NUMERICAL MODEL FOR PREDICTING THE SAND OUTFLOW RATE OF BACKFILL MATERIALS FROM A COASTAL DIKE

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In the case of coastal dikes and seawalls, since big waves break before reaching these structures, the frequency in which they are broken directly by strong wave force is low. On the other hand, with continuous impact of middle waves, scour arises in these fronts. Before long, incident waves infiltrate into these bodies, backfilling materials flow out, and caves in these bodies become big. Owing to these phenomena, the frequency of destruction of these dikes and seawalls becomes high. Therefore, the development of methods for predicting scour rates in these fronts and sand outflow rates of backfilling materials is useful. Regarding scour rates in these fronts, there are already some accurate methods that specialists can use under various conditions. However, for sand outflow rates of backfilling materials, there are some prediction methods limited to simple types of dikes and seawalls.

In this research, the authors develop a numerical model that calculates the flow velocity and pressure in the dike or seawall with arbitrary form using “CADMAS-SURF.” The model can predict the time change in the sand outflow rate and the development of the cave. First, for a sand outflow rate simulation, the authors propose empirical equations to modify the pressure calculated by CADMAS-SURF using hydraulic experiment data. Then, they confirm the practical feasibility of the numerical model by applying it to field cases on sand outflow damage in Japan and Thailand.

Key Words: sand outflow rate changeable with elapsed time, numerical simulation model, CADMAS-SURF, dike and seawall with arbitrary shape

1. INTRODUCTION

In the case of coastal dikes and seawalls located in beaches or shallow areas, there are a few field cases showing these structures being destroyed by strong wave force. There are also a lot of field cases showing that “erosion and scour in these fronts” and “sand outflow from these bodies” were caused by the continuous action of waves and caused gradual destruction. Sand outflow is the process in which sand flows out from bodies of the dike and the seawall by pressure difference between the inside and the outside of bodies. This continuous process progressively makes the cavity inside the body bigger. It is believed that the causes of these destructions are mainly erosion, scour, and sand outflow.

There are many studies on the destructive phenomenon caused by sand outflow. Ohkawa et al.1) mentioned that in the case where the dike or the seawall was destroyed, the main reasons were coastal erosion, scour, and sand outflow. Iwasaki et al.2) indicated that the liquefaction of backfilling materials was the cause of sand outflow. Maeno et al.3) and Kotani et al.4) showed that the outflow of backfilling materials was the cause of the destruction of a simple seawall by using a numerical model based on the pore-elastic theory. The formation of the cavity inside the seawall was intimately linked to the cyclical action of water pressure acting on the sand surface. Nakamura et al.5) proposed a numerical model based on the volume of fluid (VOF) and the Biot model for simulating the outflow of backfilling materials from the lowest edge of a rubble revetment.
In the case of typical-sized concrete and asphalt-covered dikes or seawalls, Yamamoto and Minami\(^{9}\) elucidated the following, by using stability calculations and hydraulic experiments: if the water depth at the front of the dike or the seawall is smaller than approximately 3 m, the structure break is not directly caused by the water power. As the sand layer in the front of the dike or the seawall is thinned by the scouring, the sand outflow force by a return flow (shear on a sand outflow surface of the inside) becomes stronger, while the sand outflow resistance (shear resistance on the sand outflow surface) becomes weaker (refer to Fig. 1). Moreover, as the mean diameter of backfilling materials becomes bigger, the sand outflow force becomes weaker, while the sand outflow resistance becomes stronger. In addition, they proposed a method that could predict whether the dike or the seawall was broken or not using the wave overtopping rate by incident waves and net sand outflow resistance at the time of the return flow.

Ioroi and Yamamoto\(^{7,8}\) proposed a method for evaluating the sand outflow rate of backfilling materials using maximum excess pore water pressure and maximum velocity at the time of the return flow from the dike or the seawall that the front slope, the landward slope and the crown are covered by concrete expressed by Eq. (5). Moreover, they showed that the accuracy of the sand outflow rate when using the pore water pressure and the velocity by the numerical simulation model “CADMAS-SURF” became lower than those that used the experimental equation. They said this was probably because CADMAS-SURF could not sufficiently consider the effect of the different characteristics of the backfilling materials. CADMAS-SURF is a convenient model that can consider the different sizes of a wide range of materials on the pressure by using the drag force coefficient or Dupit-Forchheimer method with great accuracy. However, the Dupit-Forchheimer method can consider the effect of median grain size, \(D_{50}\), only. Furthermore, the Dupit-Forchheimer method was designed to be used under steady flow state and some experimental coefficients should be determined before using this method. Therefore, when using this method to consider other properties of sand, e.g., uniformity and dry density, and using it under unsteady flow state, the accuracy will become low. Yoshizawa et al.\(^{9}\) proposed an empirical method to improve the above defect.

