氏　　名	P. K. C. DE SILVA
博士の専攻分野の名称	博士（学術）
学位記号番号	博理工甲第 928 号
学位授与年月日	平成 25 年 9 月 20 日
学位授与の条件	学位規則第 4 条第 1 項該当
学位論文題目	Study on Middle-class Flood Disturbance in Middle Stream of Rivers and Sedimentation in Compound Channels （中流域河川の中規模撹乱と複断面河道における土砂堆積に関する研究）
論文審査委員	委員長　教　授　田中　規夫 委　員　教　授　淺枝　　隆 委　員　教　授　川本　　健 委　員　准教授　藤野　　毅

論文の内容の要旨

Forestation in a river creates a valuable natural environment, which is mainly important in terms of bank stabilization and ecological restoration, but sometimes it can become a problem because it enhances flow resistance, reduces river flow downstream and accumulated debris of vegetation can increase the drag force around bridge piers while causing large scour holes around them. Furthermore, excessive forestation by a single species can sometimes affect the biodiversity of the river ecosystem.

Therefore, for proper rehabilitation and management of river environment, it is important to determine what kind of flood disturbance can increase the diversity of vegetation but control the rate of forestation in a river habitat. When the vegetation condition on the gravel bars of the river is considered, with the increase of flood disturbance, the possibility of washout of vegetation on gravel bars increases, but on the other hand, i.e., when the flood disturbance decreases, the possibility of vegetation existence on gravel bars will be increased. Moreover, it has been found that vegetation existence on gravel bars is affected mainly by flood intensity and frequency. Since flood disturbance is the combined effect of flood intensity and frequency, some indices are required to define middle-class flood disturbance for the above purpose.

The middle-class flood disturbance proposed in early studies have focused on tropical forests but did not define it for river habitat, and it was not included in previously defined biodiversity indices. In previous studies such indices have been derived to define middle-class flood disturbance based on investigations on Arakawa and Tamagawa Rivers, Japan, but the trend of diversity of vegetation with those indices was found to be different for the two rivers. Therefore the applicability of the flood indices needs to be verified with other rivers, while determining the reasons for the differences. In predicting the possibility of forestation in rivers, previous studies discussed mainly the washout condition of trees. However, the degree of damage on trees is also considered in this study because trees that were broken or bent down by a flood might regenerate after the flood, and the washout condition of grasses is also considered.

Therefore in this study the relationship between the diversity index of vegetated area calculated by the vegetation species map and flood disturbance index, a kind of expectation value of flood disturbance, was investigated for four

gravel bars in the Karasu River and compared with the results of previous studies of the Arakawa and Tamagawa Rivers. The relationship between the diversity of vegetated area on gravel bars in the middle stream of a river and flood disturbance characteristics was investigated. Six Regions (A-E) were defined to classify the possibility of forestation in a river based on two indices: BOI, to evaluate trunk breakage, and WOI, for washout condition of trees and grasses. According to definition, in Region A there is a high possibility to be a forest and in Region E forestation is not easy to be occurred. The diversity of vegetated area was found to be correlated with the flood disturbance index in Regions A and E for the investigated rivers. In addition, the diversity of vegetated area in Regions A and E showed the same trend for the Karasu and Arakawa Rivers and a different trend for the Tamagawa River, where the trend was affected by previous floods of the investigated gravel bars. However, this indicates the possibility of expressing middle-class flood disturbance of gravel bars in the middle stream of rivers and confirms the applicability of studies of other rivers investigated.

But Regions B, C, and D did not show any noticeable trend. In case of Region D, there can be several reasons for that. Firstly, tree-type vegetation was found less frequently on the investigated gravel bars, and at the same time, the existing trees were almost grown ones that were rarely subjected to breaking. Secondly, most of the gravel bars were occupied by perennial grasses rather than annual grasses, because by definition, Region D is related to breaking or bending of trees and washout of annual grasses.

In Regions B and C, flood disturbance values were found to be small and no trend could be identified. According to definition, the tree diameter in Region B is small (related to initial development of vegetation) with a large gravel size, and Region C has a larger tree diameter with a smaller gravel size. However, the trees on the investigated gravel bars were not very young, having a larger tree diameter and large gravel size diameter, so that the flood disturbance in Regions B and C was small.

Furthermore, middle-class flood disturbance was not clearly defined in terms of flood return period (frequency) in previous research, so this study was focused on defining a specific range of flood return periods for middle-class flood disturbance in rivers. Based on the analysis it was found out middle class flood disturbance for the investigated rivers can be defined for return periods of flood between 3 – 12.5 years. Also based on the above results a methodology was proposed for river cross-section design towards increased diversity of vegetation in river habitat.

