EFFECT OF DRIFTED HOUSES ON INUNDATION REGION AND THE WASHOUT REGION OF HOUSES AT THE TSUNAMI CAUSED BY THE GREAT EAST JAPAN EARTHQUAKE

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Abstract

Breaking or washout condition of houses by a tsunami was usually analyzed using fluid force and moment by drag force. However, the condition was not validated in actual large tsunami that could cause catastrophic damage on houses, and produce a large amount of debris including a floating houses or broken houses. Therefore, the objective of this study is to develop a numerical model considering the effect of drifted house on the tsunami inundation distance from the shore line and washout situation of neighboring houses at large tsunami event.

Field investigations were conducted at 18 locations in Sendai Plain between April to May after the tsunami caused by the Great East Japan Earthquake. In the field survey, tsunami water depths and situation of broken or washed out houses were investigated. In this study, to elucidate the effect of the drifted house on the damage of neighboring houses, one location was selected. The effects of the drifted house were included into numerical model as an additional resistance. In addition, the numerical model was validated by the observed water depths and washout region of houses at the 2011 Japanese tsunami. The numerical simulation demonstrates that the drag force by debris or floating houses on flow reduces the washout region of houses, but on contrary, it also increases the drag force on the neighboring house and thereby increases the washout region of houses. The washout region of houses was reduced because the effect of the drag force by debris or floating houses on flow are greater than that of the additional drag force on the neighboring house. This result indicates that evaluating the effect of the drag force acting on the debris or floating houses on flow is quite important. Moreover, the simulation could reproduce well the washout region within the reasonable limits. The model enables the analysis of large tsunami that produces large amount of debris in densely populated area.

Keywords: drifted house, debris, neighboring house

1. INTRODUCTION

The tsunami due to the Great East Japan Earthquake at 14:46 JST on 11 March 2011, which had a magnitude of 9.0 and an epicentre 129 km east of Sendai, destroyed many disaster prevention structures in the coastal area. In addition, the tsunami intruded to the hinterland and destroyed many houses. Particularly, many damaged houses could be seen in a densely populated area in Arahama, Wakabayashi-ward, Sendai-city(Fig.1). Most of houses located around 1000 m from the shoreline were washed away. Even in the inland area where was more than 1000 m away from shore line, the pillars, walls or windows of the houses had severe destruction.

From some video images recorded at the tsunami, it was confirmed that the drifted house collided or accumulated to the neighboring houses. The drifted houses have a possibility to extend washout region of houses by adding additional drag force to the neighboring houses. Moreover, it is important to consider not only additional drag force acting on the neighboring house but also resistance to tsunami flow by drifted houses for forecasting the inundation area by destructive large tsunami with high accuracy. Some knowledge regarding washout condition of houses by the flow have been obtained in the previous researches (e.g. Takahashi et.al(1985)). However, there are few studies that considered the effect of drifted house on tsunami flow and the neighboring house.

