ANALYSIS OF IMPULSIVE TSUNAMI FORCE ACTING ON TIDAL BARRIER BEHIND COASTAL DUNE

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A hilly topography protected in the intrusion of tsunami due to the 2011 Great East Japan Earthquake in a northern coastal flat area. Similar topography like sand dunes may be effective to reduce the tsunami force acting on tidal barriers behind them. Some atomic power stations are located behind such coastal dunes in Japan. In the paper, the reduction effect of the dunes for tsunami force was investigated in experiments and a numerical model to design the tidal barrier of the atomic power stations.

Keywords: tsunami force; tidal barrier; power station; coastal dune

INTRODUCTION

Coastal dune is widely located along the shoreline of Japan, and about 7% of the total coastal line is considered as the dune. Its total length is about 1900km. If we can confirm that the coastal dunes or mounds like them are capable to reduce tsunami height and delaying the arrival time, we may build up a tidal barrier (tidal wall) and plan a town arrangement applying the coastal dunes. Maekawa et.al. (2013) revealed the reduction effect of a low dune widely spreading along coastal area by measuring the inundation depth distribution in the flat area behind it after the 2011 Great Tohoku Earthquake Tsunami. Therefor many tidal barriers will have tendency to be installed on the inner side of the coastal dunes for the purpose of multi-layer disaster prevention. The newly constructed tidal barriers (tidal wall) may receive the pressures of the bore-type tsunami overflowing it. The tsunami wave pressure distribution with the coastal dune may be much different from that in the case without dune. However, the research contents concerning the structure just behind the coastal dunes are not so many.

Matsuyama et.al. (2012) studied experimentally on tsunami pressure acting on a tidal barrier with a mound in front of it. They revealed that the maximum pressure distribution is similar like the still water one, and the mound on shoreline causes a little influence on the maximum tsunami pressure. However, they applied only long waves as tsunami waves. Meanwhile, Nakamura et.al. (2018) expressed that the drift dense sands flied up on the mounds and included in tsunami waves cause a high possibility of the increasing of impulsive tsunami pressure at the tsunami surge front.

This paper proposes one of the multi-protection systems against tsunami, and studies on the case for a tidal barrier (tidal wall) just backside of the coastal dune. Check points are 1) Reduction effect of coastal dune for tsunami forces, and 2) Influence of drift sand inside tsunami waves. At the same time, a numerical model simulation is carried out and verified employing the experimental tsunami force distribution. After the verification, tsunami force variation in the different topography is simulated numerically. Finally, the most appropriate sand dune length and width are proposed.

HYDRAULINC EXPERIMENT AND ITS RESULTS

Model and Condition

A long tsunami generation channel 45m long, 4m wide and 1m deep was employed to reproduce the model tsunami. Fig.1 shows the cross section of the channel installed a coastal dune and tidal barrier model. The model scale is 1/80, and the height of dune, tidal barrier and tsunami correspond to 6m, 20m and 10-15m, respectively in the prototype. The seven wave pressure sensers were attached to the surface of the tidal barrier, and the total wave force was analyzed in the integration of the obtained wave pressure in the vertical direction. In the paper, impulsive wave forces at the front of tsunamis are investigated, and a single sinusoidal wave generated in a piston-type generator was applied to reproduce the bore-type tsunami wave with height of 12.5cm offshore. Experimental conditions for coastal dune models are the following four cases; 1) "NS" Flat (no dune), 2) "FS" Fix(mortar), 3) "MS" Movable (sand with 0.20mm diameter), 4) "MS' " Movable (sand with 0.11mm diameter). Table 1 shows the experimental conditions. In the movable bed condition, the sand is blown up per side and the drift sand zone is formatted, but it is not in case of the fixed bed. The trial number in the experiments is 3 and 5 for the case of NS and, (FS, MS, MS'), respectively.

Fig.1 also shows the location of the target tidal wall. It is 137.5cm apart from the shoreline and it is secondary moved to the upper side of 80cm. The distance of backside of dune from the tide wall is 625 and 5cm, respectably. The width of the dune model is 70cm.

