ANALYSIS OF TSUNAMI BEHAVIOR AND THE EFFECT OF COASTAL FOREST IN REDUCING TSUNAMI FORCE AROUND COASTAL DIKES

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Many coastal dikes in Iwate, Miyagi and Fukushima prefectures in Japan were damaged due to the *2011 Great Eastern Japan Earthquake Tsunami.* The primary failure mode of these dikes was scour failure at the leeward toe by the overflowing tsunami. However, the forces exerted by the tsunami wave against the dikes were reduced to the presence of some obstacles (such as trees) located behind the dikes, increasing the tsunami inundation height immediately behind the structure and actually helping to reduce the force on the dike itself. In order to analyze how tsunamis affected coastal dikes, the authors carried out post-tsunami field surveys and laboratory tests using dikes and different coastal forest models. The critical failure mechanism of dikes was analyzed and co-related to tsunami overflowing pattern. In addition, the experimental results show how coastal forest can help to reduce the damage caused by the tsunami to coastal dikes by increasing water depth and changing the tsunami motion pattern. Thus, the placement of coastal forests behind dikes can help to increase their resilience against tsunami attack, and should be considered as part of a disaster management strategy for certain tsunami prone areas.

Keywords: coastal forest; overflowing tsunami; coastal dike

INTRODUCTION

Many coastal dikes in Iwate, Miyagi and Fukushima prefectures in Japan were damaged due to the 11March *2011 Great Eastern Japan Earthquake Tsunami*. The Mw 9.0 earthquake exceeded that which had been expected by many scholars and was one of the highest recorded in history. The tsunami flowed over the coastal dikes and flooded the area behind them, as many dikes in the Sendai plain were designed to prevent inundation by a storm surge, not a tsunami, and especially not the case of a tsunami overtopping the coastal dikes (Mikami et al. 2012). Therefore, many coastal dikes were destroyed due to the tsunami attack and the tsunami proceeded to travel many kilometers inland along the Sendai plain. The primary failure mode of these dikes was due to scour at the leeward toe (Jayaratne et al. 2014), caused by the overflowing tsunami. However, the forces exerted by the tsunami against the dikes were lowered due to the obstacles located behind the coastal dikes, which increased inundation height and created a water cushion (e.g. Tanimoto et al. 2012).

Recently, coastal forests have attracted as a means of tsunami mitigation, motivated partly because of the added co-benefits they represent in terms of scenic beauty and environmental regeneration. In previous studies, some of the roles that coastal forests can provide to attenuate tsunami impact have been indicated. For example, Tanaka et al. (2007) showed how a horizontal coastal forest structure which consisted of small and large diameter trees could increase drag and trap floating objects, broken branches, houses, and people. Trees can also provide an effective soft landing place for people washed away by the tsunami or for vertical evacuation, provided that branches can provide an easy mean of ascending them.

This study aims to analyze how tsunamis affect coastal dikes and to evaluate the resistance added structural resilience that can be provided by coastal forests located immediately behind them. In order to do such, the authors carried out post-tsunami field surveys and experiments

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using dikes and different coastal forest models. As a result, the relationship between tsunami behavior and dike failure and the effect of coastal forest in reducing tsunami force around the coastal dikes were analyzed in detail.

COASTAL DIKE FAILURES

The authors carried out three field surveys on coastal dikes in Tohoku area, taking detailed recordings of how the leeward toe and slope was damaged by the scour due to the overflowing tsunami and evaluating the relationship between the scale of scour and the damage rate to the coastal dikes and forest (Jayaratne et al. 2013, 2014). The survey results are shown in Table. 1. The inundation heights behind the dikes at each location are taken from the survey results of the 2011 Tohoku Earthquake Tsunami Joint Survey Group (2012). The dike height and the scour length were determined by the authors using survey instrumentation at each site. The coastal forest length which existed before the tsunami attack and distance between the dike and coastal forest model were estimated using satellite photographs. Comparing the coastal forest length before and after the tsunami attack the damage rate to the coastal forest was measured (See Watanabe 2011 and Sasaki et al. 2011)

Table.1 Survey results of damaged dikes and coastal forests.