In this research, the authors propose a numerical model and empirical equations that can modify the previously mentioned defect of calculated results from CADMAS-SURF and can predict the changing sand outflow rate with elapsed time.

## 2. THEORETICAL CONSIDERATION

(1) **Sand outflow rate formula**

Ioroi and Yamamoto\(^{7,8}\) applied the static stability theory of soil mechanics to the sand outflow phenomenon. They derived the sand outflow rate \(q\) at the lowest edge of a covered coastal dike with an arbitrary shape, which is proportional to the difference between the shear resistance \(\tau_r\) and the shear force \(\tau_f\) at the bottom of the structure. The shear resistance is dependent on the thickness of backfilling materials, density of backfilling materials, and pore water pressure of the return flow; while the shear force is dependent on the velocity of the return flow. Thus, when the sand layer thickness in front of a structure becomes smaller owing to continuous incident waves, the shear resistance becomes smaller. As a result, the sand outflow rate inside the structure becomes larger. This phenomenon is expressed by Eqs. (1)-(3).

\[
q \propto (\tau_r - \tau_f),
\]

\[
\tau_r = (\rho_s gd_i - \rho_w gd_i - P_{ob \ max}) \tan \phi,
\]

\[
\tau_f = \frac{1}{2} f \rho_w V_{max}.
\]

where, \(q\) is the sand outflow rate per unit width at the lowest edge of the structure; \(\tau_r\) is the shear resistance; \(\tau_f\) is the sand outflow force (= shear force); \(\rho_s\) is the density of backfilling materials (= 1,800 kg/m\(^3\)); \(\rho_w\) is the density of water; \(g\) is the gravitational acceleration; \(d_i\) is the thickness of the sand layer in front of the structure; \(P_{ob \ max}\) is the biggest excess pore water pressure during all of the return flow; \(\phi\) is the internal angle of backfilling materials; \(f\) is the coefficient of the sand outflow force at the lowest edge of the structure (= 1); \(V_{max}\) is the biggest flow velocity during all of the return flow, which can be calculated by Eq. (4).

![Fig 1 Illustration of sand outflow phenomenon.](Image)
\[ V_{\text{max}} = \sqrt{2\left(\frac{P_{\text{sat,max}}}{\rho_w}\right) \left(\frac{h}{H} + 1.0\right)^{-1.11}}, \]  

(4) 

where, \( h \) is the water depth in front of the structure, and \( H \) is the incident wave height.

They performed wave flume experiments to find the relationship between the sand outflow rate and the main concerned parameters. The results show the sand outflow rate is proportional to the grain size. Then, they got the sand outflow rate equation expressed in Eqs. (5)-(9):

\[ \frac{q}{w_{s}D_{50}} = \beta(\theta - \theta_{c}) \left(\frac{1}{2} \cos \left(\frac{\alpha T}{t}\right)\right), \]  

(5) 

\[ \alpha = \begin{cases} 
-9.0 \times 10^{-5} \left(\frac{D_{50}}{0.2}\right) + 0.0031, & 1 \leq \frac{D_{50}}{0.2} \leq 25 \\
-3.39 \times 10^{-5} \left(\frac{D_{50}}{0.2}\right) + 0.0017, & 25 \leq \frac{D_{50}}{0.2} \leq 50 
\end{cases} \]  

(6) 

\[ \beta = 0.028e^{-0.35 \left(\frac{w_{s}}{D_{50}}\right)}, \]  

(7) 

\[ \theta_{c} = \tau_{r} / (\rho_s - \rho_w) g D_{50}, \]  

(8) 

\[ \theta = \tau_{r} / (\rho_s - \rho_w) g D_{50}, \]  

(9) 

where, \( w_{s} \) is the settling velocity of Rubey’s; \( D_{50} \) is the median grain size (unit in Eq. (5) is mm); \( \theta_{c} \) is the dimensionless critical sand outflow force; \( \theta \) is the dimensionless sand outflow force; \( T \) is the wave period; \( t \) is the time; \( \alpha \) is the reduction coefficient; and \( \beta \) is the proportional coefficient.