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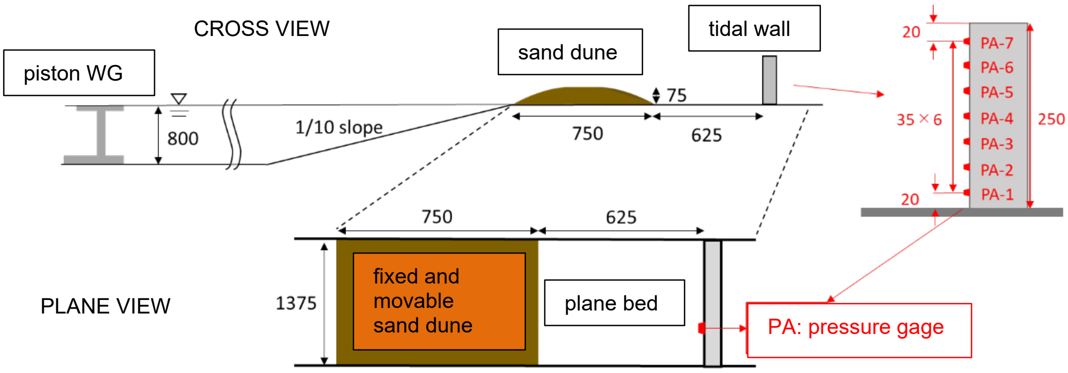


Figure 1 Implementation of experimental tidal wall and coastal dune model

Table 1 Experimental condition for measurement of tsunami force acting tidal wall

Experimental Case			Experimental Condition			
Dune	Symbol	Case No.	Wave(H=12.5cm)	Tidal wall Location (cm)	sand diameter	trial
Flat(No)	NSII	1	sinusoidal wave	-137.5cm	-	3
Flat(No)	NSI	2	sinusoidal wave	−80.0cm	-	3
Fixed	FSII	3	sinusoidal wave	-137.5cm	-	5
Fixed	FSI	4	sinusoidal wave	−80.0cm	-	5
Movable	MSII	5	sinusoidal wave	-137.5cm	dm=0.20mm	5
Movable	MSI	6	sinusoidal wave	−80.0cm	dm=0.20mm	5
Movable	MSII	7	sinusoidal wave	-137.5cm	dm=0.11mm	5

Fig. 2 shows the profiles of the tsunami and wave forces acting on the tidal wall during experiments. The rigid and broken line indicates the variation of water level and tsunami wave force acting tidal wall, respectively. The generated tsunami is a soliton in front of the wave paddle, but it becomes twisted profile at the vicinity of tidal wall due to the wave transformation in shallow water. The wave pressure profiles have several peaks as shown in the figures due to such wave transformation.

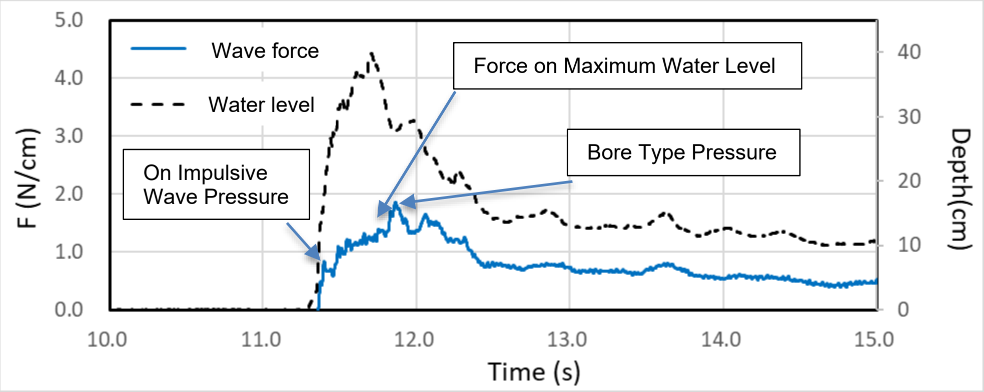


Figure 2 Profiles of sinusoidal wave level and tsunami force acting on tidal wall

In this paper, the peak pressure that appears first in the profile is defined as the impulsive tsunami force. After this, the water level becomes the maximum, and the falling water gives active pressures on the tidal wall. The tsunami wave force becomes the maximum and it is defined as the bore wave pressure. When the wave force is almost uniform, the water pressure distribution is similar like the static one. The distribution is defined as the continuous wave pressure. The maximum wave force is mainly applied in the comparison of the experimental results in different cases.