Survey Results	Locations of surveyed city		
	Iwanuma City	Shichigahama City	Soma City
Tsunami innudation height behind the dike	8.8m (Tohoku survey group)	7.16m (Tohoku survey group)	13.85m (Tohoku survey group)
Dyke height	5.76m	2.71m	5.87m
Scour length	10m (Google Earth)	5m (Google Earth)	31.78m
Coastal forest length	300m (Google Earth)	100m (Google Earth)	60m (Google Earth)
Distance between dike and coastal forest	20m (Google Earth)	10m (Google Earth)	0m (Google Earth)
Damage rate of the coastal forest	0～20% (Watanabe, 2011)	10～20% (Sasaki et al. 2011)	100%

Details of the three coastal dikes surveyed are given in Figures 1-3, all of which were built on a 1:2 slope. The leeward slope and toe of the coastal dike at the Iwanuma city completely collapsed due to the effect of the tsunami attack. Most of the concrete superstructure fell down because the soil which was used in its core was washed away by the overflowing tsunami, as shown in Fig. 1.

Damage to the coastal dikes in Shichigahama city was not as extensive as in Iwanuma city, though the leeward slope of the coastal dike collapsed in some places, as shown in Fig. 2. The dike was not so high in this location because people often use this beach for a variety of leisure activities, and thus the tsunami flooded over the dike easily.

The scale of the scour damage in Soma city was the largest amongst the dikes surveyed, measuring 31.78 m in width. At this location the coastal forest completely disappeared, while the coastal forest had a depth of 60 m before the tsunami attack, as shown in Fig. 3. From this survey results, it was clear that there is a relationship between the damage to coastal forest and the progressive scour.

Fig. 1 Iwanuma city.

Fig. 2 Shichigahama city.

Fig. 3 Soma city.

VIDEO RECORDS

Some videos clips captured by people who experienced the 2011 Tohoku tsunami show the tsunami overflowing coastal dikes. Figure 4 shows a snapshot of a recorded video at Oirase Town, Aomori Prefecture. At this point the inundation height was 3.2 m behind the coastal dike, which had been built to a height of 6.0 m. The video clip shows that as the tsunami arrived to Oirase port the water depth gradually became higher, with the tsunami behavior looking like a long period flooding or flow, not a wave. The tsunami started to overflow the coastal dike 7 minutes after the first part of the wave reached this port. When the tsunami started to flow over the coastal dike a supercritical flow takes place, which has very high velocity at the leeward of the slope and toe.

Fig. 4 Snapshot of recorded video clip at Oirase Town in Aomori prefecture (from video sharing website).

However, paying attention to the tsunami behavior between the coastal forest and the coastal dike, the tsunami force looks as if it is being by the effect of the coastal forest, reducing in velocity and force as a consequence of it. About this tsunami reduction effect, Hatogai et al. (2012) suggested that the progress of scour can be reduced by a water cushion created due to obstacles located behind coastal dikes. In this video clip, the water gradually accumulated behind the dike due to the increased resilience provided by the coastal forest, and as a result there was no severe damage to the dike in this area.

LABORATORY EXPERIMENTS

In order to analyze the pattern of tsunami behavior around the coastal dike and the effect of the coastal forest on reducing tsunami force, two types of tsunami overflowing experiments were carried out at the 2D wave flume at Waseda University, Japan. First, laboratory experiments using only dike model were carried out to analyze the pattern of tsunami damage. Based on the results of this experiment, a second series of tests were carried out to analyze the effect of the coastal forest on reducing tsunami forces around the coastal dike.

The experiments were performed using tsunami flow waves generated by a pump in a wave flume of dimensions $14 \times 0.41 \times 0.6$ m). The pump could generate the effect of a tsunami overflowing the dike by generating a uni-directional flow of controllable intensity, allowing the generation of stronger or weaker currents. A slope of 1/10 was installed as the sandy beach in front of the coastal dike. The dike and the coastal forest model were set up as shown in Fig. 5. By changing the length of the coastal forest model *Lv* and the distance between the dike and coastal forest model *L*, four experimental cases were carried out, as shown in Fig. 6. The water depth *h* was also changed in each of the cases. Case1 had only the dike model installed in the tank, whereas the remaining case had both the coastal dike and forest models. The pressure profile was measured using 6 pressure gauges installed to the dike model.