The second stage of this study was based on the sedimentation and flow structure in compound water channels. Compound water channels are one of the most important flood control methods used in river engineering since in many areas where flooding cannot be allowed because of infrastructure around the rivers. For the purpose of increasing flow capacity, extension of only low channel width would not be enough in some cases because with time, sand bars can be formed in the low channel due to reduction of flow velocity and cause the reduction of flow capacity. Therefore construction of middle water channel by excavating floodplain would be a better solution in this matter.

However, it also creates opportunity for frequent inundation on middle water channel bed due to lowered floodplain. Then due to the velocity difference between low channel flow and middle channel flow, complicated flow patterns are generated and the shear layer that develops at the interface between main channel and middle water channel (floodplain) affects the turbulent flow structure. This complex turbulent flow structure leads to generation of two types of vortices. One is horizontal vortices that are generated due to shear layer of the streamwise flow and other type is vortices with longitudinal axis called secondary currents due to anisotropy of turbulence. Since these vortices enhance lateral mass and momentum exchange, it causes a net transfer of sediment from the low channel to the floodplain. Moreover, sediment will tend to settle out once transferred to the floodplain region because of the reduced transport capacity of the flow. Therefore with time there is a possibility of increasing sedimentation on floodplain, which can promote the growth

of vegetation and decrease of depth. This study hypothesized that the slope of the middle water channel in transverse direction could be an important factor to control the sedimentation on middle water channel bed so that vegetation growth also can be controlled on it. Although many studies have been conducted related to compound channel flow, the studies related to the effect of inclined floodplain on sedimentation and flow structure with physical simulation of sedimentation are still rare. Therefore this study was focused on turbulent flow structure and sedimentation on flat and inclined as well as smooth and vegetated floodplain. Two types of experiments (PIV-Particle Image Velocimetry to evaluate the change of the secondary flow, and the Reynolds stresses related to sediment transportation and sediment experiment to observe sediment deposition) were conducted for flat/inclined floodplain, plain/vegetated floodplain, and low/high water depths.

From the results it can be seen that possibility of sedimentation on floodplain is increased with vegetation due to the momentum transport towards floodplain from the interface of low channel. Also it can be concluded that construction of middle water channel with inclined floodplain can be effective in minimizing sediment deposition on middle water channel bed in short term, but in long term when vegetation starts growing on it, it would become less effective towards that purpose. (Still it performs better than flat floodplain). Furthermore sediment deposition on inclined floodplain would be less for low water depths in comparison to high water depths with or without vegetation on floodplain. This situation in high water depth is similar also in case of flat floodplain. In addition, it can be concluded that on vegetated floodplain, for low water depths sediment deposition would be distributed over the floodplain while for higher water depths sediment deposition would be prominent in the middle of floodplain.

Finally, this information on river cross-section shape can be used to discuss the relationships between flood indices of middle class flood disturbance and diversity of vegetation of first part of this study, based on the proposed method for design of river-cross section shape. In future studies, it needs to be checked with different river channel morphologies, with different flood disturbance effects and vegetation conditions. It will lead for more effective and economical river bed design with increased diversity of vegetation and proper management of river habitat.

論文の審査結果の要旨

当学位論文審査委員会は，平成 25 年 7 月 25 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．

近年，洪水撹乱頻度の減少や強度の低下などにより，河道内に樹木が繁茂する問題（河道内樹林化問題）が生じており，流下能力のみならず，生物の多様度にも影響を与えている．そのため，適度な洪水撹乱を誘発し河川環境を保全するという観点から，樹林化防止対策としての高水敷の切り下げなどが行なわれている．生物多様度が中規模の撹乱状態で増加するという中規模撹乱仮説があるものの，河川における適用性についての知見が不足している．既往研究では，樹木以外の河道内植生分布の動態に影響を与える樹木破断・倒伏といった破壊形態も含めて樹林地の動態評価を行う手法が開発され，それらがどのような確率で生じるかという期待値で表現し，砂礫州における生物多様度との関係が荒川・多摩川において明らかにされている．しかし，他河川への適用性が不明であること，また，中規模撹乱の定義手法について課題が残されている．