Experimental Results

Fig.3 shows a vertical distribution of tsunami wave pressure on appearance of the maximum tsunami force. Different color lines indicate different trials, and five trials are carried out in the case of FSII (Fixed Sea bottom). The disturbance between each trial is not so wide and the distribution profiles are similar each other. The profile has a peak near the bottom and the height above the ground is 50mm. In the analysis, the average value of these five trials is adapted as the representative value of the FSII case. Similar analysis was carried out in the case of NS, FS and MS.

Fig.4 shows the analyzed maximum tsunami force for each dune type. The right and left axis of each figure corresponds to the dimensional and non-dimensional force, respectively. The non-dimensional force is calculated as the ratio of the FS and MS force to the NS (no dune) case. Fig.4(1) and (2) indicates the case of the tidal wall location for -137.5cm and -80cm, respectively. As shown in Fig.4(1), the maximum wave force is reduced as much as 20% in case of FS compared with NS case. Therefore, the coastal dune is capable to reduce the tsunami height by about 20% when the dune form is not changed. In the movable bed indicated in MS and MS', both cases express that the dune is capable to reduce the tsunami height by 15%. The difference between the sand diameter may cause a little difference to the result. The reduction rate becomes smaller in the case of Fig.4(2) and the non-dimensional tsunami reduction rate in FS and MS is 10% and 3%, respectively.

Therefore, the most appropriate length of the dune and distance between that and tidal wall exists. Location of -137.5cm becomes the most appropriate one in the case for the dune length of 75cm. In case of MS (Movable bed), the drift sand causes contamination on the wave overtopping over the dune, and the water density is slightly increased. The tsunami force also slightly increased, and the reduction rate is relatively increased. Fig.5 shows the variation profile of contamination in water. The contamination is clearly high at specified times, but the reduction of tsunami force does not appear clearly in the figure. However, the phenomena that the reduction rate becomes the maximum at the position of -137.5cm is adapted to both cases of -137.5cm and -80cm is capable to be applied in both types of fixed and movable seabed. So, the numerical analysis is applied only to the fixed bed case (FS).

