Sand Wave Evolution model for Efficient Channel Depth Management

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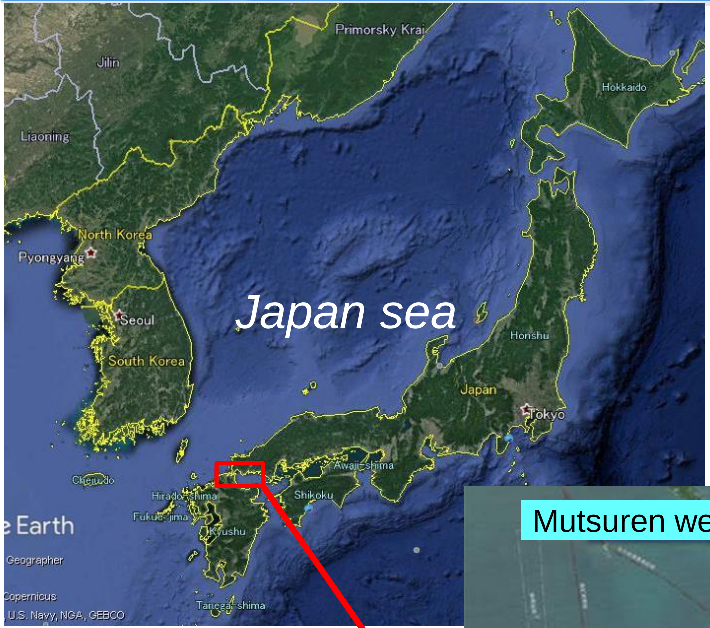
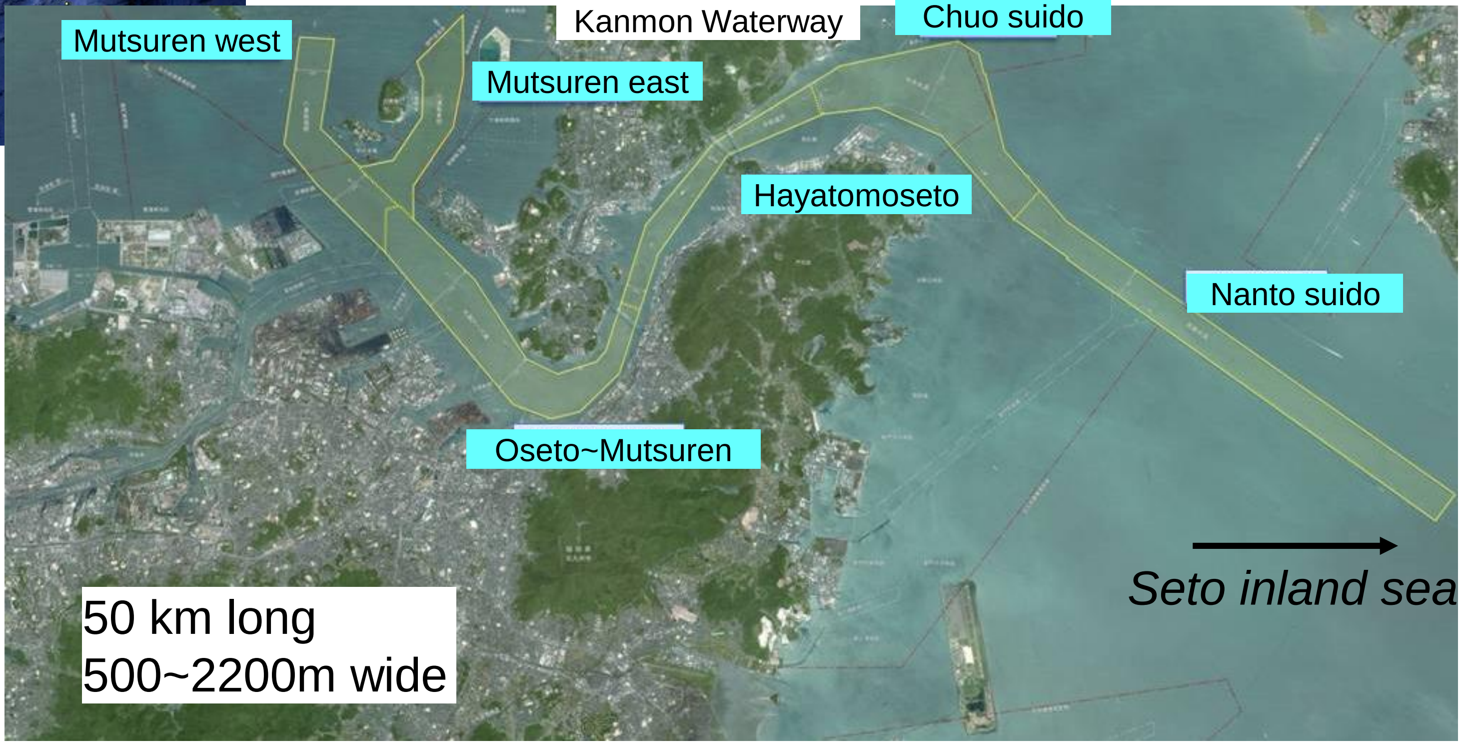
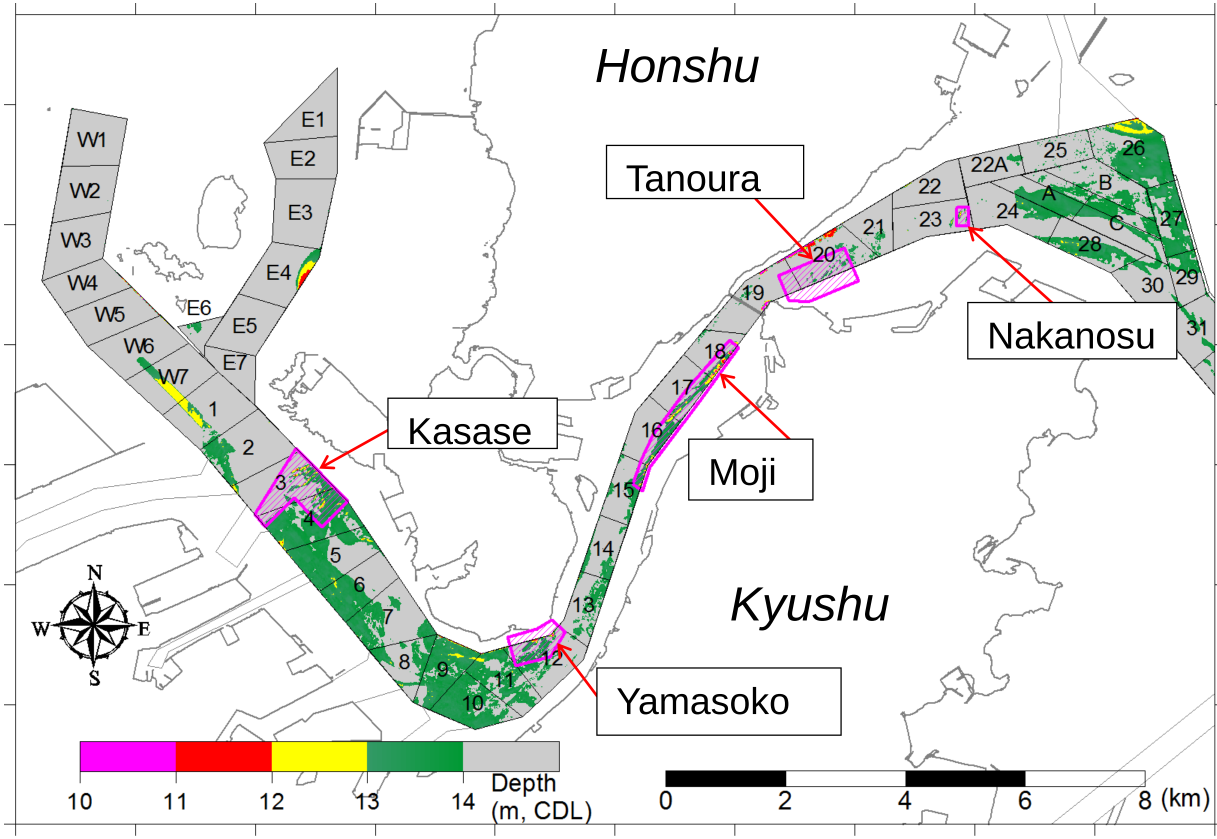
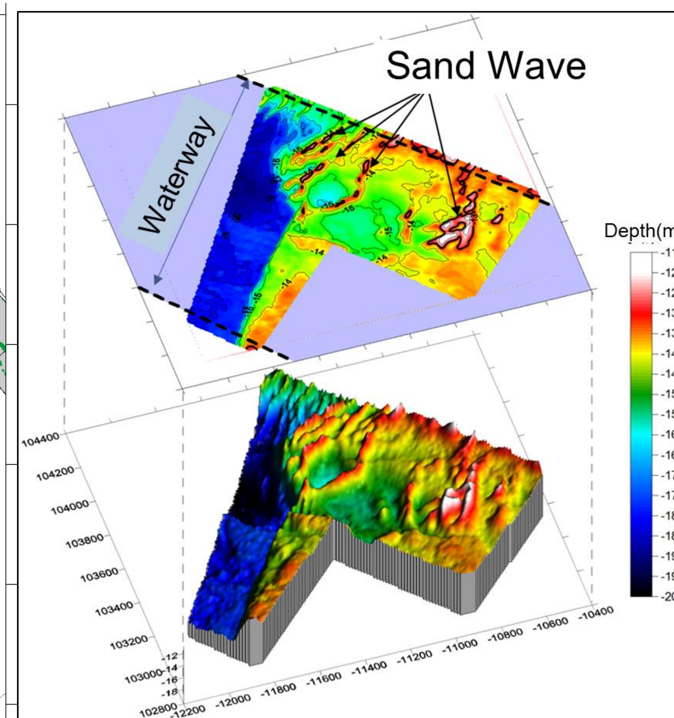
1. Kanmon Waterway