申請者は，学位論文の第二章で，烏川において洪水撹乱指標の適用性を検討した上で，植生動態・生物多様度の視点で中規模撹乱を明らかにすることを行っている．まず，河川空間を洪水撹乱により分類する手法について，従来は樹木の破壊流失を中心に分類され，草本は既往知見により推定されていたが，申請者は烏川砂礫州での洪水前後の観測より，その流失限界を草本タイプに関連させて明らかにした．その上で，洪水撹乱のタイプ（従来提案されていた 5 分類の洪水撹乱指標）を明確に定義し，洪水撹乱の期待値と植生面積の多様度の関係を調査し，烏川と荒川・多摩川の類似点と相違点を植生動態の変化のあった期間（1998 年から 2005 年）の洪水撹乱の頻度と規模で明らかにした．このことから，中規模撹乱洪水を洪水の再現期間から表現することを考案し，裸地や樹林地の存在可能性を，洪水撹乱特性 RegionA（1 年生草本が流失しない洪水）と RegionE（樹木や多年生草本が流失する規模の洪水）の存在可能性から，植生多様度が増加する洪水再現期間として，3 から 12.5 年が重要であるということを明らかにした．学位論文の第三章では，荒川の本田地点の砂礫州を対象として，砂礫の切り下げパターンを，水平型，傾斜型，流路活用型の 3 種類について検討を行い，切り下げが洪水撹乱指標に与える影響を解析している．水平型・傾斜型とも河道の流下能力を上げ，冠水頻度を増加させるものの，水位を全体的に下げ，砂礫州上の底面せん断力を下げてしまうため，砂礫州の植生の更新にかかわる洪水撹乱指標を小さくしてしまい（すなわち，更新の期待値を下げてしまい），樹林化対策や多様度の維持という観点では，適さない場合があることを明らかにした．一方，流路型は流下能力を大きく変えることなく，流路の部分のせん断力を増加させるため，洪水撹乱指標を増加させ，適度に植生が更新する多様度の高い砂礫州に近づけられる可能性があることを示した．

次に，樹林化問題に大きな影響を与える要因として，申請者は高水敷または砂礫州への土砂堆積に注目して研究を行っている．複断面河道での流下能力向上策の一つとして低水路の拡幅が挙げられるが，砂州（寄り州）の形成により低水路幅が元に戻る場合がある．また，砂州による形状抵抗や植生繁茂による抵抗の増加により，時間が経過すると流下能力の向上が期待できない場合がある．そこで，河川の中規模河床形態を変化させないよう，高水敷の一部を平らに掘削し中水敷を形成する対策も存在する．しかし，複雑な乱流構造により中水敷において土砂が堆積し，様々な問題が発生する可能性がある．土砂堆積抑制のために中水敷の斜面形状化が有効な可能性があるが，具体的な土砂堆積に関連する乱流構造の把握は行われていない．複断面での特徴的な流れとして，大規模平面渦と二次流がある．これらは低水路水深 H_m と高水敷高さ h の比

H_m/h によって変化し，H_m/h が大きいときに二次流が卓越し，H_m/h が小さいときは大規模平面渦が卓越することが既往研究により示されている．学位論文の第四章では，この 2 つの流れについて，複断面開水路の掘削形状を水平タイプと斜面タイプに変化させ，その際の乱流構造の変化と土砂堆積の関係を把握することを目的として水理実験をおこなっている．実験の結果，1)中水敷の斜面化により斜面に沿った低水路方向への流れが発生し，中水敷上および境界部付近の二次流構造に大きな影響を与えること，2)斜面化による横断方向レイノルズ応力への影響は境界部で見られることの理由として，斜面化したことで中水敷全体の斜面に沿った輸送が発生し，中水敷全体から低水路への運動量輸送が大きくなったこと，3)中水敷端（低水路から離れた側）に近くなると境界部とは逆に中水敷への輸送が増加するのは，中水敷端に近くなると水深が小さくなることで流速が低下し，中水敷端への輸送は多くなるものの，低水路側への輸送が少なくなるためであること，を明らかにし，中水敷の傾斜化は境界部において有効であるが，中水敷奥では中水敷向きの運動量輸送により逆に土砂の堆積を促進させる可能性を示唆した．

以上のように，本論文は現地調査，数値解析をもとに，河川空間の植生面積多様度を増加させるのに必要な中規模撹乱に関する知見を得ていること，水理実験により高水敷傾斜型複断面河道における乱流構造の解明とそれにもとづく堆積形態に関して重要な示唆を与えている．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，第一著者として，国際学術誌 Landscape and Ecological Engineering に受理されている．さらに，国際学術シンポジウムでも 1 回発表予定である．