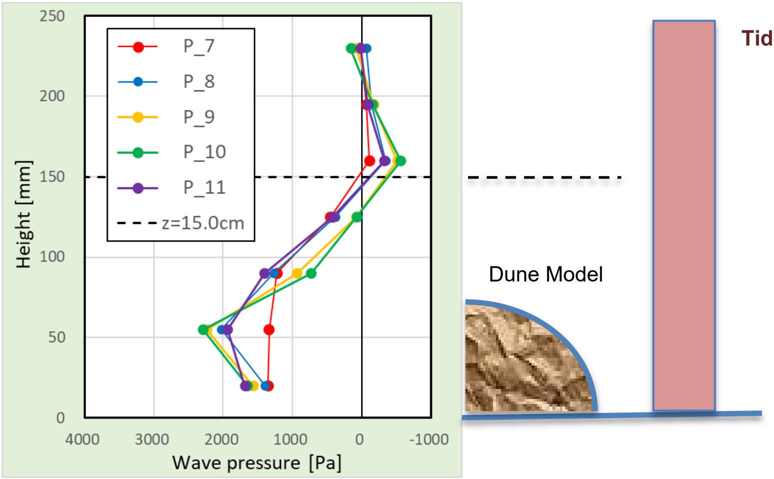
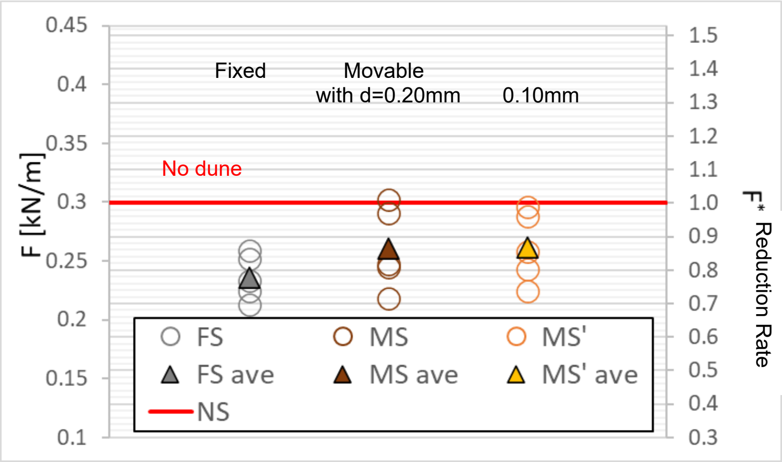
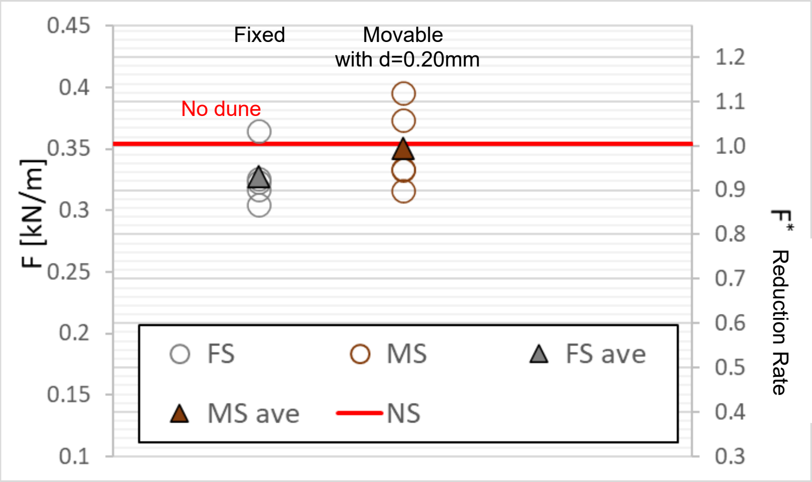


Figure 3 Wave pressure distribution in vertical axis



(1) Tidal wall location: -137.5cm



(2) Tidal wall location; -80cm
Figure 4 Reduction rate due to coastal dune for tsunami wave force

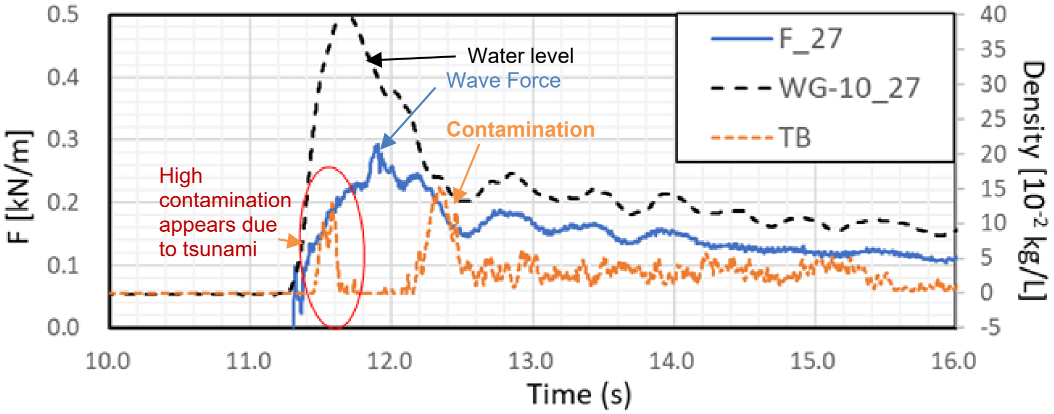


Figure 5 Contamination profile in wave flume (dune location; -137.5cm)

NUMERICAL MODEL SIMULATION USING OpenFOAM

Outline of Numerical Model

A 3-dimensional hydraulic numerical model OpenFOAM is applied to reproduce tsunami transformation in the basin (Phuc el.al., 2013). The purpose of numerical analysis is determination of the most appropriate length of sand dune, and the applicability of the numerical model is verified by the comparison with the experimental results. The most appropriate length of sand dune is investigated numerically using the verified model. Table 2 shows the mesh size and computation time. Fig.6 shows an example of mesh configuration, and the size in the vicinity of tidal wall is 5*5mm. The maximum Kuran number is 0.8.