Locations sand waves exist



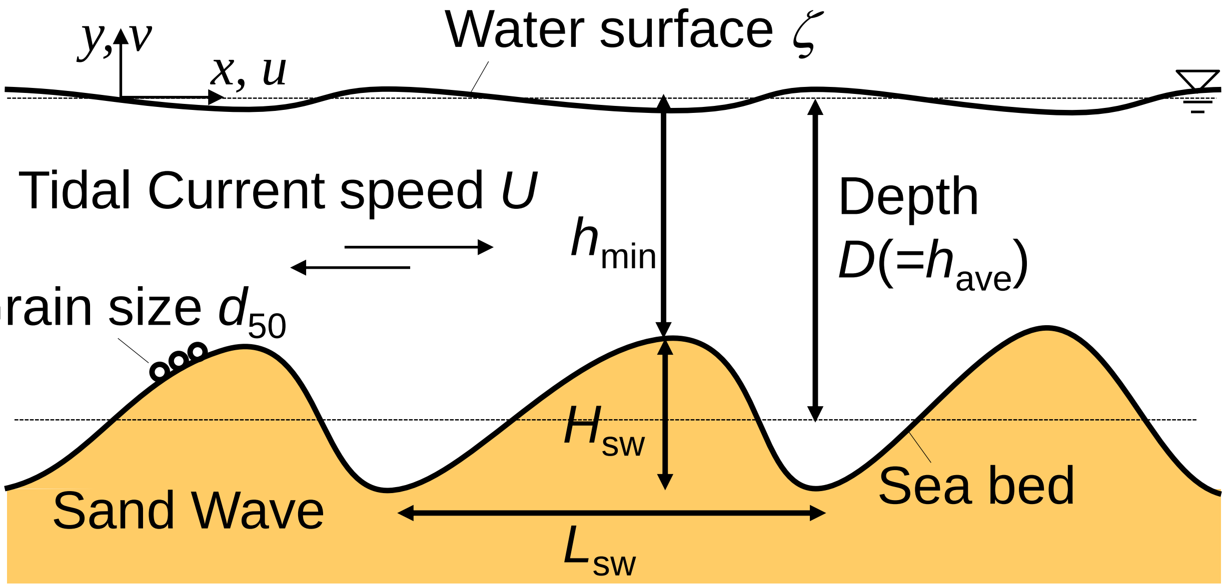


Sand waves in Kasase

Kanmon waterway：12 m in depth (Present), Deepening to 14m is in progress.
Sand waves exists at 5 locations→Shallow point →Dredging