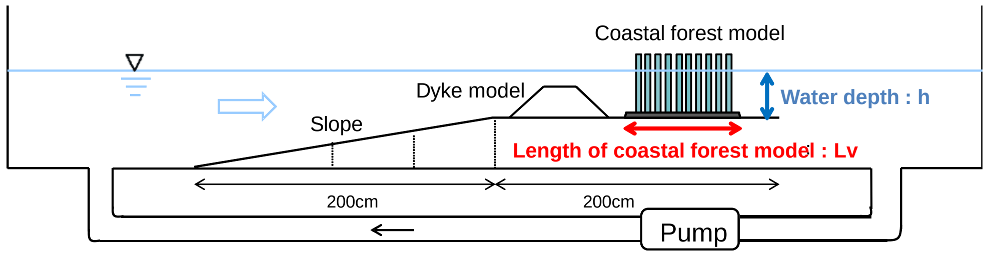


Fig .5 Schematic experimental set-up of coastal forest model.

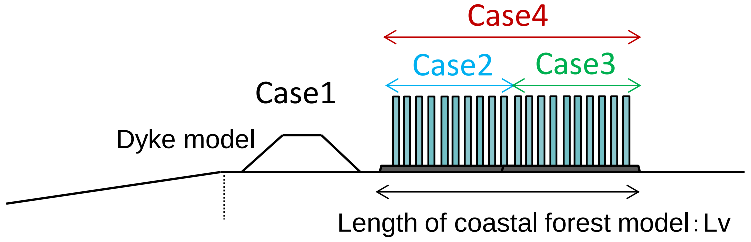


Fig. 6 Tested laboratory cases.

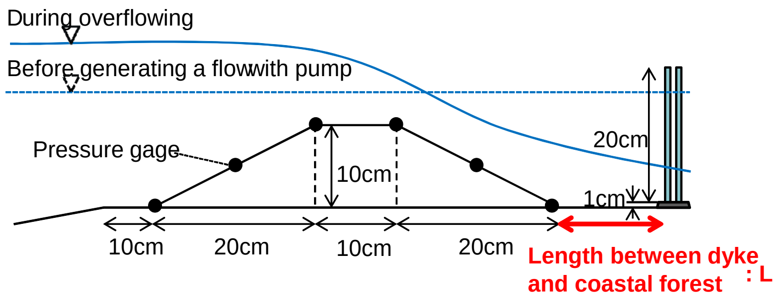


Fig. 7 Dimensions of model dike used in the laboratory experiments.

A number of experiments with coastal forest models have been carried out in the past by various researchers to examine the tsunami mitigation effects of vegetation. In such researches typical considerations are made on how to accurately reproduce a coastal forest in the lab. For example, Matsutomi et al. (2004) considered the selection of tree material based on the similarity rules of the tree trunk. These authors examined how to model the tree and what material is suitable to do so, with Table 2 providing details of how this should be carried out. For the case of Japan typical coastal forests consist of pine trees. It is also important to consider what type of material is adequate to model the trunk of such forests. In the present study urethane with an E value = 500 kgf/cm^2 was chosen to model the trunks, where E is Elastic modulus. The reason for this is that an $E= 2\times10^3$ kgf/cm^2 in a 1/50 scale (which was the scale used in the present experiments) would be equivalent to the $E=10\times10^4$ kgf/cm^2 of an actual tree trunk.

Table. 2 Parameters used for the examination of tree models.