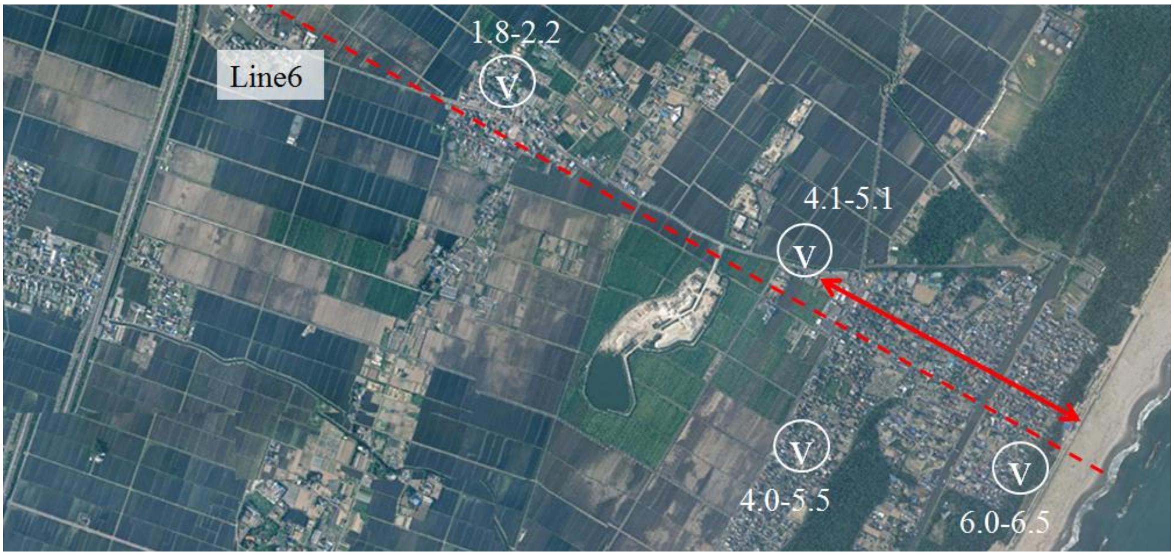

Fig.1 Analysis place (v : verified place , the numerical value : tsunami water depth , the dotted line : the inundation region , the solid line : wash out region of the houses (Modified the aerial photo provided by Geospatial Information Authority of Japan))

According to above context, the objectives of this study are 1) to develop the numerical simulation model including the effect of drifted house on tsunami flow and additional resistance by a drifted house to the neighboring house, and 2) to confirm the validity of developed model by the observed water depths and washout region of houses at the 2011 Japanese tsunami.

2. MATERIALS AND METHODS

2.1 Site locations and measurement method

Field investigations were carried out in April and May of 2011 in tsunami-affected area for investigating the damage situations of coastal forests and houses in the Tohoku area of Japan (Tanaka 2012; Tanaka et al., 2012a, 2012b). The post-tsunami field investigations were conducted at 22 locations for obtaining the tsunami water depth at each location to analyze the tsunami damage quantitatively by numerical simulations. Within the 22 locations, one location (Arahama area) was selected in this study.

The tsunami water depth at each site was determined by evidence of collisions, e.g., the height of scars made by debris on tree trunks or by broken branches and water marks on the walls of damaged buildings, marks on broken roofs, or debris located on roofs.

2.2 Numerical simulation

To elucidate the tsunami inundation region and washed out region of the houses at the 2011 tsunami event, numerical simulations were conducted using the model of Thuy et al. (2009), which is formulated by two-dimensional nonlinear long-wave equations (continuity equation: Eq.(1), momentum equations: Eqs.(2) and (3)), and an sub-depth scale (SDS) turbulence model (Nadaoka and Yagi, 1998):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (hV_x)}{\partial x} + \frac{\partial (hV_y)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial V_x}{\partial t} + V_x \frac{\partial V_x}{\partial x} + V_y \frac{\partial V_x}{\partial y} + g\frac{\partial \zeta}{\partial x} + \frac{\tau_{bx}}{\rho h} + \frac{F_x}{\rho h} - \frac{E_{Vx}}{h} = 0 \tag{2}$$

$$\frac{\partial V_y}{\partial t} + V_x \frac{\partial V_y}{\partial x} + V_y \frac{\partial V_y}{\partial y} + g\frac{\partial \zeta}{\partial y} + \frac{\tau_{by}}{\rho h} + \frac{F_y}{\rho h} - \frac{E_{Vy}}{h} = 0 \tag{3}$$

$$\left(\tau_{bx}, \tau_{by}\right) = \frac{\rho g n^2}{h^{1/3}} \times \left(V_x\sqrt{V_x^{\,2}+V_y^{\,2}}\,,\ V_y\sqrt{V_x^{\,2}+V_y^{\,2}}\right) \tag{4}$$

$$\left(F_x, F_y\right) = \gamma \frac{1}{2}\rho C_{D-all} b_{ref} h \times \left(V_x\sqrt{V_x^{\,2}+V_y^{\,2}}\,,\ V_y\sqrt{V_x^{\,2}+V_y^{\,2}}\right) \tag{5}$$

$$E_{vx} = 2\frac{\partial}{\partial x}\left(h\nu_e \frac{\partial V_x}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\nu_e \frac{\partial V_x}{\partial y} + h\nu_e \frac{\partial V_y}{\partial x}\right) \tag{6}$$

$$E_{vy} = 2\frac{\partial}{\partial y}\left(h\nu_e \frac{\partial V_y}{\partial y}\right) + \frac{\partial}{\partial x}\left(h\nu_e \frac{\partial V_x}{\partial y} + h\nu_e \frac{\partial V_y}{\partial x}\right) \tag{7}$$