Needs for a sand wave evolution model for efficient channel depth management

2. Sand wave evolution model



H_{sw}=2~5m≒0.2D

L_{sw}=50~300m

Definition of the averaged depth, the minimum depth, and the sand wave profile

Nakamura Model（Nakamura, 2015）

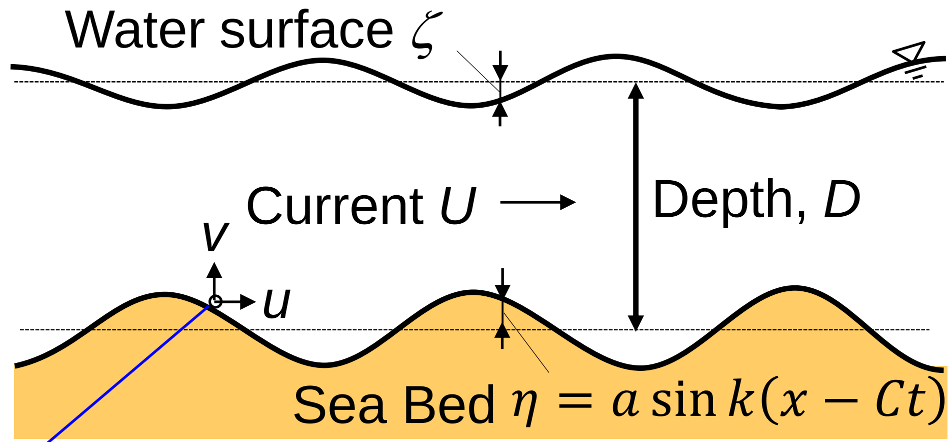
- Based on the stability theory of river bed wave by Kennedy(1963)
- Extended the stability theory to predict the sand wave development by tidal oscillatory currents

Objectives of the study

- ■ To verify the applicability of Nakamura model for the sand waves in Kanmon waterway.
- ■ To examine the methodology in the depth management against sand waves.

Basic equations of Nakamura Model

Nakamura model is an analytical model to calculate time development of wave height and wave length of the sand wave. The model is based on a river bed stability theory and is expanded into sand waves under tidal oscillation.



Potential flow along the wavy bed form

$$\begin{cases} u = U + Uak \left\{ \dfrac{\cosh kD - U^2(k/g)\sinh kD}{\sinh kD - U^2(k/g)\cosh kD} \right\} \sin k(x - Ct) \\ v = Uak \cos k(x - Ct), \qquad k = 2\pi / L_{SW} \end{cases}$$

Sediment transport rate on the sand wave profile:

$$Q = Mu^3(1 + \alpha\eta_x), \quad M = \text{Coeff. [s}^2\text{/m]} \qquad \eta_x = \text{Bed slope}$$

Limitation of the sand wave development

$$\alpha = 1 - a/a_{max}$$

- Wave steepness of ak < Repose angle
- Velocity at the trough of sand wave > the reshold velocity u_c

$$a_{max} = \min\left\{ \frac{\tan\phi}{k}, \left(1 - \frac{u_c}{U}\right) \Big/ k \left(\frac{\cosh kD - U^2(k/g)\sinh kD}{\sinh kD - U^2(k/g)\cosh kD} \right) \right\}$$

The growth rate of sand wave height:

$$\frac{a_t}{a} = \left(1 - \frac{a}{a_{max}}\right) k^2 M U^3 \qquad a_t = \text{Time derivative of } a$$

Migration speed of sand wave under tidal oscillation

In order to reproduce the actual evolution of sand wave, the coefficient of sediment transport rate, *M*, is adjusted based on the measured values of height, length, and celerity of sand wave which are actually measured at the site.

<u>Input parameters</u>

Averaged Depth : D
Grain size : d_{50}
Tidal Current: U (Flood and Ebb)

Sand wave celerity:

$$C = 3kMU^3 \left\{ \frac{\cosh kD - U^2 (k/g) \sinh kD}{\sinh kD - U^2 (k/g) \cosh kD} \right\}$$

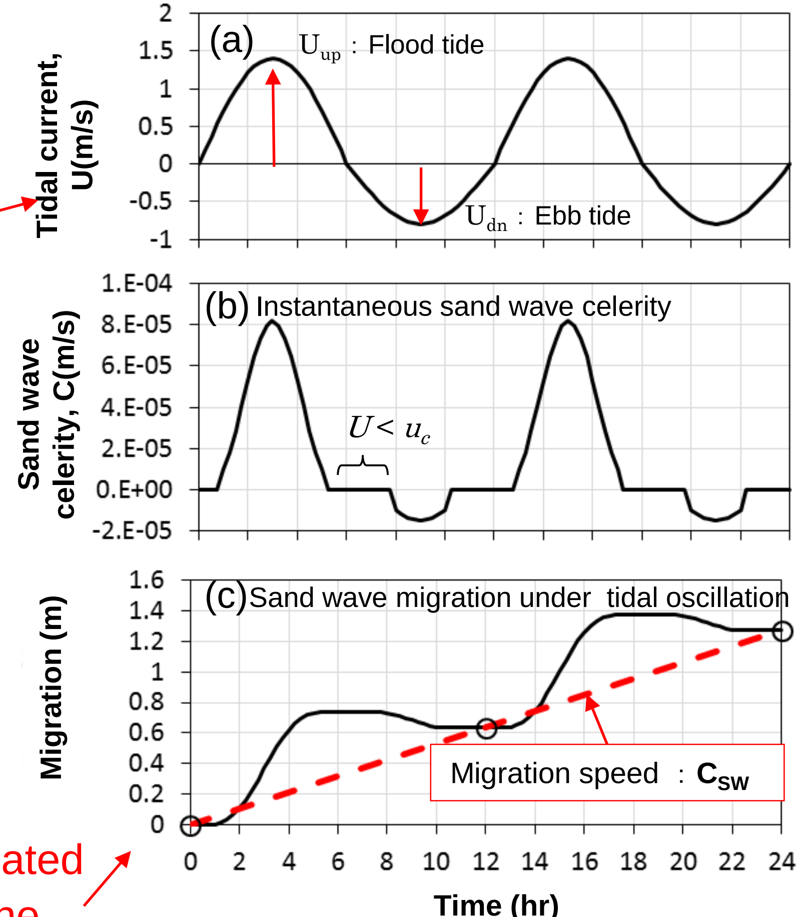
Threshold velocity: $u_c = \sqrt{\theta_c (s-1) g d_{50} / C_f}$