	Actual tree	Model (1/50)	Model (1/100)	Model (1/200)
Tree height（m）	10	0.2	0.1	0.05
Tree width (m)	3	0.06	0.03	0.015
Trunk diameter（m）	0.2	0.004	0.002	0.001
Innudatin height（m）	7	0.14	0.07	0.035
Specific gravity	0.62	1.13	1.13	1.13
E（kgf/cm²）	10×10^4 (9.8GPa)	2×10^3 (196MPa)	1×10^3 (98MPa)	5×10^2 (49MPa)

The experimental conditions are summarised in Table.3. However, it is also necessary to examine the coastal forest density d_n and the arrangement pattern to model what an actual forest looks like. Shuto (1985) examined the limitations of coastal forest to protect against tsunami attack by collecting reports about the behavior of coastal forest of past tsunami disasters. The number of coastal tree models was decided by examining the coastal forest thickness d_n, where d is the diameter of the trunk and n is number of trees per unit length.

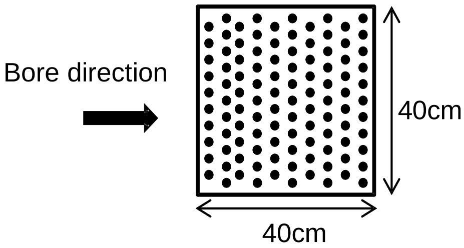


Fig. 8 Plant view of coastal forest model.

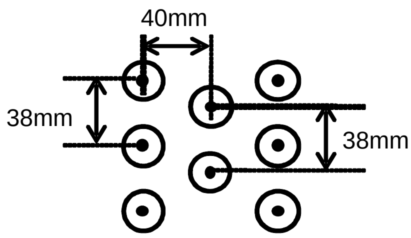


Fig. 9 Set pattern of coastal forest model.

A number of coastal forest density configurations were tested, corresponding to thicknesses of d_n = 105, 210, 315, where d_n = 130〜400 represents actual forests in nature, according to Imai et al. (2003). An example of a staggered pattern placement of the trees in such a model (for a d_n = 105) is shown in Figs. 8 and 9. Two different arrangement types actually exist, namely a tandem and staggered pattern. However, only the staggered pattern was tested in this study, as there appears to be no significant differences between them for the case of tsunami attack, according to the Imai and Matsutomi (2006).

Table. 3 Tested conditions of laboratory experiments.

	Case1	Case2	Case3	Case4
Scale	1/50			
Type of the dike model	Slope 1: 2 Inclined structure			
Height of the dike model	100mm			
Material of the coastal forest model	—	Urethane		
Diameter of the tree model	—	4mm		
Height of the coastal forest model	—	200mm		
Length of coastal forest model : Lv	—	40cm	40cm	120cm
Distance between the dike and coastal forest : L	—	10cm	50cm	10cm
The coastal forest density : dn	—	105	210	315
Set pattern	—	Staggered		

The initial step of the study was to analyze Case 1, which only included the coastal dike. In this series of experiments the water depth in the tank and the flow volume were changed by regulating the pump. The water depth *h* was set to five conditions (10, 12.5, 15, 17.5, 20 cm) and the flow quantity per unit width *q* was set to four different conditions (0.011, 0.040, 0.054, 0.059 m^2/s). By using a laser it was possible to visualize the fluid motion, with three types of overflowing patterns being identified, as shown in Fig. 10. The Pattern A corresponds to the start of tsunami overflowing. This pattern appears to be the most dangerous for the case of dike failure because of the generation of a supercritical flow behind the dike, which has very high velocities hence resulted in large pressures exerted on the toe of the dike. As the water depth becomes higher, the flow pattern switches to Pattern B and then eventually to Pattern C, which corresponds to the moment when the maximum tsunami overflowing height is reached. The Pattern C is characterized by having a subcritical flow at the upper part of the flow and a vortex at the leeward of the slope. The Pattern B is somehow a combination of Patterns A and C, with a hydraulic jump taking place at the leeward side of the dike.