where x and y are the horizontal coordinates; V_x and V_y are the depth-averaged velocity components in x and y directions, respectively; t is the time; h the total water depth ($h = h_0+\zeta$); h_0 the local still water depth (on land, the negative height of the ground surface); ζ the water surface elevation; n the Manning roughness coefficient; g the gravitational acceleration; and γ the tree density (number of trees/m^2). $C_{D\text{-}all}$ is the depth-averaged equivalent drag coefficient considering the vertical stand structure of the trees, which was defined by Tanaka et al. (2007) The eddy viscosity coefficient ν_e is expressed in the SDS turbulence model (Nadaoka and Yagi, 1998; Thuy et al., 2009).A set of the model equations was solved by the finite-difference method using a staggered leap-frog scheme, which is used widely in numerical simulations of tsunamis (Thuy et al., 2009). A sinusoidal incident tsunami was given as a time-dependent boundary condition at the most offshore side of the wave-generation zone. The initial conditions were given for a waveless state in the computational domain including the wave-generation zone. In the numerical simulation, a uniform grid size of 10 m was applied. The Manning roughness coefficient n was set as 0.025 s/m$^{1/3}$ for a relatively bare rough ground. Forest length and tree density were set as conditions of the site being evaluated.

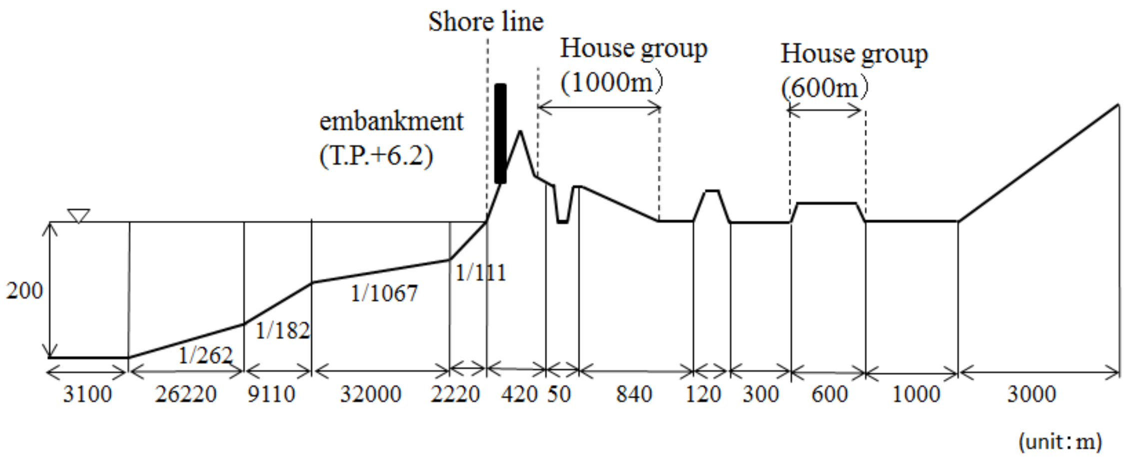

Fig.2 Topography with a cross-shore section perpendicular to a shoreline and location of the house groups in Line 6 (aerial photo of this line is in Fig.1)

A uniform coastal topography with a cross-shore section perpendicular (x-axis) to a straight shoreline, as shown in Fig.2, was selected as a model case. The density of houses here was high compared with other districts, so the effect of drifted houses could be evaluated in this area. The offshore water depth at an additional wave-generation zone with a horizontal bottom was 200 m below the datum level of z = 0. The direction of the incident tsunami was perpendicular to the shoreline. In the present paper, the run-up of only the first wave is discussed. The maximum tsunami water depth at the shoreline was set at 10 m, which is the average value in this area.