$\theta_c =$ Threshold Shields parameter

Friction factor: $C_f = \left[\frac{1}{\kappa} \ln \left(\frac{11D}{k_s} \right) \right]^{-2}, \quad k_s = 2.5 d_{50}$

The coefficient *M (or A)* has to be set so that the calculated migration speed, Csw, corresponds to the measured one.

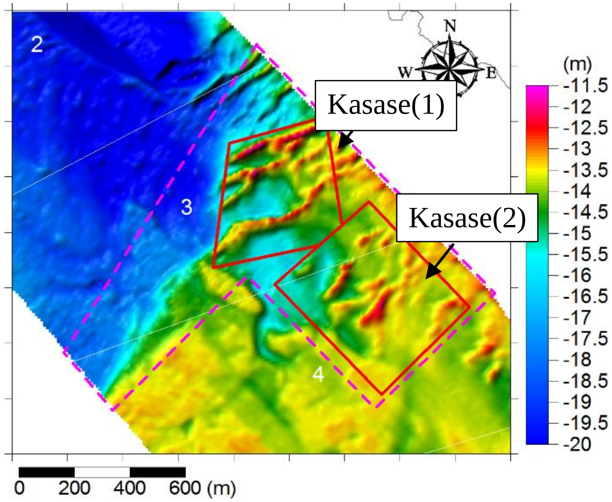
$$M = \frac{A C_f^{1.5}}{(s-1) g}, \quad A =$$ Dimensionless Transport rate coefficient

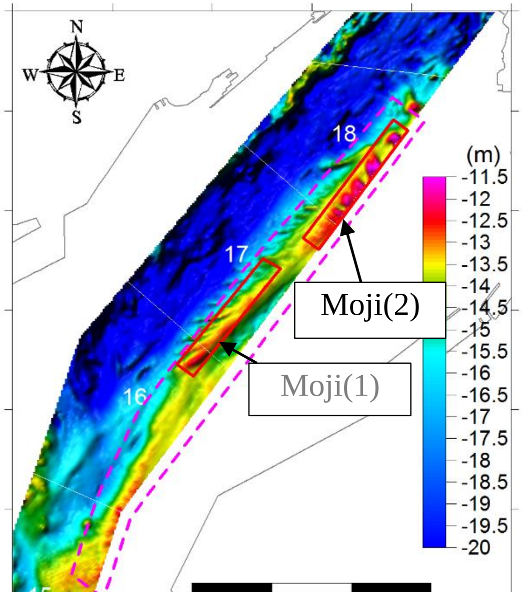


Sand wave movement under the asymmetric tidal current

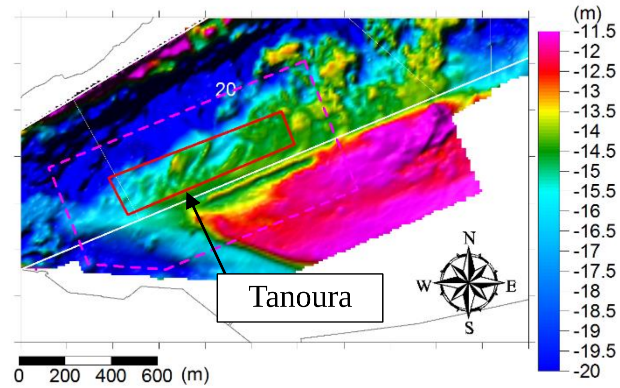
3. Reproduction of sand wave development