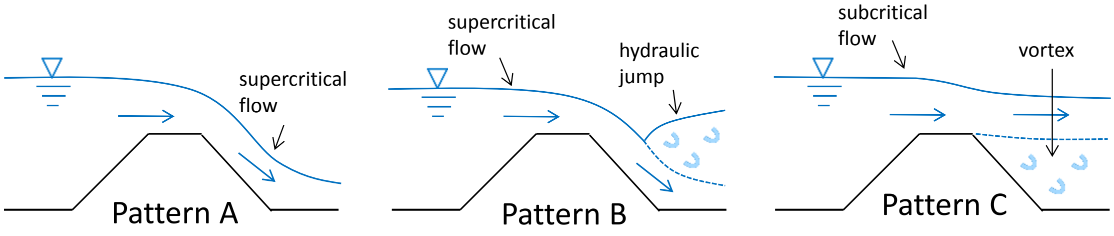
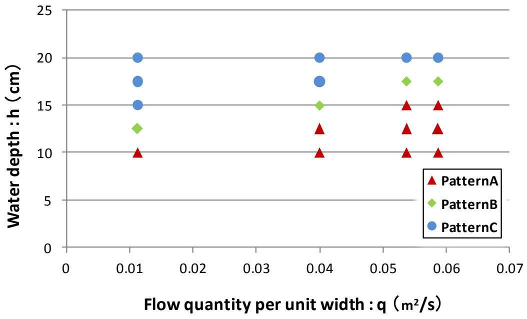


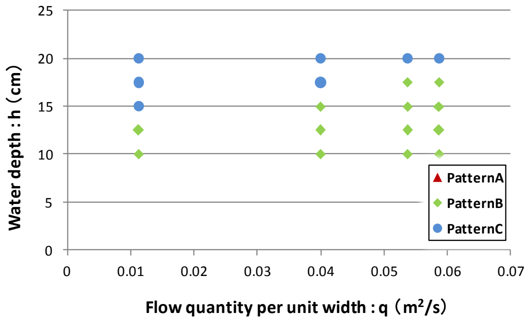
Fig. 10 Different tsunami flow patterns.

Based on the results of Case 1, the Cases 2, 3 and 4 were carried out using the same procedure as Case 1 in order to examine the differences in tsunami behavior around the coastal dike with the presence of a coastal forest, where Fig. 11 illustrates the results for each tested case. In Case 1, Pattern A occurred when the water depth was low and the flow quantity per unit width was high. On the contrary, Pattern C occurred in case that the water depth was high and the flow quantity per unit width was low. Pattern B occurred under the conditions between occurrence of Pattern A and Pattern C. For Cases 2 and 3, with a coastal forest, all result combinations of water depth and flow that had yielded Pattern A under Case 1were changed to Pattern B, though other results did not change. Case 4 was similar to that of Cases 2 and 3, though in addition to one result, further results also switched from Pattern B to C (h = 17.5 cm, q = 0.051 m^2/s).

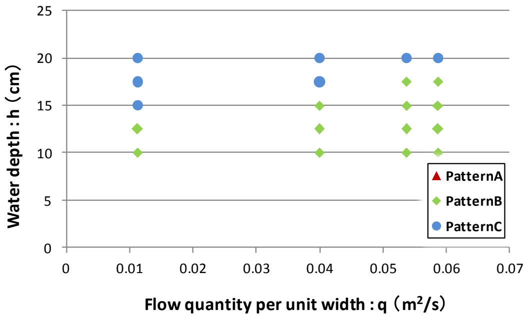
Table 4 shows the increase in water depth for each Case, in comparison with Case 1. The water depth was measured at the leeward of the coastal dike. The maximum leeward water depths recorded were those for the Case 4, which could be 9.3 cm higher than for Case 1, whereas the maximum values for Case 2 and 3 were 3.8 and 3.2 cm respectively. The average value of the increase in water depth for each case was also evaluated. The highest average value for all cases was 4.7 cm, while the average values were 1.8 cm for the Case 2 and 1.5 cm for the Case 3. From these results, Case 4, which has longest coastal forest length, appears to be able to significantly increase the water depth at the leeward of the slope, creating a water cushion that can reduce the damage to the coastal dike.