\( \text{(2) CADMAS-SURF} \)

CADMAS-SURF\(^{(b)}\) was developed by Coastal Development Institute of Technology, Japan. It is a 2D or 3D wave flume simulation model based on non-compressible continuity, and Navier-Stokes formula (refer to Eqs. (10)-(17) in the case of 2D). Here, the free surface is handled by the VOF technique of Hirt and Nichols\(^{(b)}\). This model can simulate the velocity and the pressure at any point of the simulated wave flume, including porous media, surface of a structure, and so on. This model is a very useful tool for researchers and general engineers. The reliability of this model is proven by some researches (e.g., Honda and Ito\(^{(b)}\), Hanzawa et al.\(^{(b)}\))

\[ \lambda_{v} \frac{\partial \gamma_{v, u}}{\partial t} + \frac{\partial \lambda_{v, uu}}{\partial x} + \frac{\partial \lambda_{v, wu}}{\partial z} = 0, \]  

(10) 

\[ \lambda_{w} \frac{\partial u}{\partial t} + \frac{\partial \lambda_{w, uu}}{\partial x} + \frac{\partial \lambda_{w, wu}}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \gamma_{v} \frac{\partial}{\partial x} \left(\gamma_{v} V_{v} \left(\frac{\partial u}{\partial x} + \frac{\partial w}{\partial x}\right)\right) + \frac{\partial}{\partial z} \left(\gamma_{v} V_{v} \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial z}\right)\right) - R_{s}, \]  

(11) 

where, \( x \) and \( z \) are the horizontal and vertical coordinates; \( \gamma_{v} \) and \( \gamma_{w} \) are the sectional permeability in horizontal and vertical direction, respectively; \( \gamma_{v} \) is the porosity; \( u \) and \( w \) are the velocities in horizontal and vertical direction, respectively; \( v_{c} \) is the kinematic viscosity; \( p \) is the water pressure; \( \rho \) is the water density; \( \lambda_{v}, \lambda_{w} \) are coefficients expressed in Eqs. (13)-(15); \( C \) is the coefficient of inertia; \( R_{s} \) and \( R_{e} \) are the drag forces in the horizontal and vertical direction, respectively; \( C_{D} \) is the drag force coefficient; and \( \Delta x, \Delta z \) are the mesh sizes in horizontal and vertical direction, respectively; and \( F \) is the VOF function.

\( \text{3. METHODOLOGY} \)

\( \text{(1) Hydraulic experiments} \)

Yamamoto and Minami\(^{(b)}\) confirmed the reliability of the hydraulic experiment on the sand outflow phenomenon by reproducing the sand outflow disaster at the Hirono coast in Shizuoka Prefecture of Japan caused by Typhoon No. 9 in 1997. In their experiment, the wave flume that was 0.5m in width, 0.8m in height, and 22.0m in length and the ball-screw-driven wave generator were set up as shown in Fig. 2. The wave heights and the pressures were obtained using some wave gauges and a pore pressure meter. Since the sand outflow phenomenon happens when the wave force scours the front sand layer and reaches the tip of the sheet pile of a dike, a pore pressure meter was set below the lowest edge of the sheet pile of the dike. As the average significant wave height at offshore was 6.69m and the average significant wave period was 14.5s when this typhoon hit the Hirono Coast, the significant wave height in the experiments was scaled to 0.223m (0.0782m as the incident wave height in the front of the model) and the significant wave period was set to 2.65s by using the Froude law.
In consideration of the scale of grain size, according to the backfilling materials of the prototype dike, which consisted of grain sizes of 0.5-1mm and 2-3mm at the ratio of 2:1, the grain sizes in the experiment were scaled to 0.2mm and 0.66mm at the ratio of 2:1 by using the similitude of beach profile of Ito and Tsuchiya\(^1\). **Figure 3** shows the example of their experiment. After they confirmed the reliability of the method, they implemented experiments on the wave flume to get detailed information on the sand outflow phenomenon and confirmed the mechanism of sand outflow. Moreover, Ioroi and Yamamoto\(^7,8\) performed many experiments on the sand outflow phenomenon (refer to **Table 1**) by using the same method of Yamamoto and Minami\(^9\) in order to get an empirical equation for getting the sand outflow rate.