2.3 *Broken and washed out condition of houses*

The fluid force index (u^2h) and the moment index (u^2h^2) were utilized to determine the breaking or washout condition of houses. The critical value of the moment index (M_{cr}) was around 76 (m^4/s^2) according to a real-scale experiment (Takahashi et al., 1985). For the critical value of the fluid force index (F_{cr}) for breaking houses, the study by Hatori (1984) showed that most houses were washed out when F_{cr} exceeded 100 (m^3/s^2), and one-third of houses were lost when F_{cr} was around 15 (m^3/s^2) in three previous Japanese tsunamis. Tanaka (2012) evaluated the M_{cr} values for 33% and 0% washout were 91 (m^4/s^2) and 51 (m^4/s^2), respectively. This is similar to the value that Takahashi et al. (1985). Moreover, F_{cr} values for 33% and 0% washout values were 36 (m^3/s^2) and 24 (m^3/s^2), respectively, which is slightly larger than the figures of Hatori (1984). In addition, M_{cr} was estimated at Miyagino, close to Arahama in this study, was estimated around 34 (m^4/s^2) (Tanaka et al., 2012b). In this study, M_{cr} obtained from Tanaka et al.(2012b) is used as the critical condition of washing out house.

2.4 *Additional resistance by a drifted house*

For dense housing area, the effects of additional resistance by drifted house on the neighboring house needs to be considered. Previous numerical simulation of tsunami usually neglects this kind of effect because many and large floating debris like houses were not produced in previous disaster in urbanized area. This study includes the effect and develops a new model. Where the density of houses is low, drag coefficient is changed from 2.1 to 0 when the houses in low

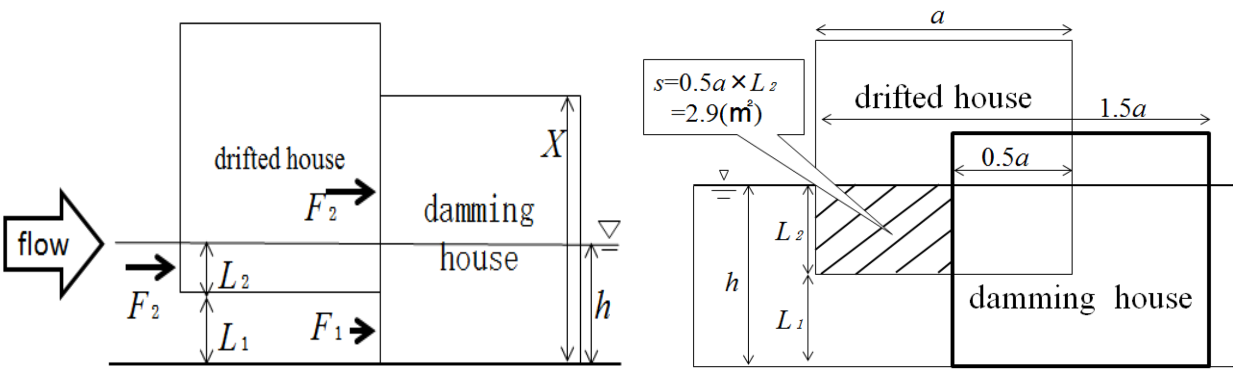

Fig.3 The effect of drifted house on neighboring house

(a) The change of load centre due to fluid forces, (b) Increment of the projected area

density area were judged to be washed out. On the other hand, drag coefficient for high density residential area is changed from 2.1 to 1.2. The value of 1.2 is the calibrated value for reproducing well the maximum tsunami water depths. Secondly damming up phenomenon of floating house in front of not washout house is considered as shown in Fig.3. Eq.8 means the correction of the moment considering the change of the location of resultant fluid force. Eq.9 expresses the change of the projected area by the attached debris. This study does not include the effects of collision force because the drifted house soon collides the neighboring house.

$$\frac{M_1}{M_2} = (1.0 + \frac{2X * L_2 - L_2{}^2}{2h^2}) \tag{8}$$

$$\frac{A_1}{A_2} = (1.0 + \frac{L_2}{2 * h}) \tag{9}$$

Where, M_1 or M_2 is the moment by fluid force acting on a house when drifted house exists or not, respectively; h is water depth; A_1 or A_2 is the expanding projected area including the dammed house or not, respectively; X is the height of a two storey house (X=6 m); L_2 is the draft of a dammed house calculated by buoyancy and weight (600 kg/m^3).