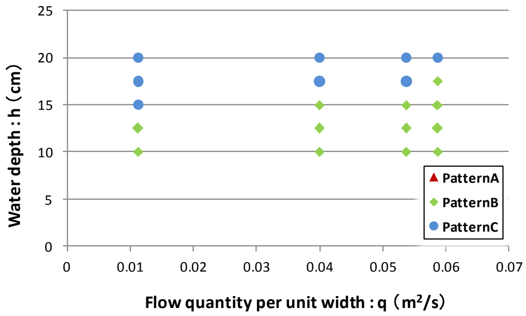
Case 1



Case 2



Case 3



Case4

Fig. 11 Tsunami behavior around the coastal dike.

Figure 12 shows the results of pressures and water surface profiles around the coastal dikes for each tested case. The upper figure shows the measurements by the pressure gauges attached to the coastal dike model (as shown in Fig. 7), and lower figure illustrates the water surface profile around the model dike. The sampling frequency was set to 200 Hz, with the hydrostatic pressure set to zero before the flow was generated. The pressure was recorded and examined for 30 sec interval, with the average value for this period was taken.

For the Case 1 it is interesting to note that negative pressure was recorded at the top of the dike slope, which then rapidly transformed into high wave pressures further along the leeward of dike slope, which then rapidly transformed into high wave pressures further along the leeward of the slope. For the Cases 2, 3 and 4, the value of the negative pressure was relatively lower than for the Case 1. The pressures were lower for the Case 4, which also corresponded to the higher value of water inundation. With respect to this result, Nakao et al. (2012) examined how the pressures at the top of the landside slope of a coastal dike overtopped by a tsunami becomes lower due to the lifting force exerted by the centrifugal force of the convex streamline of the overflowing current. These results clearly indicated how the top of landside slope and toe must be carefully designed if there are concerns that a dike can be overtopped by a tsunami.

Table. 4 Increase in water height for each tested case, in comparison with Case 1

Case2

Increase of water height from Case1		Flow quantity per unit width : q (m^2/s)			
		0.011	0.040	0.054	0.059
Water depth : h	20cm	0	0.3	0.4	0.4
	17.5cm	0	0.4	2.2	2.9
	15cm	-0.1	3.8	3.1	2.6
	12.5cm	0.4	2.6	2.5	2.8
	10cm	2.3	3.1	2.9	2.5

Case3

Increase of water height from Case1		Flow quantity per unit width : q (m^2/s)			
		0.011	0.040	0.054	0.059
Water depth : h	20cm	-0.2	0.2	0.2	0.4
	17.5cm	0	1	2.4	2.9
	15cm	-0.4	2.5	2.5	2
	12.5cm	0.6	2.5	2.4	2.1
	10cm	1.6	3.2	2.5	2.2

Case4

Increase of water height from Case1		Flow quantity per unit width : q (m^2/s)			
		0.011	0.040	0.054	0.059
Water depth : h	20cm	-0.1	0.2	0.7	0.7
	17.5cm	0.2	0.7	3.9	5.6
	15cm	0	6.7	9.1	9
	12.5cm	1.9	8.3	9.1	9.3
	10cm	4	7.3	8.7	8.9

CONCLUSIONS

One of the main causes of coastal dike failure during the 2011 Great Eastern Japan Earthquake Tsunami was due to the overflowing nature of the tsunami. The present paper analyzed the critical failure mechanism of dikes and co-related it to tsunami overflowing patterns. The primary failure mode of the coastal dikes was scour failure at the leeward toe and slope. Three types of tsunami overflowing patterns were identified, and the possible relationship between the tsunami behavior and failure mode of dike was examined. In addition, the possibility that a coastal forest situated immediately behind the dike can contribute to reducing damage to the structure was investigated. In order to do so, a number of laboratory experiments were carried out by varying water depths and fluid motion of the overtopping currents. It can be concluded that the coastal forests indeed can play a major role in mitigating tsunami damage, and their placement behind dikes can contribute to increase their resilience. Also, it appears that the length of the coastal forest is an important factor that can contribute to make the structure more resilient, and thus coastal forests of appropriate length should be considered.