Near the exit of strait（Kasase）

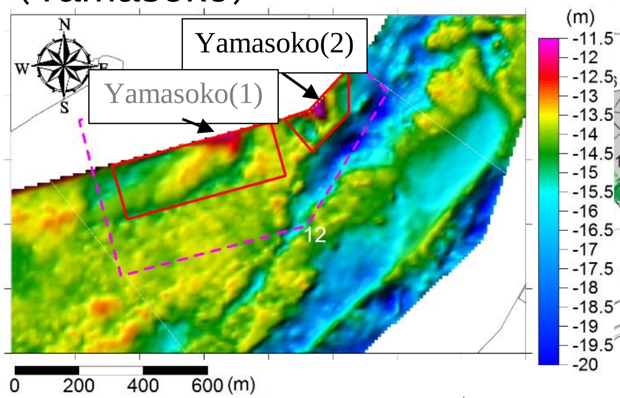


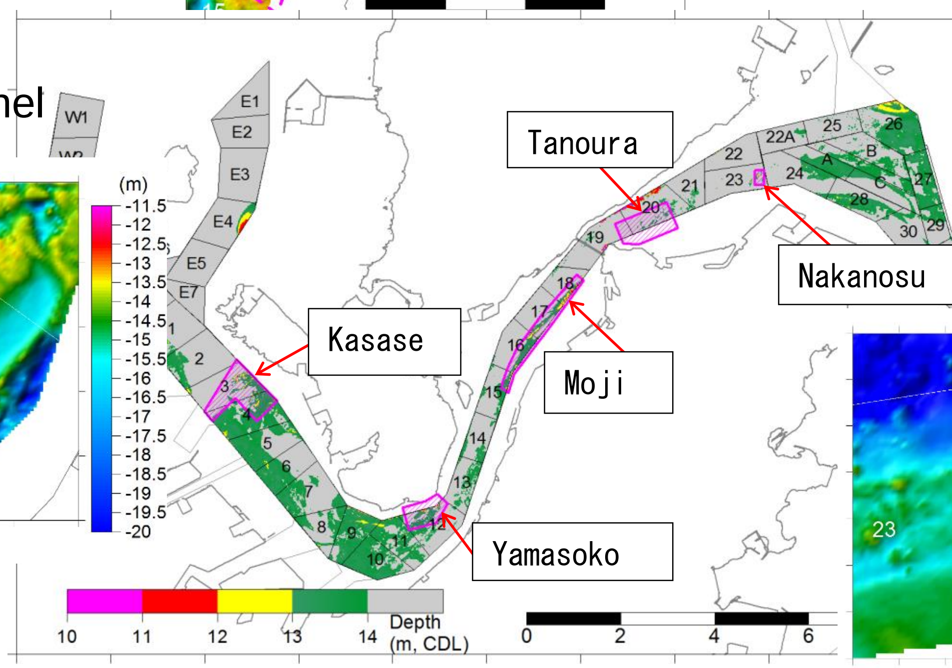


The narrowest point of the strait（Moji, Tanoura）

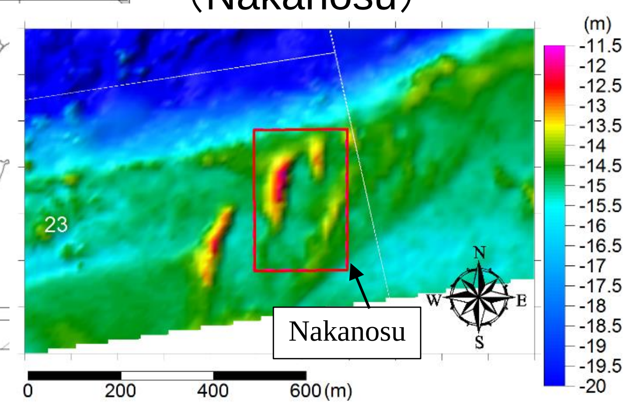


The large curved channel（Yamasoko）





Near the exit of strait（Nakanosu）

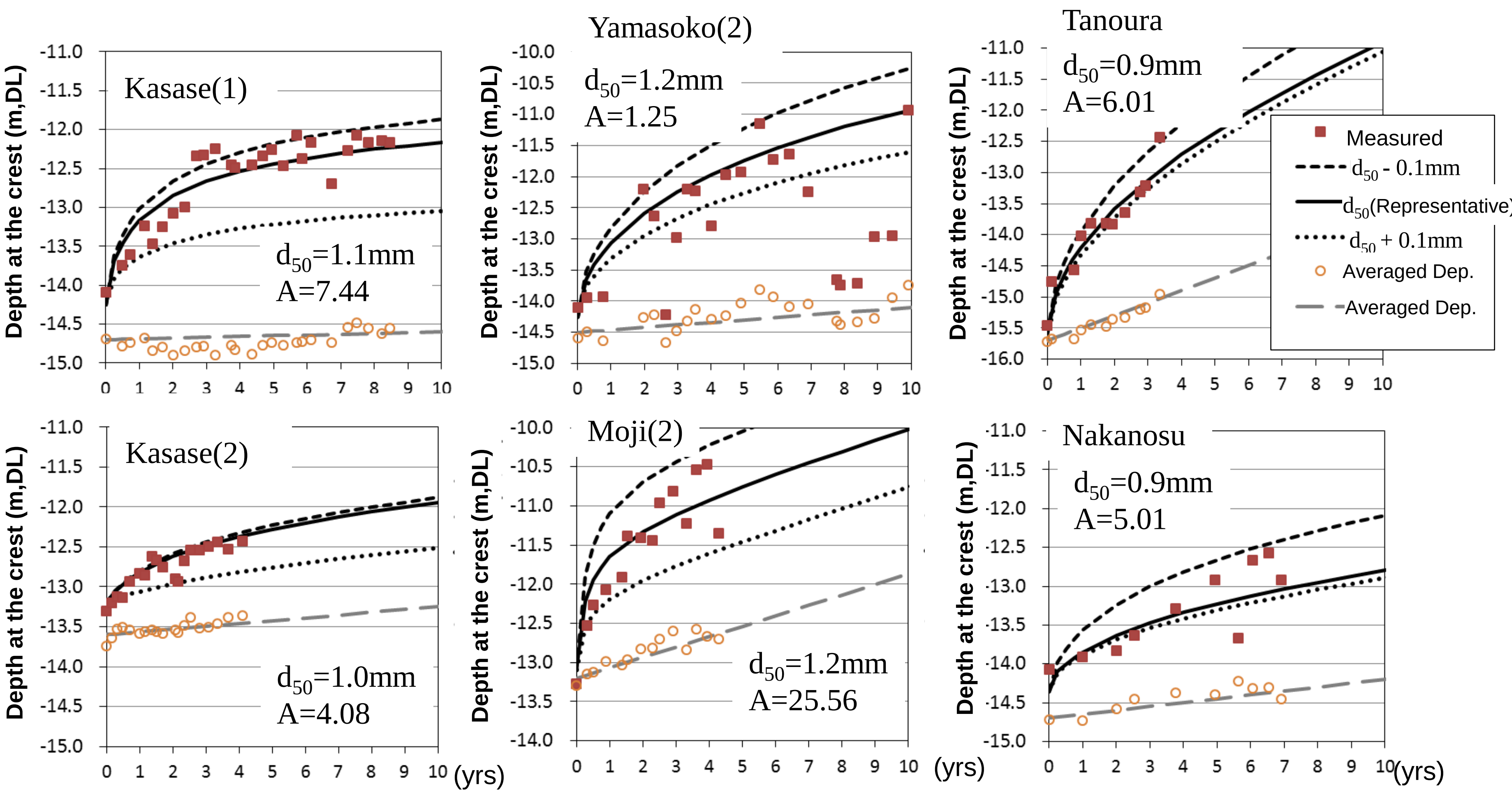


Site specific data of sand waves

Area	Averaged Depth D (m,DL)	Datum z_0(m)	Grain size d_{50}(mm)	Tidal Current U(m/s)	Mean accretion speed dD/dt (cm/yr)	Sand wave height H_{sw}(m)	Sand wave length L_{sw}(m)	Migration speed C_{sw}(m/yr)
Kasase(1)	14.4	0.8	1.1 (0.4-1.4)	1.2 1.1	2.5	2.3 (1.6-3.4)	196 (140-290)	12
Kasase(2)	13.3	0.8	1.0 (0.8-1.1)	1.1 1.0	3.5	1.6 (1.0-2.8)	145 (100-300)	4
Yamasoko	14.5	1.0	1.2 (0.8-2.9)	1.8 0.8	1.6	1.9 (1.0-3.6)	136 (80-275)	32
Moji	13.0	1.3	1.2 (1.1-5.2)	1.4 1.0	13.3	1.8 (0.9-3.0)	125 (60-270)	243
Tanoura	15.7	2.0	0.9 (1.0-2.0)	1.4 1.0	10.6	2.3 (1.7-4.0)	111 (60-270)	30
Nakanosu	14.5	2.1	0.9* (no data)	1.2 0.9	4.9	1.3 (0.7-2.2)	105 (70-170)	26

- The depth-related data, the averaged depth, the sand wave height, the wave length, and the migration speed, are collected by bathymetric survey results.
- The grain size is obtained by the data directly sampled from the crest of sand wave.
- The tidal current velocity at the location of sand wave is estimated by a numerical simulation of tidal currents

Verification results of the model



