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# 論文の内容の要旨

Large tsunamis can cause dreadful natural disasters. Following the Great East Japan tsunami (GEJT) in 2011, the methods of mitigating tsunami damages have been changing form single to a multiple defense system (combination of natural and/or artificial countermeasures). This study investigated the mitigation effect of a hybrid tsunami defense (a combination of natural and artificial structures) system comprising a sea embankment followed by a coastal forest. For enhancing the mitigation effect of a finite width forest, different types of vertical and horizontal double layer forest models were introduced by innegrating short and tall trees. Flume experiments were conducted to investigate the effects of the double layer forest in single and as a secondary countermeasure in the hybrid defense system respectively. The following summary could be derived from the different schemes in this study:

In the first scheme, the energy reduction mechanisms of different types of vertical double layer forest models were investigated against a high inundating tsunami current. The results showed that, although the resistance against the flow depends upon the porosity of both layer (submerged and emergent), it is more dependent on the submerged layer's porosity. Decreasing the porosity of this layer increases the resistance against the flow and produces a large water rise in front of the forest as well as low inundation depth downstream of the forest. Around the vegetation, a less porous short layer, in single or combined with the tall layer vegetation, creates a low velocity near the bed and a relatively high velocity above the short layer vegetation, as well as it generates a mild water surface slope inside and behind the vegetation.

By having a double layer, the resistance of the forest is increased as well as the high velocity observed above a single submerged layer is reduced. In addition, since the combined layer vegetation creates a low-velocity zone at the forest back, the scope of forest damage due to scouring may be assumed to be less in this model compared with a single layer emergent vegetation model. Moreover, air entrainment by the double layer vegetation contributes to a further decrease in velocity at the backside as well as to the downstream flow compared with the single layer submerged vegetation.

Secondly, the effects of a submerged layer contained in an emergent sparse forest was elucidated, which showed the following findings:

The presence of a submerged layer in an emergent vegetation enhanced the hydraulic resistance (water rises increased around 36–42% and 25–54% in front of the vegetation compared to only submerged layer (OSL) and only emergent layer (OEL), respectively of the vegetation zone and provided more energy reduction. The double-layer vegetation also produced a large number of air bubbles inside and behind the vegetation. This raised the water level behind the vegetation in Case ESL (emergent with submerged layer) which was around 12–18% compared to Case OSL and created a mild water surface gradient behind the vegetation.

Introducing a submerged layer within an emergent layer further reduced maximum velocity behind the vegetation by 25%. The velocity near the ground in front, within, and behind the vegetation was reduced by maximum 18%, 74%, and 33%, respectively. This could effectively reduce the bed erosion in the vegetation zone. The double-layer vegetation generated a mixing velocity zone inside the vegetation that may contribute in reducing velocity behind the vegetation further.

Moreover, the double layer vegetation generated a low-velocity region behind the vegetation that contributed to the reduction of the fluid force around 23–29% relative to a single layer of emergent vegetation. Reducing this fluid force, coupled with the air bubble effect creating a mild water surface, implies reducing the erosion of the ground just behind the vegetation and reduction of breakage or washing-out incidents downstream of the vegetation. Thus, not only for strengthening the emergent forest but also reducing the vulnerability to a secondary disaster due to the driftwood production caused by washing-out of trees (especially the backward portion of the forest) could be minimized by implementing double- layer vegetation.

The next scheme focuses on the mitigation effects of a hybrid defense system on reducing the energy of a tsunami current where the role of the vertically double layer forest as a secondary defense structure behind a sea embankment was elucidated. To investigate the flow structure and energy loss mechanisms, different combination of embankment model (EM) and single layer forest model (SLM) or vertically double layer forest models (DLM) were placed in an experimental flume against a supercritical flow. The following findings could be summarized:

In the case of the single embankment, the overtopping discharge had high energy on the ground and no hydraulic jump was found downstream in the experimental range of an initial (without EM and forest models) Froude number ($Fr_0$) in between 1.08 and 1.56.

