For the relationship between the flow velocity around the rubble mounds of the breakwaters and the stable mass of armor stones, etc., this study uses the Isbash equation in “Stable mass of covering materials against flows” in “Technical Standards for Port and Harbor Facilities and Commentaries.”1) This equation is shown by the Coastal Engineering Research Center (CERC) in the US as the mass of rubble necessary to prevent scouring by tidal flows, and considers the balance of forces due to steady flows. Based on the Isbash equation, scattering is considered to occur when the mass of the covering materials used is less than the stable mass.

A plane 2-dimensional tsunami simulation of the Port of Shimizu was performed, and the results of the calculations were used as the tsunami flow velocities at the front of the breakwater in this study. An outline of the tsunami simulation and the tsunami flow velocities used in the study are shown in Table 1 and Table 2, respectively. For your information,the plan view of Port of Shimizu is shown in Figure 1.

The Isbash equation as follows:

$$M = \pi \rho_r U^6 / 48 g^3 y^6 (S_r - 1)^3 (\cos\theta - \sin\theta)^3$$

It means that stones with mass greater than this M is stable under the given tsunami velocity.

Table 1 Conditions of assumed tsunami

Mesh spacing	1,350m～12.5m
Time interval	Δt=0.10s
Basic equation	Nonlinear long wave theory equation
Sea bottom roughness	Considered(Manning's coefficient of roughness and land use roughness data were also considered)
Sea level conditions	H.W.L.(=T.P+0.86m)
Calculation time	180min(3hr)after occurrence of tsunami
Regions considered	6 regions were considered

Table 2 Tsunam flow velocities used in study

Study item Facility		Tsunami velocity(m/s)	
		Outer side	Inner side
Outer harbor Breakwater	A section	2.0	1.5
	C section	1.3	1.6
	E section	1.7	1.5
Miho breakwater		1.3	1.5

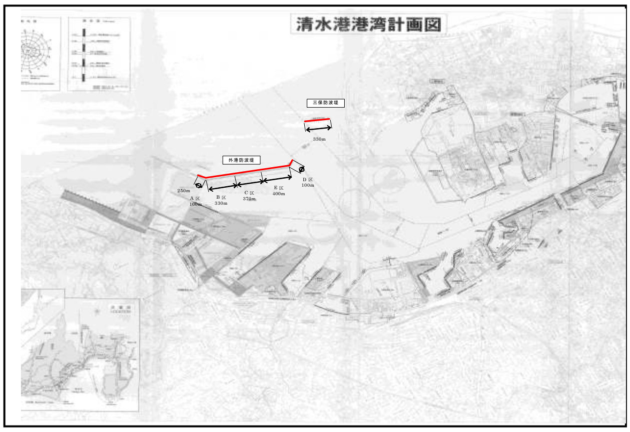

Fig.1 The plan view of Port of Shimizu.

where, M :Stable mass of rubble, etc. (t)

ρ_r :Density of rubble, etc., ρ_r =2.65 (t/m^3)

U :Velocity of water flow on top surface of rubble, etc. (m/s)

g :Acceleration of gravity, $g = 9.8$ (m/s^2)

y :Isbash constant(For buried stones: 1.20, for exposed stones: 0.86.)

S_r :Specific gravity of rubble, etc. in water (2.65/1.03)

θ :Angle of inclination of water surface or angle of inclination of mound (1 : 2.0, θ = 26.565°)

Next, the results of the study of scattering of the armor stones, etc. due to the flow velocity of the tsunami are shown in Table 3. The object stone material used in case of the Miho breakwater is the foundation rubble in the deepest part of the structure, which weighs 5-200 kg/piece.

From these results, it is considered that the possibility of scattering of the armor stones during the assumed tsunami attack is low at the outer harbor breakwater (sections A, C, and E) and the Miho breakwater. However, because the deep part of the foundation mound of the Miho breakwater is a structural cross-section exposing of foundation rubble weighing 5-200kg/piece, the ratio of the stable mass and actual mass in this part is high in comparison with that of the outer harbor breakwater, being 0.18 (outer side) and 0.42 (inner side). Considering this, it is difficult to say that this part possesses adequate safety against scouring. Furthermore, it should also be added that rubble with a larger mass than the stable mass obtained with the Isbash equation is necessary in locations where violent vortex can be expected. Figure 3 shows the relationship between the tsunami flow velocity and the critical stable mass obtained using the Isbash equation with the values assumed in this study.