- The model has reproduced the reformation process of sand wave just after dredging events.
- Depth at the sand wave crest = Change in the averaged depth + Sand wave development

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- The property of sand wave is site-specific, and therefore the transport rate coefficient has to be adjusted for each location to reproduce the sand wave evolution accurately.

Critical depth for Sand wave development

Critical depth in sand wave development

Area	Datum z_0(m)	Depth D (m,DL)	Grain size d_{50}(mm)	Tidal Current U (m/s)	Transport rate coeff. A	Critical Depth h_{cr}(m, DL)
Kasase(1)	0.8	14.4	1.1	1.2 1.1	**7.44**	**17.0**
Kasase(2)	0.8	13.3	1.0	1.1 1.0	**4.08**	**15.5**
Yamasoko	1.0	14.5	1.2	1.8 0.8	**1.25**	**18.0**
Moji	1.3	13.0	1.2	1.4 1.0	**26.50**	**14.5**
Tanoura	2.0	15.7	0.9	1.4 1.0	**6.01**	**19.0**
Nakanosu	2.1	14.5	0.9	1.2 0.9	**5.01**	**16.0**

Predicted sand wave development started from different initial depths. (Moji-case)

･When the initial depth is 13m, the sand wave develops rapidly.
･While the initial depth is 14.5m or deeper, the sand wave does not develop.

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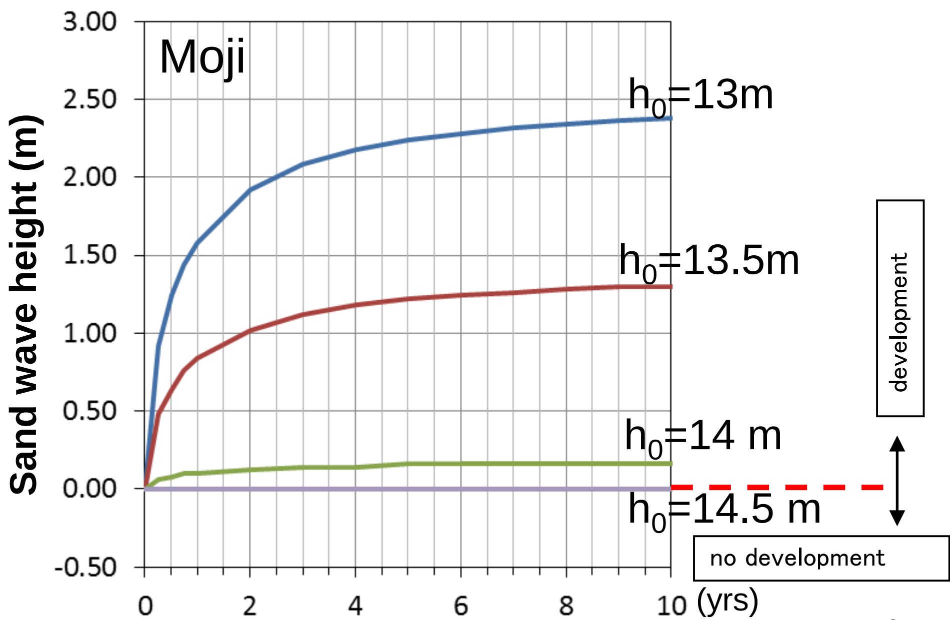
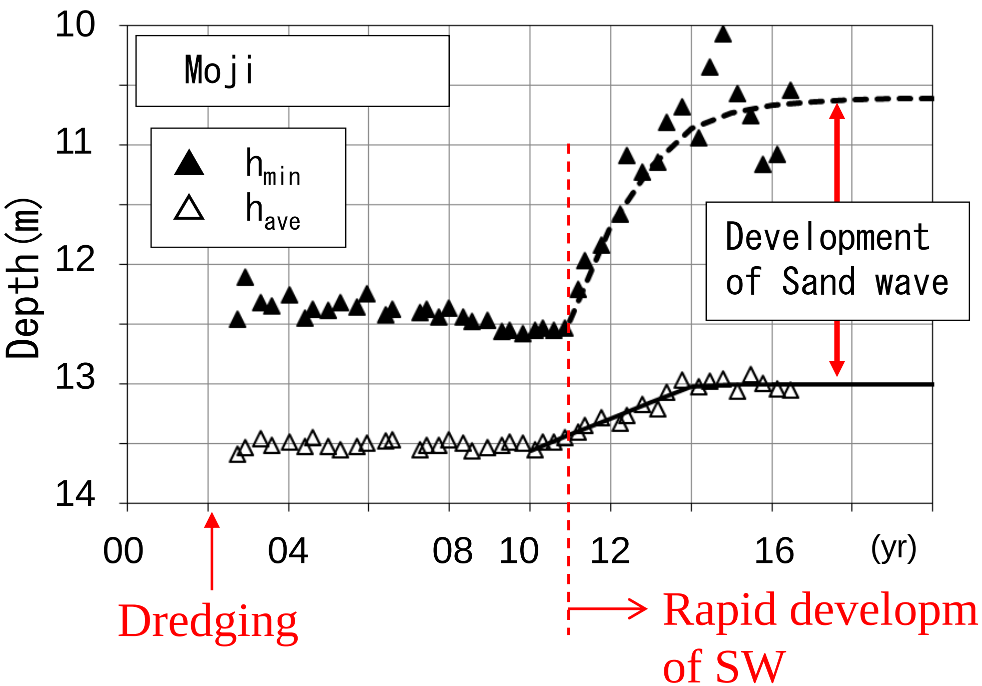
The deeper initial depth, the smaller sand wave develops, because the tidal current velocity gets smaller.