On the other hand, different types of hydraulic jumps were observed in the hybrid defense system. Two types of hydraulic jump, Type-A (jump occurred on the flume bed downstream of the EM) and Type-B (jump started on the leeward slope of the EM and continued on the flume bed downstream of the EM) were observed in the combination of EM and SLM or DLMs. Because the embankment remained unchanged and the gap between the forest and embankment models was fixed, forest types, especially the porosity of the submerged layer (L1), and flow conditions influenced the hydraulic jump characteristics. When the SLM with a porosity of 98% was implemented, the Type-A jump formed. The water depth within the gap increased and the jump toe moved further upstream sufficiently when DLMs were respectively implemented as a secondary defense structure. Due to this, the jump type changed from Type-A to Type-B when $Fr_0$ increased and the porosity of L1 decreased respectively. The jump type was changed from A to B, its occurrence position was almost controlled and reduction of flow velocity in the jump was significant. Therefore, for the safety of the structure, the jump could be controlled around the embankment slope by forming the Type-B jump if the embankment slope is protected.

In the case of the single embankment, the energy reduction was found to be approximately 45% and 30% against lower $Fr_0$ (1.08 and 1.29) values in the range, but it dropped to 2–3% for higher $Fr_0$ values. In the hybrid defense system, the energy between the structures was reduced approximately 19% to 39% by hydraulic jumps in the range of $Fr_0$ 1.08 and 1.52, whereas the total energy reduction downstream was between 27% and 54%. When SLM or DLM was implemented, this hybrid defense system reduced the energy ~30–40% more compared to the single embankment case. However, the total energy reduction downstream of SLM or DLMs was increased when the hydraulic jump within the gap of the models changed from Type A to Type B.

Although the Type A jump was found to be effective to reduce the flow energy, Type B is preferable to sustain the structures. When a Type B jump is formed, the water depth within the structure increased sufficiently, and due to this, the erosion around the defense structures could be reduced. However, when a forest is implemented downstream of an EM, the total resistance of the forest needs to be increased as much as possible to store some water in between the structures so that the Type-B jump could be formed.

The final scheme focuses on enhancing the mitigation effect of a finite width coastal forest by a horizontal combination of dense short trees and sparse tall trees and elucidates the mitigation of a hybrid defense system when the horizontally double layer forest is employed behind a sea embankment. Different combination of an embankment model (EM) and finite with forest models of a single layer (SLM) or horizontally double layer (HDLM) was placed in the hydraulic flume against a supercritical flow. Those were $EF_{TT}$ (a combination of EM and SLM), $EF_{ST}$ (a combination of EM and HDLM keeping short trees in front of tall trees) and $EF_{TS}$ (a combination of EM and HDLM having short trees behind the tall trees). The following conclusions are derived:

In Case of only embankment model (EMN), the overtopping flow appeared on the flume bed with higher fluid force and there was no hydraulic jump in the downstream. The Froude value increased about 2-3.2 times compared to the $Fr_0$. Energy reduction was around 51% and 40 % in lower value of non-dimensional overtopping flow depth ($h'_c$) of 0.10 and 0.16, respectively, but with increasing the $h'_c$, energy reduction reduced sharply and dropped to 2-5%.

In the hybrid defense system, the hydraulic jump occurred within the structures and flow depth increased downstream which reduced the flow velocity. Two types of hydraulic jump, Type-A (jump occurred on the flume bed downstream of the EM) and Type-B (jump started on the leeward slope of the EM and continued on the flume bed downstream of the EM) were observed in the combination of EM and SLM or HDLMs. Type-A jump was generated in Case $EF_{TT}$, the water surface elevation downstream was highest for this combination which provided 47-67 % energy reduction. Whereas, water depth within the gap increased sufficiently and Type-B jump was formed in Cases $EF_{ST}$ and $EF_{TS}$. The energy reduction downstream was in between 42% and 67% in Case $EF_{TS.}$ The reduction percentage was almost the same (46-67%) in Case $EF_{ST}$ compared to Case $EF_{TT}$.