According to this figure, stable mass exceeds the maximum mass of the foundation rubble (200kg) used at the Port of Shimizu at a flow velocity of 3.2m/s. Considering ordinary hydraulic properties, there are normally many cases in which armor stones are not placed in the deep part of the foundation mound of a breakwater, particularly on the inner side. Consequently, this part may be a structural weak point in a tsunami attack. There is also concern that a chain reaction beginning with scattering of the deep foundation mound material on the inner and outer sides may lead to deformation of the main body of breakwater.

In the calculations of the flow velocity in the tsunami simulation used here, flow velocity is regarded as being uniform in the vertical direction. Therefore, in order to obtain a more precise grasp of

Table 3 Results of study of scattering of covering stones, etc. by tsunami flow

Position			Tsunami flow velocity (m/s)	Stable mass (t)	Armor stone used (t)	Judgement
Outer harbor breakwater	A section	Outer side	2.0	0.0119	2.0000	OK
		Inner side	1.5	0.0021	0.5000	OK
	C section	Outer side	1.3	0.0009	1.0000	OK
		Inner side	1.6	0.0031	0.5000	OK
	E section	Outer side	1.7	0.0045	1.0000	OK
		Inner side	1.6	0.0031	0.5000	OK
Miho breakwater		Outer side	1.3	0.0009	0.0050	OK
		Inner side	1.5	0.0021	0.0050	OK

the scouring phenomena affecting the foundation ground and mound, a more accurate reproduction of the actual phenomena by a 3-dimensional numerical tsunami simulation and hydraulic model experiments are important. These are tasks for the future.

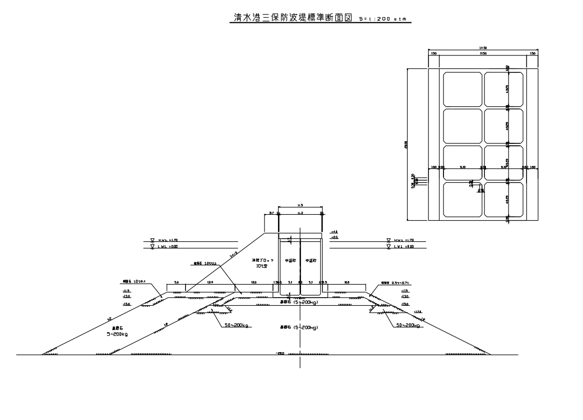

Fig.2 The cross section of Miho breakwater.

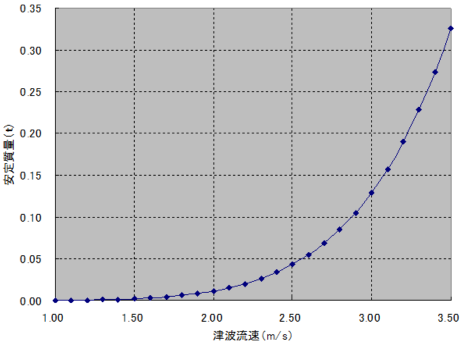

Fig.3 Relationship between tsunami flow velocity and stable mass.

3. SCOURING OF GROUND BEHIND SEAWALLS IN THE SAMATRA EARTHQUAKE(2004)$^{2)}$

In a tsunami, the initial attacking wave and the return flow of the runup wave can be expected to move large quantities of ground materials. This can cause buildings to collapse due to scouring, and deposited sediments may impair port and harbor functions. In the Indian Ocean Tsunami triggered by the Sumatra Earthquake in 2004, damage due to movement of ground materials could be seen in all affected areas. For example, at Ambarangoda in Sri Lanka, it is estimated that the ground around the bridge abutments adjoining a rail line was affected by scouring due to the return flow of the tsunami wave that had run up in a water channel (Figure 4, Figure 5).

Fig.4 Damage caused by Indian Ocean Tsunami in 2004 Sumatra Earthquake.Ambarangoda, Sri Lanka
Railway where bridge abutments were affected by scouring due to tsunami runup in water channel (photograph courtesy of Kyoto University Disaster Prevention Research Institute (DPRI-KU)).

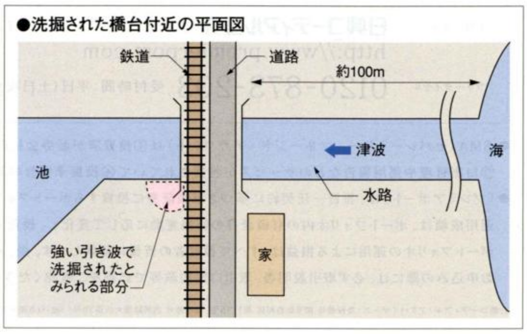

Fig.5 Outline of tsunami damage in Indian Ocean Tsunami.
Picture of area around scoured bridge abutments

It is generally thought that large quantities of ground materials are moved in a tsunami, suspended sediments are predominant, because the flow velocity of the tsunami is large and a powerful shear force acts on the bottom. However, research on scouring and related phenomena associated with tsunamis has been limited mainly to geological site surveys, and there are few examples of research on hydraulic parameters or the formation of sedimentary strata.[3)4)] Furthermore, because the transport of sediments by the backwash is considered to have a large effect on the results in studies of scouring, accurate reproduction of the flow velocity of the attacking tsunami and the return flow of the tsunami after runup is important.