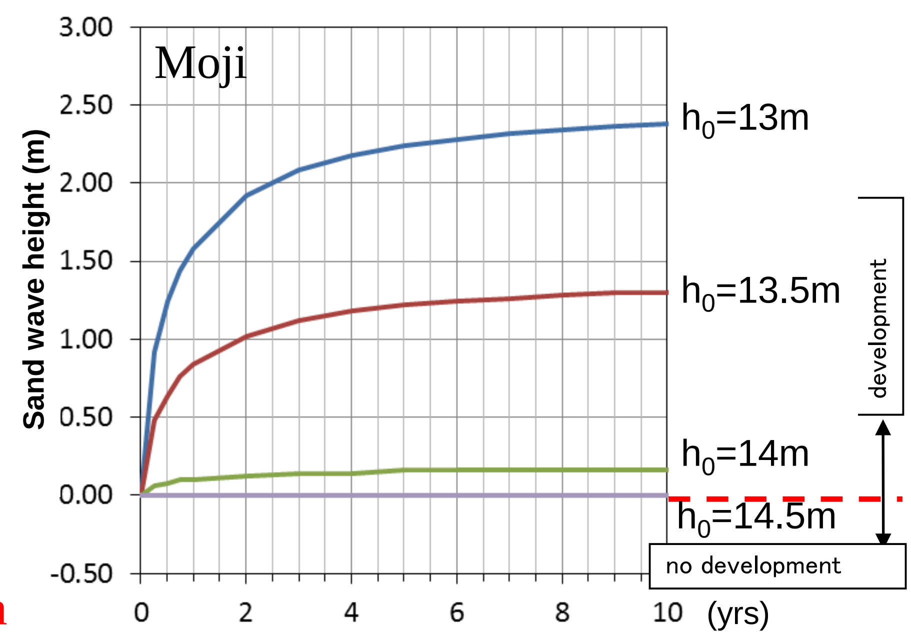


Sand wave development after dredging



Time variation in the averaged depth and that in the minimum depth (measured)

- After dredging in 2002, the minimum depth had changed little by 2011 without growth of sand wave.
- The averaged depth had been shallower since 2010.
- The minimum depth has rapidly been getting shallower just after the averaged depth become 13.4m



Calculation results of sand wave evolution with respect to the different initial depth.

<u>Nakamura model predicted that</u>

- the large sand wave will develop if the initial depth is shallower than 13.5m.

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- Consistent with the measurement
- Applicable for prediction when channel deepening

4. Applicability in depth management

(1)Minimizing the dredging volume

Countermeasure against Sand wave
⇒Secure the depth by dredging of the shallow

Dredging volume
- Initial Dred. : Dredging volume to deepen to the target depth for the first time.
- Maintenance Dred. : Dredging volume accumulated for 50 years against sand wave development

- The shallower target depth
  → Maintenance Dredging gets larger
- The deeper target depth
  → Initial Dredging gets larger

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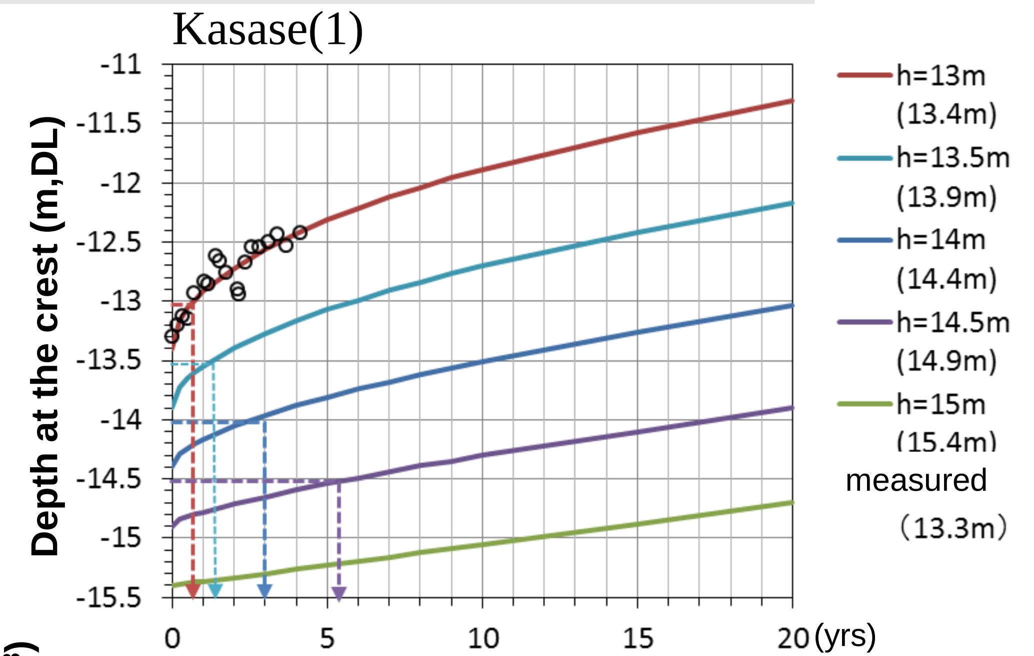
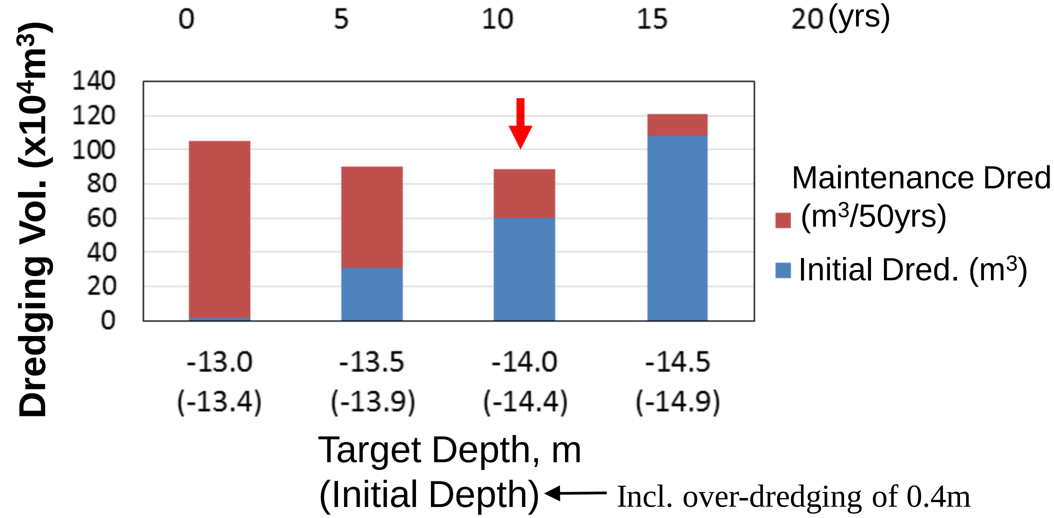
The total dredging volume is minimized on the condition of -14m in target depth, where the both of them balance.