It is noticed that Type-A jump provided maximum energy reduction in the downstream. Whereas, Type-B jump was found effective for reducing the flow velocity around the structures as well as energy reduction downstream. Although the combination $EF_{TS}$ found to be more efficient for reducing flow velocity around the structure, the combination $EF_{ST}$ was effective in reducing the energy downstream. In addition, when the tall layer forest exists behind the short trees, it could trap the broken branches if breakage occurs to the short trees. Therefore, the combination of an embankment and a landward forest having short dense and sparse tall trees in the horizontal direction may have a better mitigation capability to reduce damage to the structures due to erosion as well as reducing the flow energy in the landward.

Therefore, with the above viewpoints, it can be concluded that the resistance of a forest could be enhanced by a double layer forest (combination of short and tall trees) and it could provide more energy reduction against a tsunami, than a single layer forest (submerged or emergent) when the inundation depth is relatively high. Moreover, forest damage due to scouring or erosion might be reduced by having a submerged layer in an emergent sparse forest. Besides the energy reduction, the double-layer forest in horizontal or vertical direction downstream of an embankment could be effective to control the hydraulic jump position and reduce the flow velocity around the embankment as well as reducing the tsunami energy downstream.

However, for an improved tsunami countermeasure by a coastal forest is required to provide higher resistance as well as a larger trunk diameter to reduce trunk breakage and trap tsunami-borne floating debris. Because achieving a denser and thicker emergent forest in practice is somewhat difficult, a combination of a sparse tall trees and a less porous layer of short trees may be a viable option to provide higher resistance against the tsunamis current. In addition, the stability of a hybrid defense system against the destructive tsunami forces could be improved by a combination of a protected embankment on the seaward side and a double-layer forest on the landward side. These findings will be helpful for designing an optimum bio-shield against tsunamis as well as for the resilience of the hybrid defense structures.

# 論文の審査結果の要旨

当学位論文審査委員会は、令和元年８月２日に論文発表会を開催し、論文内容の発表に続いて質疑と論文内容の審査を行なった。以下に審査結果を要約する。

2004 年インド洋大津波や、2011 年の東北地方太平洋沖地震津波は、広範囲にわたって沿岸部の海岸堤防や樹林帯を破壊し、その背後の地域の人々と建物に甚大な被害をもたらした。日本では、国土交通省が数百年から千年に一度発生し、甚大な被害をもたらす最大クラスの津波をレベル２津波と設定し、レベル２津波に対しては多重防御による減災が推進されている。多重防御にはハード対策（構造物による被害軽減）と、ソフト対策（避難システムやハザードマップなどによる被害軽減）があるが、申請者は、ハード対策、特に海岸堤防などの人工構造物と海岸林などの自然的要素を含む構造物の組み合わせ（以下、ハイブリッド構造）に着目した。実際に、北海道白糠町では津波の流体力低下や遅延効果が期待される構造として、海岸堤防と堀と樹林帯を組み合わせたものが構築されている。岩手県大槌町では、防潮堤背後に海岸林を植林した二線堤で津波エネルギーを減衰させることを計画している。しかし、そうしたハイブリッド構造物の減災機能を一般化するには、知見が不足している状況である。