3. RESULTS AND DISCUSSION

3.1 *Verification results of additional resistance by a drifted house*

Fig.4 shows the comparison between calculated and observed maximum tsunami water depths in Line 6. Three lines in this figure represent the different simulation results for how C_d value of drifted house is modelled (AR1: C_d value of washed out house is assumed 0, AR2: C_d value of washed out house is assumed 1.2, AR3: It considered the additional resistance of the house in addition to AR2). The maximum tsunami water depth increases AR2 in seaward region (0-1000m from the shore line) in comparison with AR1 and decreases in the inland region (1000-3000m from the shore line). The calculated maximum tsunami water depth by AR2 can express

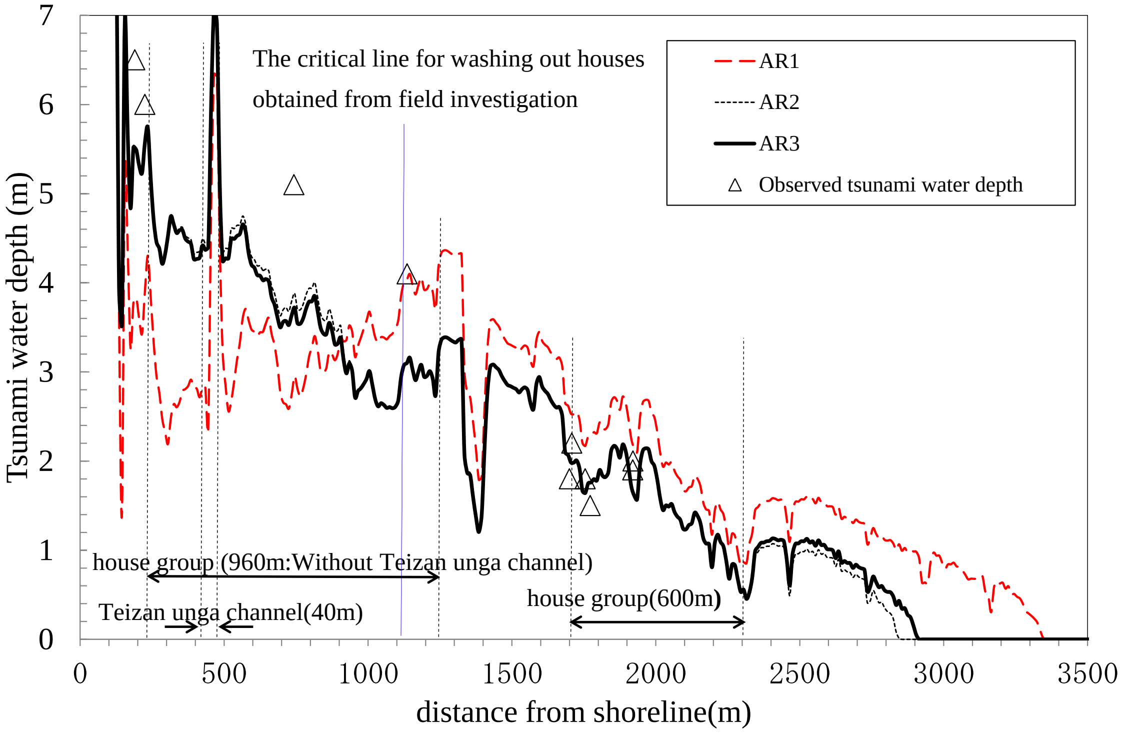

Fig.4 Maximum tsunami water depth in Line6 (AR1: Cd value of washed out house is assumed 0, AR2 : Cd value of washed out house is assumed 1.2, AR3 : Cd value of washed out house is assumed 1.2 and additional drag force on the neighboring house due to drifted house is also considered

well the observed values. This result indicates the importance to consider the effect of drifted house on the resistance to tsunami flow. On the other hand, when the tsunami water depth calculated by AR3 is compared with AR2, maximum tsunami water depth in the seaward region decreases slightly. As for this, maximum tsunami water depth of AR3 supposes to be decreased because the additional drag force due to the drifted house expands the wash out region of house, and decreases the drag force that is not washed out.

Fig.5 shows the comparison between calculated maximum moment index (u^2h^2) in Line 6 and critical moment index for washing out house. The value of critical moment index for washing out house (34 m^4/s^2) is from previous research (Tanaka et al., 2012b). The distances that washing out of house occurs for AR1 and AR3 were 1620 m and 1110 m, respectively. In the case of AR3, the effect of drifted house on additional force to neighboring house is included. However, wash out region of houses is reduced 510m comparing with AR1 case, because AR3 case is considered the effect of drifted house on resistance to tsunami flow. The distance that washing out house obtained from AR3 case express well the observed one (1170m). In contrast, the distance of washing out house obtained from AR2 case (1020m) is decreased in comparison with AR3 case (1110m). This result indicates that considering the effect of drifted house on additional drag force to the neighboring house is important for evaluating the wash out region of houses in the area where houses are densely located.