Predicted changes in minimum depth (top) and total dredging volume (bottom) with respect to the target depth

(2)Required dredging depth for appropriate dredging cycle

- Development speed of sand wave is different from place to place.
- Under the condition to minimize the total dredging volume, the frequency of maintenance dredging is sometimes estimated less than one year. (unrealistic!)

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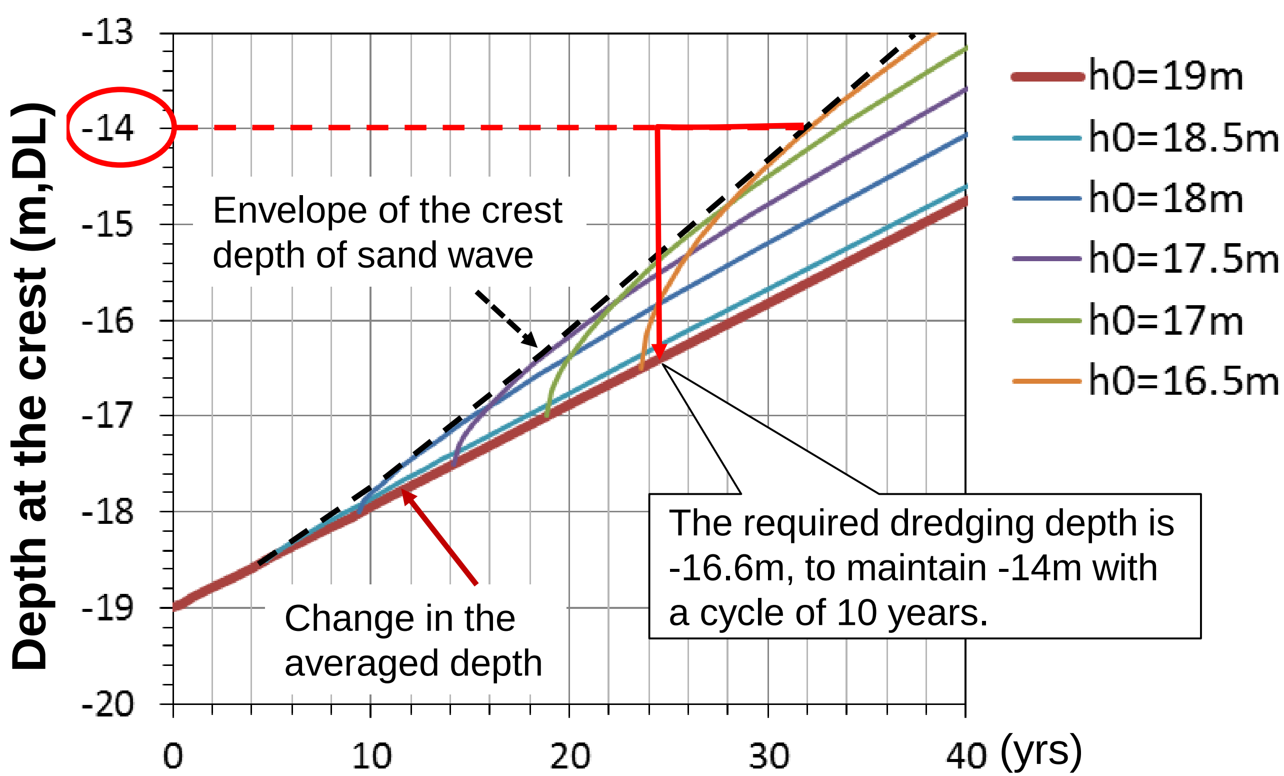
Superposition of variations of crest depth calculated from different initial depths.
→ The envelope shows the actual change of minimum depth.
→ The required dredging depth for arbitrary maintenance cycle can be estimated by the diagram!



Predicted depth change at the crest of sand wave (Tanoura)

5. Summary

- The present model can calculate the sand wave evolution easily and accurately for practical purpose by setting model parameters appropriately from the depth, the grain size, the asymmetric tidal current velocities, and the migration speed of sand wave.
- The present model predicted that the channel deepening reduces the development speed of sand wave. The property is also confirmed by the observation data of Moji case.
- The present model is applicable for estimation of minimizing dredging volume and setting appropriate dredging frequency for the efficient management of sand waves.

Thank you for your kind attention.