申請者は、学位論文の第１章で海岸林の津波減衰に関する研究レビューを行う中で、災害調査後に減災効果があったと推定されている二層林の力学に関する研究が少ないこと、人工構造物なしでは機能が発揮されない場合もある中で堤防と海岸林のハイブリッド構造に関する知見が不足していることを指摘している。そして、第二章で鉛直方向に密度の異なる樹林帯の効果を明らかにすることを試みている。二層タイプの樹林帯は、ヒルギ属のマングローブや、アダン・モクマオウという砂丘植生が熱帯・亜熱帯地方には存在している。日本においても松林の前面部にトベラなどの密集した低木が植林されている事例もある。特に、アダンとモクマオウの混成林は、インド洋大津波後の災害調査で、樹林帯背後の被害状況から定性的に有効であると指摘されていたものである。申請者は二層林をモデル化した水理模型実験によりそのエネルギー減衰機構の解明を行った。樹木は木製円柱で約 1/100 スケールでモデルを作成している。樹高が大、小なものに対して、樹林帯密度を疎、密と設定し、下層植生の導入により、樹林帯前面部のせき上げは二層の場合は 36–42% で一層（25–54%）よりも大きく上昇し、エネルギー減衰量も大きくなる。二層林は水面勾配が大きくなることに伴い、樹木モデル前後の水位差が大となって樹木背後に空気を巻き込む現象が生じる。2011 年の東北地方太平洋沖地震津波の映像においても同様の空気混入が確認されている。空気を巻き込むことにより、樹林帯背後の水位が上昇し、背後における水面勾配が緩やかになる。そのため、下層植生はまた底面付近の流速を植生前面、植生間、背後において 18%、74%、33% も減少させた。これは、流木の発生現象の一要因である洗掘を減少させるのに大きな効果がある。また、上層下層の流速差はエネルギー減衰にも貢献することを示している。

第三章では、前章で確認した二層林を堤防の陸側に配置した場合の流況変化とエネルギー減衰について、そのメカニズムを水理実験により明らかにしている。堤防のみの場合、堤防の裏法面で加速された流れは越流後も底面に沿うように高速で流れるが、樹林帯を陸側に配置した場合には、樹林帯抵抗により跳水現象が生じる。その跳水現象は越流条件と樹林帯条件により変化する。申請者は、跳水現象の変化点先端が堤防法面上で発生するかどうか（Type-B 跳水が発生するかどうか）に注目し、その発生条件やエネルギー減衰を調べている。堤防のみの条件と比較して、30–40% もエネルギー減衰が増加することを示している。また、Type-B 跳水は一層林の場合に容易に発生しやすく、同現象が生じているときは堤防背後の流速が低減されるため、堤防の粘り強さという点でも重要であるとしている。

第四章では、ハイブリッド構造として、樹林帯を水平二層化した場合（樹高低いが密な樹林帯Sと樹高高いが疎な樹林帯Tで構成される構造の場合）の効果を調べている。条件としては、第三章の鉛直二層樹林帯と同じ位置に水平二層林を設置しているが、樹林帯の位置関係を堤防から樹林帯S,Tにした場合（Case EFST）とその逆（Case EFTS）を調べている。鉛直二層林の場合と同様に、水平二層林の場合においても跳水がエネルギー減衰において重要な役割を果たしており、Type-A跳水が発生した場合には47-67 % のエネルギー減衰に対し、Type-B跳水が発生した場合は46-67%とほぼ同様の効果を示し、跳水タイプはトータルのエネルギー減衰という観点よりも流速低減をさせる箇所が重要であるとした。すなわち、Case EFTSは構造物周りの流体力を減少させるのに有効で、Case EFSTは樹林帯背後の流速低減に有効であった。樹林帯Tが陸側にあったほうが、流木の捕捉効果があることからトータルとして考えると、水平二層林の構造としてはCase EFSTが適していると結論付けている。

以上のように、本研究は、水理模型実験をもとに、樹林帯の鉛直構造がエネルギー減衰に果たすメカニズムや、ハイブリッド構造にした場合の効果を特に堤防の粘り強さや樹林帯背後の流体力低減という観点で明らかにしている。このことから、当学位論文審査委員会は、本論文が博士（学術）の学位に相応しい内容であると判断した。

なお、本論文の内容は、国際学術雑誌Geosciencesに掲載済み、国内学術雑誌（土木学会論文集（水工学））に受理されており、国際学術シンポジウムISE2018（日本）で発表済みである。