![Wave gauge and Wave generator](image1)

*Fig.2 Illustration of experimental setup.*

![Elapsed time](image2)

*Fig.3 Experimental result of Yamamoto and Minami*\(^9\),

| Case No. | Actual value | Scaled value |
|----------|--------------|--------------|
|          | Significant Wave Heights \(H_{1/3}\) (m) | Wave Period \(T\) (s) | Median Grain size, \(D_{50}\) (mm) | Significant Wave Heights \(H_{1/3}\) (m) | Wave Period \(T\) (s) | Median Grain size, \(D_{50}\) (mm) |
| 1        | 6.69         | 14.5         | - | 0.223 | 2.65 | 0.20 |
| 2        | 6.69         | 14.5         | - | 0.223 | 2.65 | 0.66 |
| 3        |              |              |   |        |      | 5.00 |
| 4        |              |              |   |        |      | 10.0 |

**Table 1** Experimental setup of Ioroi and Yamamoto\(^7,8\).

In this research, an applied case of Ioroi and Yamamoto\(^5,8\) was executed. The same external force as that of Hirono Coast and grain size of 0.2mm were used in experiments as shown in **Table 2**. **Figure 4** shows the sample experiment results after the scouring, and accumulated sand outflow rate of the experiment is shown as dash-line in **Fig. 5**. In this figure, since there was no sand layer in front of the dike, the backfilling materials flowed out during the return flow, and the sand outflow rates gradually decreased with elapsed time.

![Elapsed time](image3)

*Fig.4 Progress situation of backfilling flow from a dike model.*

**Table 2** Experimental setup of the authors.

| Case No. | Actual value | Scaled value |
|----------|--------------|--------------|
|          | Significant Wave Heights \(H_{1/3}\) (m) | Wave Period \(T\) (s) | Median Grain size, \(D_{50}\) (mm) | Significant Wave Heights \(H_{1/3}\) (m) | Wave Period \(T\) (s) | Median Grain size, \(D_{50}\) (mm) |
| 1        | 6.69         | 14.5         | 0.5-3 | 0.223 | 2.65 | 0.20 |
| 2        | 6.69         | 14.5         | 0.5-3 | 0.223 | 2.65 | 0.66 |
| 3        |              |              | 0.5-3 |        |      | 5.00 |
| 4        |              |              | 0.5-3 |        |      | 10.0 |

**Fig.5 Relation between accumulated sand outflow rate and elapsed time (\(D_{50} = 0.2\)mm). (The calculated values were calculated by CADMAS-SURF and Eqs. (19)-(27)).
(2) CADMAS-SURF
The wave flume and the dike model in the CADMAS-SURF were set with the same conditions in the hydraulic experiments. Then, the authors compared the pressures and the velocities from the simulation results with the measured results in the experiments to confirm the applicability of the simulations. The pressures and the velocities were calculated at every designated mesh. After that, the pressures and the velocities in every time step were used to calculate the sand outflow rate \( q; \text{m}^3/\text{m/s} \) in each grid using Eq. (19). Moreover, when the outflow reduced the thickness of backfilling materials, the sand continuity law and the repose angle could be used for adjusting the shape and slope of the cave. Finally, the sand outflow rates and the accumulated sand outflow volume could be calculated.

\[
\frac{q}{w_s D_{50}} = \beta (\theta - \theta_c) . \tag{19}
\]

(3) Proportional coefficient
The proportional coefficient \( \beta \) is used for converting the difference between sand outflow force and sand outflow resistance to the sand outflow rate. According to the sand outflow rate formula of Iori and Yamamoto\(^7\), \(^8\), the empirical equation, Eq. (7), for getting this proportional coefficient was proposed by using results from hydraulic experiments. However, this equation was designed to calculate the sand outflow rate by using maximum pore water pressure at the lowest edge of the dike or the seawall only. Thus, to calculate the sand outflow rate on each grid and time using Eq. (19), a new empirical equation for getting the proportional coefficient must be proposed. The proportional coefficient can be obtained by using the relationship between the sand outflow rate, the sand outflow force, the sand outflow resistance, and the median grain size, which can be measured from hydraulic experiments, and some trial simulations. Therefore, the authors obtained the new empirical equation, Eq. (20) for getting the proportional coefficient using experimental data mentioned above.

\[
\beta = 0.321 e^{-0.25 \left( \frac{D_{50}}{0.2} \right)} , \tag{20}
\]

where the unit of \( D_{50} \) must be in mm.