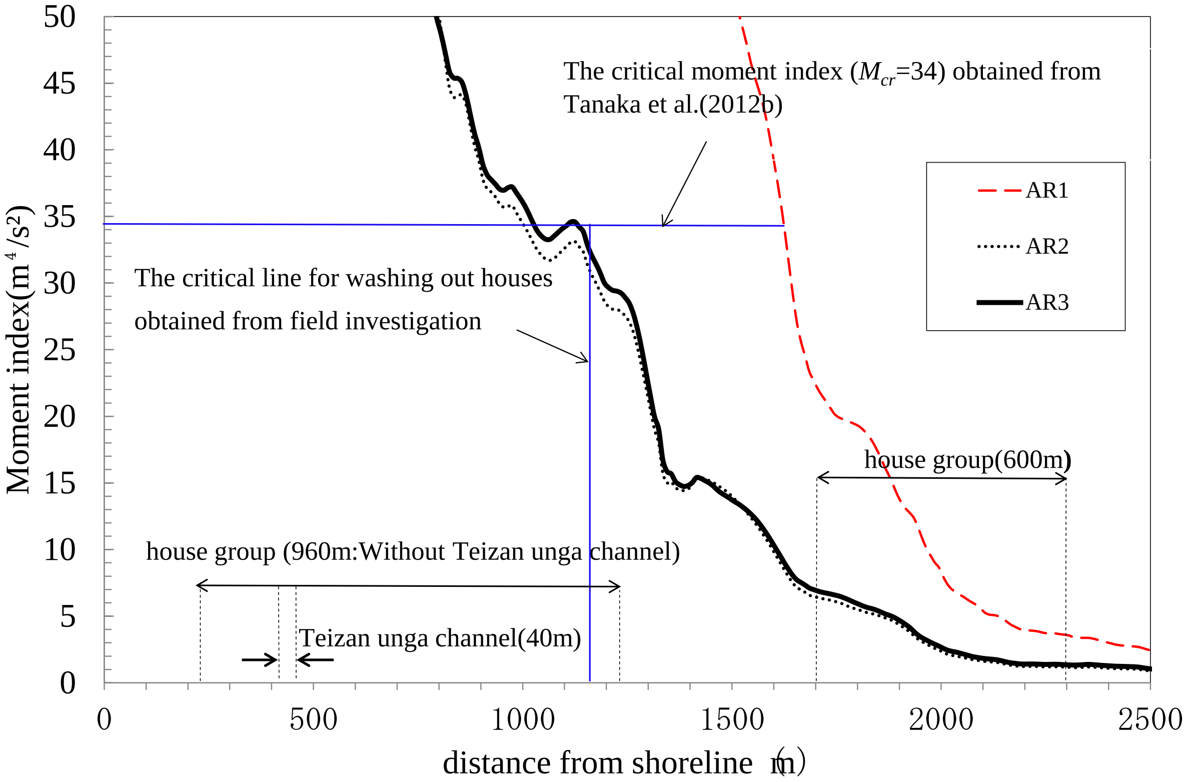

Fig.5 Maximum moment index in Line (AR1 : C_d value of washed out house is assumed 0, AR2 : C_d value of washed out house is assumed 1.2, AR3 : C_d value of washed out house is assumed 1.2 and the additional drag force on the neighboring house due to drifted house is also considered.)

4. CONCLUSION

This study analyzes the effect of the drifted house on the damage of neighboring houses. Effects of the drifted house on flow and the neighboring house were included into numerical model as resistance by floatings (change in drag coefficient) and an additional resistance to the neighboring house. In addition, the numerical model was validated by the observed water depths and washout region of houses at the 2011 Japanese tsunami. The numerical simulation demonstrates that the drag force by debris or floating houses on flow reduces the washout region of houses, but on contrary, it also increases the drag force on the neighboring house and thereby increases the washout region of houses. The washout region of houses was reduced by 510 m comparing with AR1 and AR3 because the effect of the drag force by debris or floating houses on flow are greater than that of the drag force on the neighboring house. This result indicates that evaluating the effect of the drag force acting on the debris or floating houses on flow is quite important.

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