Finally, the distribution of overtopping pressures on the dike was measured for each experimental case. Though it was clear that the pressures were reduced due to the presence of coastal forests, all experiments indicated that negative pressures were exerted on the top of the dike, and maximum pressures were recorded on the leeward of it. This makes it imperative to consider carefully for the design of this part of the structure, for the cases that the structure could be overtopped, as otherwise it could fail catastrophically and offer no protection to subsequent tsunami waves.

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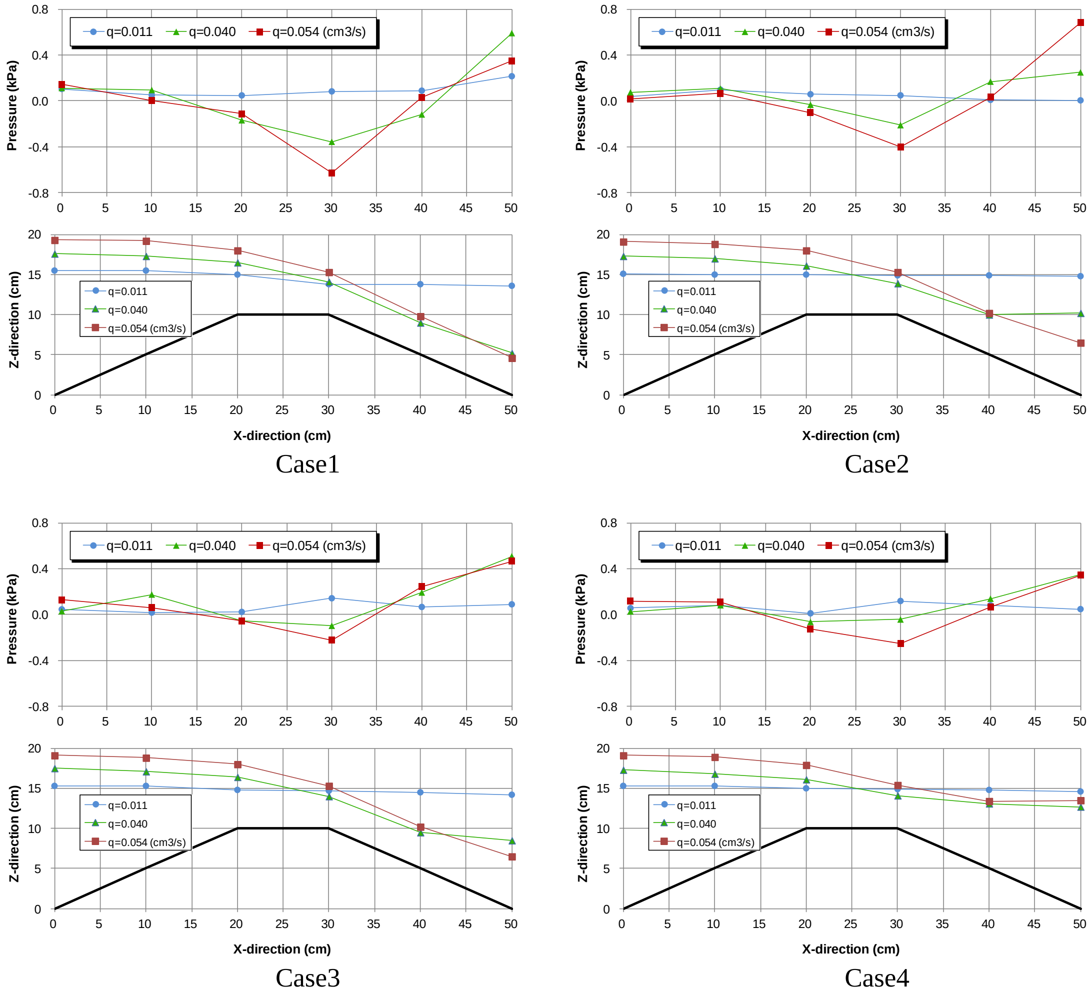

Fig. 12 Pressure and water surface profiles of tested model scenarios.

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