4. IMPROVEMENT OF CALCULATION METHOD USING CADMAS-SURF
As mentioned above, CADMAS-SURF considers the effect of the different grain sizes of backfilling materials to the pressure by using the drag force coefficient or Dupit-Forchheimer method. However, the calculated pressures distribution inside the dike did not match the experiment’s results as shown in Fig. 7 due to the reasons mentioned in section 1. Thus, to evaluate the sand outflow rate by using CADMAS-SURF, some modification coefficients were introduced to arrange the calculation pressure instead of using the Dupit-Forchheimer method. These coefficients were obtained using experiments that could take the effects of grain size and sand layer thickness into account. In these experiments, some pore water pressure meters were set at the dimensionless length inside the dike model (ratio between the inner length from the front of the dike and total length of the dike \( (x/x_{\text{max}}) \) of 0, 0.067, 0.200, and 0.677 indicated by the points 1, 2, 3, and 4 in Fig.6 in order to get the pressure distribution ratio inside the dike. Moreover, to consider the change in sand layer thickness in relation to the pressure, the experiments were performed by varying the sand layer thickness in three situations: 1) before the start of outflow, 2) the middle of outflow, and 3) the end of outflow as shown in Table 3. With these setups, the authors could obtain the pressure distribution inside the dike and the pressure changing with the sand layer thickness. The results are shown in Table 4.

From Table 3 and Table 4, we can get the relation between the ratio of maximum pore water pressure to pore water pressure and the dimensionless length.

![Fig. 6 Position of pore pressure meters.](image)

| Situation                  | \( d_1 \) (cm) | \( d_2 \) (cm) | \( d_3 \) (cm) | \( d_4 \) (cm) |
|----------------------------|----------------|----------------|----------------|----------------|
| 1 (Before start of outflow) | 8              | 29             | 29             | 25             |
| 2 (The middle of outflow)  | 1              | 10             | 19             | 25             |
| 3 (The end of outflow)     | 0              | 5              | 9              | 25             |

| \( x/x_{\text{max}} \) | 1 (Before start of outflow) | 2 (The middle of outflow) | 3 (The end of outflow) |
|------------------------|-----------------------------|--------------------------|------------------------|
| 0                      | 0.067                        | 0.067                     | 0.067                  |
| 0.200                  | 0.501                        | 0.510                     | 0.299                  |
| 0.677                  | 0.161                        | 0.100                     | 0.022                  |
inside the dike \((x/x_{\text{max}})\) in each situation as shown in Fig. 7. When we consider the trend of the pressure distribution before the start of the outflow, the pressure reduces when the inner length inside the dike reduces. According to this trend, the empirical equation for getting maximum pressure distribution to the dimensionless length inside the dike can be determined as Eq. (21). Moreover, when we consider the trend of the pressure due to the difference in sand layer thickness, the results show that the pressure reduces when the sand layer thickness reduces. By considering the reduction of pressure from before the start of the outflow (the maximum case) to the sand layer thickness, a reduction factor diagram could be determined as shown in Fig. 8. Using this result, we could consider the effect of the thinning of the sand layer thickness by using Eq. (22). By these equations, we could get the pressure distribution factor for every point inside the dike.

\[
C_x = 0.00022^{x/x_{\text{max}}} , \quad (21)
\]

\[
C_d = e^{\ln(d/d_{\text{max}})} x_{\text{max}}^{0.269} \ln(d/d_{\text{max}})^{0.953} , \quad (22)
\]

\[
\chi = 45.0 - 23.7e^{-(x/x_{\text{max}})-3.265/4.953} , \quad (23)
\]

According to the sand outflow rate decreases when the grain size increases, Yoshizawa et al. proposed the empirical equation that could calculate the reduction coefficient for the grain size. However, this equation was designed for Ioroi’s formula (Eq. (5)). Thus, the authors modified the coefficients in Yoshizawa’s formula as shown in Eq. (24), by using some trial simulations. This equation can be used in the new sand outflow equation (Eq. (19)).

\[
C_{d_{\text{D}}0} = 0.65 \left(\frac{0.2}{D_{50}}\right)^{0.85} + 0.35 , \quad (24)
\]

Finally, the calculated pressure from CADMAS-SURF was modified by three coefficients: the non-dimensional maximum pore pressure distribution for horizontal length inside the dike, the reduction coefficient for the sand layer thickness, and the reduction coefficient for the grain size, as expressed by Eq. (25). This improved pressure was used to calculate the sand outflow force and the sand outflow resistance.

\[
p = C_x C_d C_{d_{\text{D}}0} P_{\text{CAD}} , \quad (25)
\]

where, \(p\) is the modified pressure, and \(P_{\text{CAD}}\) is the pressure calculated by CADMAS-SURF.