Table 2 Computation mesh size and turbulence condition

		Mesh A	Mesh B	Mesh C
Mesh gap(mm)	x	5 - 136	5 - 50	5 - 50
	y	10 - 19	3 - 8	5 - 8
Total mesh number		39825	205600	177120
simulation time(hour)		5h	15h	10h
Turbulence model		RANS	RANS	RANS
		LES	LES	LES
Incident wave height(mm)		sinusoidal wave H=125		
Computation time(s)		15		
Computation time interval(s)		0.01		

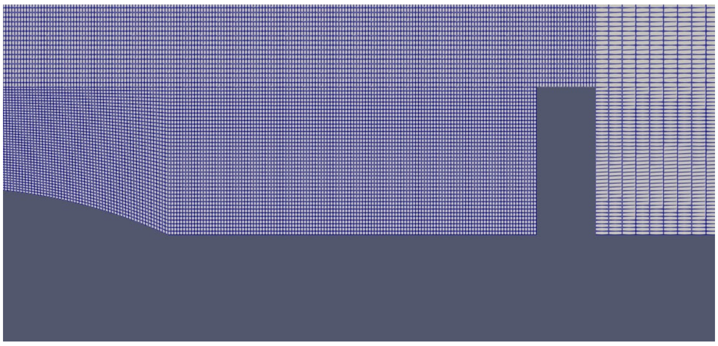
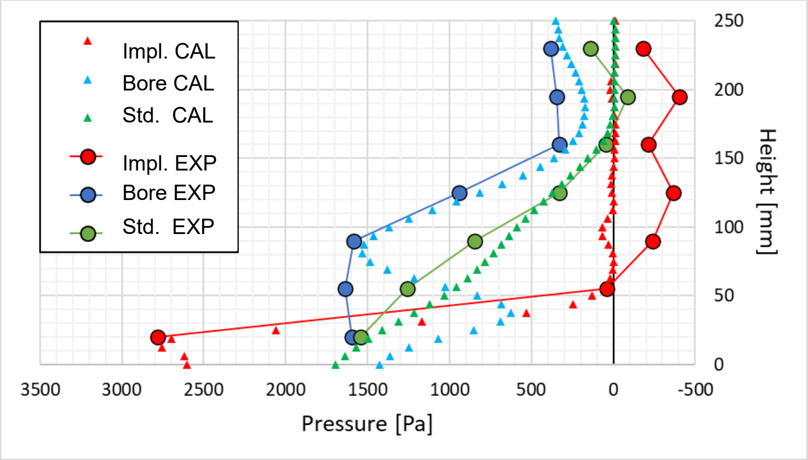


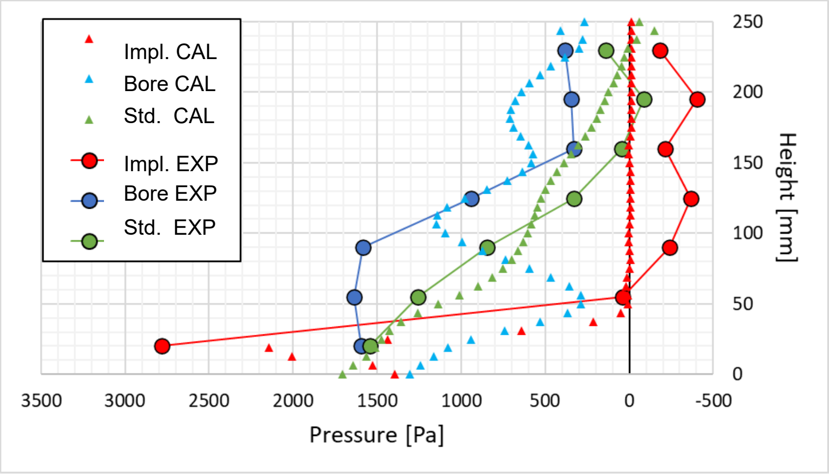
Figure 6 Example of computation mesh configuration (in case of Mesh C)