4.STUDY OF SCOURING OF BACKFILL GROUND BEHIND SEAWALL

Here, the inundation depth on the seawall used in this chapter was estimated referring to the 2-dimensional tsunami simulation described in Chapter 2. As a result, the inundation depth on the seawall and the height of the tsunami wave at the front face of the seawall were assumed to be 0.25m and 1.99m, respectively(considering cope level of seawall). For the tsunami flow velocity, this study follows the relationship between maximum runup height and runup flow velocity shows in Reference [5)].

$$C_x = 2\sqrt{g\eta_m}$$

where, C_x :flow velocity of runup tsunami, g :acceleration of gravity, g =9.8(m/s^2), and η_m: tsunami runup water depth (runnp height)= 0.25m.

$$\because C_x = 2\sqrt{9.8\times 0.25} = 3.13(m/s)$$

Similarly, the results of calculations of the runup flow velocity for runup depths of 0.50m, 0.75m, and 1.00m are shown below, where the numerical suffix corresponds to the tsunami runup water depth.

$$C_{x0.50} = 4.43(m/s)$$

$$C_{x0.75} = 5.42(m/s)$$

$$C_{x1.00} = 6.26(m/s)$$

Next, the possibility of scouring of the backfill ground behind a seawall by the flow of the runup tsunami was examined for gravelly soil. Using Eq. i) ～iii) for the tractive force of sediment transport in rivers in Reference 6) and Eq. iv), which was proposed by Iwagaki for critical tractive force, Eq. v)for the critical flow velocity for particle transport relative to the particle size of gravel was obtained by deformation and used in this study.

$$\tau = \rho u_*^{\,2} = \rho g R I_e \qquad \text{i)}$$

$$I_e = \frac{n^2 v^2}{R^{4/3}} \qquad \text{ii)}$$

$$U_* = \sqrt{\tau_o / \rho} \qquad \text{iii)}$$

$$U_*c^2 = 0.809d \qquad \text{iv)}$$

$$V = \sqrt{\frac{0.809dR^{4/3}}{gRn^2}} \qquad \text{v)}$$

where, V : Critical flow velocity for particle transport (m/s)

d : Particle diameter of gravel = 0.2, 0.3, 0.4, 0.5 (m)(Corresponding mass of gravel = 10, 40, 90, 170 kg/piece; mass when density of ρ_r = 2.65 (t/m^3) and particles are assumed to be spherical)

R : Hydraulic radius/tsunami runup water depth = 0.25, 0.50, 0.75, 1.00 (m)

g : Acceleration of gravity = 9.8 (m/s^2)

n : Coefficient of roughness = 0.04

In this study, the gravel was assumed to be spherical, the particle diameter was set at 0.2, 0.3, 0.4, and 0.5m. Scouring of the ground was assumed to be possible when the critical flow velocity was lower than the runup tsunami flow velocity.

The results of this study of scouring of backfill ground by a runup tsunami are shown in Table 4.

This critical flow velocity for particle transport is of a level which is not greatly different from the on-land runup flow velocity[7)] of a tsunami estimated referring to the condition of damage in the 1993 Hokkaido Nansei-oki Earthquake.

5. CONCLUSION

In this report, the possibility of scouring of breakwater foundations mounds and backfill ground behind seawalls in a tsunami was studied using simple models. In the future, this type of study will be more useful if permeation of the tsunami flow into the backfill ground and water flow that goes back into the sea is considered.

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Table 4 Results of study of scouring of backfill ground.

Inundation depth (m)	Flow velocity (m/s)	Critical flow velocity for particle transport (m/s)			
		d=0.20m	d=0.30m	d=0.40m	d=0.50m
0.25	3.13	2.55NG	3.12	3.61	4.03
0.50	4.43	2.86NG	3.51NG	4.05NG	4.52
0.75	5.42	3.06NG	3.75NG	4.33NG	4.84NG
1.00	6.26	3.21NG	3.93NG	4.54NG	5.08NG

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