5. PROCEDURE OF THE SIMULATION

To apply the sand outflow equation, and modification equations to CADMAS-SURF, the following procedure was used for the simulation:

1. Set the dimension and properties of the porous media, the structure, and the external force in the CADMAS-SURF (in this research, the authors used Froude laws for the dimension of the structure and the external force in the experiment case; actual scale was used for the field cases).

2. Set the measuring line for pressure and velocity at the bottom or the lowest edge of the structure.

3. Calculated the pressure and the velocity by using CADMAS-SURF (Eq. (10)-(18)).

4. If the calculated pressure was greater than zero (considering only positive pressure) and the velocity was smaller than zero (negative velocity in x-direction meant the direction was outward from the structure), the sand outflow calculation subroutine was
started.
5. Calculated the modification coefficients by using \( x/x_{\text{max}} \) and \( d/d_{\text{max}} \) of each column by using Eq. (21)-(24).
6. Modified the calculated pressure of each column by using Eq. (25).
7. Calculated the sand outflow force and the sand outflow resistance by using the modified pressure to Eq. (8) and Eq. (9).
8. Calculated the sand outflow rate by using Eq. (19). Neglected the calculated result when the result was negative.
9. Calculated the sand outflow height of each column by using sand continuity law expressed by Eq. (26).

\[
\Delta d_i = \frac{\Delta q_i \Delta t}{\Delta x}
\]  

(26)

where \( \Delta d \) is the sand outflow height per column; \( \Delta t \) is the time step of the simulation; \( \Delta x \) is the mesh size in \( x \) direction; and \( i \) is the mesh number in \( x \)-direction.
10. Modified the thickness of the sand layer in each column by using Eq. (27).

\[
d_{i+1}^{t+\Delta t} = d_i^t - \Delta d_i^t
\]  

(27)

where \( d_i \) is the sand layer height of each column.
11. Checked the slope stability by using repose angle in each column by using Eq. (28).

\[
\frac{d_{i+1}^t - d_i^t}{\Delta x} \leq \tan \theta_{\text{repose}}
\]  

(28)

where \( \theta_{\text{repose}} \) is the angle of repose.
12. If the calculated sand layer heights did not agree with Eq. (28), the thickness of \( d_i \) and \( d_{i+1} \) were justified until they satisfied the condition of Eq. (28).
13. Output the sand outflow rate, the accumulated sand outflow rate, and the figure.
14. Computed the next time step.
A flowchart of the simulation is shown in Fig. 9.

6. VERIFICATION SIMULATION

The authors executed the verification simulation in which the simulation conditions were the same as those of the hydraulic experiment: The significant wave height was 0.223 m, and the wave period was 2.65 s. The simulation result agreed with the experimental result as shown in Fig. 5 and Fig. 10.

7. APPLICABILITY OF THE METHOD

The reliability of the method was confirmed by some application on field cases in Thailand and Japan. The sand outflow rate in Klong Wan Beach, South Patong Beach in Thailand, and Hirono Coast in Japan were reproduced. The external force and accumulated sand outflow rate of each coast were extracted from the field survey of Kuisorn et al. and are shown in Table 5.
According to Yamamoto and Minami\(^6\), the duration time of a typical typhoon is about 10 hours, which can be divided into two parts. The first part is the scouring time, which is about 4 hours; and the second part is the sand outflow time, which is about 6 hours. Therefore, the simulation time of 6 hours was used for all cases. Results from the simulations are shown in Figs. 11 – 13.

By using the modified pressure from CADMAS-SURF to the sand outflow formula, the accumulated sand outflow rates are close to the measured data from the field cases as shown in Fig. 14.
8. CONCLUSION

The authors propose the numerical simulation model consisting of CADMAS-SURF and Eqs. (2), (3), (8), (9), (19) – (28), which can predict the sand outflow phenomenon changing with elapsed time as shown in Fig.5 and Fig.10. Moreover, this model could reproduce the sand outflow phenomenon that occurred at Khlong Wan Beach and South Patong Beach in Thailand, and Hirono Coast in Japan with sufficient accuracy as shown in Fig.14.

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