Turbulence Model in Calculation

At first, the turbulence models in OpenFOAM are studied. The following three types are under consideration:1) Steady model, 2) RANS model and 3) LES model. Pham et al. calculated the Great East Japan Earthquake Tsunami and investigated the accuracy of the VOF model using the different turbulence mode. They applied DNS (Direct calculation), RANS and LES (Smagorinsky model) to simulate the tsunami run-up height in dam-break problem. In results, DNS model expressed the run-up velocity much larger than the experimental one, and RANS model indicated the large variation of similarity to the experimental value according to mesh sizes. The LES model made a smaller variation in the calculation values in different mesh sizes. Therefore, the paper mainly considered the RANS and LES models as the turbulence one and employed the most adapted pair with variable calculation mesh size. Fig.7 shows the comparison of numerically and experimentally obtained tsunami wave pressure distribution on vertical axis. Fig,7(1) is corresponding to the RANS model result for impulsive, bore-type and stationary tsunami wave actions in the mesh C. The agreement is well and the maximum peak wave pressures appearing at 50mm upper seabed is well reproduced in the calculation. Fig.7(2) shows the result calculated in the LES model and the distribution on the seabed is not well reproduced. Therefore, the RANS model with the mesh size Mesh C is adopted in the paper.



(1) RANS model



(2) LES model

Figure 7 Comparison of simulated and measured tsunami wave pressure distribution

Most Appropriate Dune Length

Here, the variation of maximum tsunami wave force was simulated for the variable coastal dune length in the direction perpendicular to shoreline. Fig.8 shows the snap shots of water surface profiles simulated wave in the RANS turbulence model. Tsunamis give the impulsive wave force at first step by flowing down the dune to the tide wall (Fig.8(1)). When the tsunami height becomes higher than the tidal wall, the bore wave force is generated, and the wave force becomes the maximum (Fig,8(2)). At the stationary wave force case, water becomes like a large mound with the existence of reflected waves (Fig.8(3)). Hereafter, the maximum wave force in Fig.8(2) is used as the representative one.

(1) Impulsive tsunami force (2) Bore-type tsunami force (3) steady tsunami force

Figure 8 Snapshot of numerical simulation by RANS model

Fig.9 shows the cross section of simulation condition. The symbol w_0 indicates the distance from the plate edge to the tidal wall and it is fixed to 137.5cm. The symbol l stands the length of dune and it varies from 0(no dune) to 1250mm. The dune height h_d is stable and it is 70mm. In the simulation, the length with the minimum tsunami force is investigated.

Fig.10 shows variation of the maximum tsunami force on the tidal wall. The horizontal and vertical axis indicates the variation of tsunami force, and horizontal axis the dune length. Black circles in the figure indicate the maximum tsunami force obtained in the experiment. The dune length in NS (no dune condition) is defined as 0, and the maximum force is about 0.3kN/m in the both cases of numerical and experimental one. The reduction rate at the length l of 750mm is 10% - 40%, and the value is also similar in the simulation and experiment. When the length l is increased to more than 1000mm in the

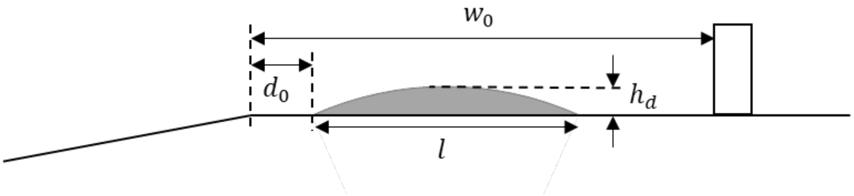


Figure 9 Calculation condition of consideration for the most appropriate coastal dune length

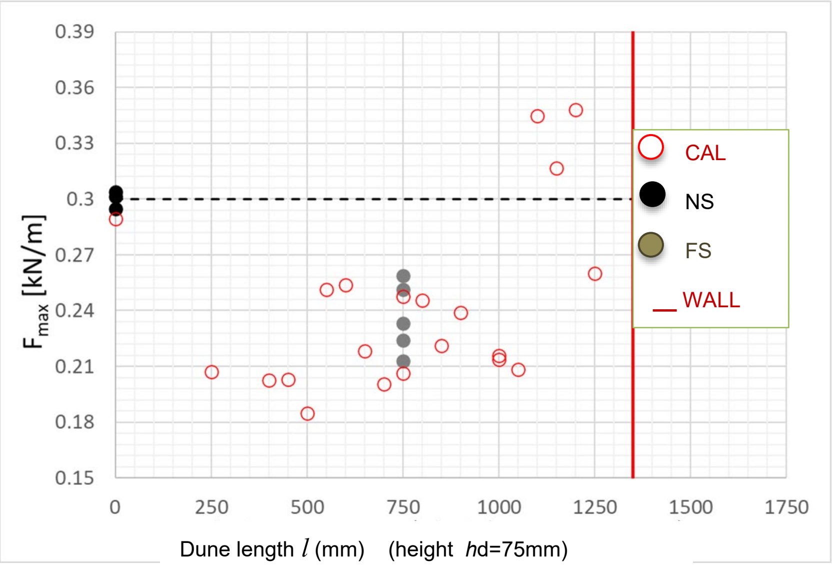
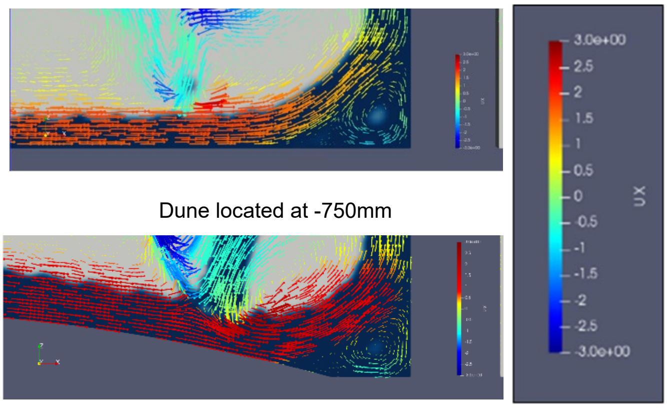


Figure 10 Variation of the maximum tsunami force for coastal dune length

simulation, the maximum tsunami wave force becomes larger, and in *l*=about 1100mm, the maximum force becomes larger than the original one at NS case. Therefore, the most appropriate length of sand dune is 750mm employed in the experimental work, and in case of that the sand dune is extended to the bottom of tidal wall step, the maximum tsunami wave force is not so suitable.

Fig.11 indicates the tsunami collision image on the tidal wall simulated in the model (l250mm). The vectors correspond to the tsunami flow. As shown in Fig.11, The fast and heavy flow come down from the dune to the tidal wall causes the large eddy at the front bottom of at the tidal wall. Therefore, the fast flow may cause the large tsunami force on the tidal wall and the larger one at the worst location. Meanwhile, the tsunami force is reduced to about 60% in case of the appropriate dune length. The safest coastal protection structure design is capable by considering the coastal dune length. The most appropriate coastal dune length is about 5 to 6 times larger than the offshore sinusoidal wave height.



Dune located at -750mm

Dune located at -1250mm

Figure 11 Flow simulation at vicinity of tidal wall

CONCLUSIONS

(1) Experimental results demonstrated that the coastal sand dune is capable to reduce the tsunami forces acting on a tidal wall behind it. This phenomenon is due to tsunami bore-flows over the dune decreasing. In the comparison between the fixed bed and movable sand bed, the case of movable sand expressed the larger tsunami force by the effect of the drift sand.

(2) In the numerical simulation result, the impulsive tsunami force is not reduced in case that the coastal dune foot is just near to the tidal wall. To reduce the tsunami wave force, the appropriate dune height and length, and the distance between the tidal wall should be implemented.

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