博 士（工 学） ディン タン ムン

学位論文題名

Computation of Flow and Bed Morphology at River Confluences

（河川合流部における流れと河床変動に関する数値解析的研究）

学位論文内容の要旨

River channel confluences are common in nature as well as in engineering. These are critical interfaces where intense changes in physical processes within drainage or fluvial networks occur. These changes influence both the local and downstream characteristics of flow dynamics and the bed morphology. Flow features in these regions are often known to be complex and highly three-dimensional. Although there are a number of studies on flow at these regions conducted in the past, there are still gaps to be studied for this complex flow, such as effect of discharge ratio between the confluent channels on secondary current, bed shear stress, and flow constriction that may be evaluated based on an accurate approach as well as characteristics of the small vortex within the separation zone and its role in relation to general flow behavior and possible sediment transport. Furthermore, behavior of bed morphology at river confluences has not still been clearly understood. Some of the problems that remain to be addressed are response of bed morphology to various hydraulic conditions at unequal-width channel confluences, short-term response of bed morphology at large river confluences, where flow rate, not discharge ratio is dominant, to different flow stages. Besides, although local configuration of the confluent river mouths may influence flow and bed morphology, this aspect has not been paid attention at all. In addition, effect of bank vegetation and bar vegetation on bed morphology within these regions has not been obviously understood.

Besides the above problems, numerical modeling of flow dynamics and bed morphology at river confluences still requires much more attempts. The 3D nonlinear k - ε model are proved to be successful in simulating complex flow. However, this model has not been developed for river confluence problems. Although a 3D model is broadly adopted to simulate flow at a small part of river course, it is difficult to predict flows and sediment transports during floods from the upper region of a river to the river mouth. In addition, at river confluences, adding a sediment-transport module to a 3D flow model remains a challenge due to difficulties in designing a suitable numerical mesh. Furthermore, 3D modeling is still a time-consumed and costly work. Therefore, development of depth-averaged 2D models, which are corrected for effect of secondary current, are still a reasonable compromise for the problems of flow dynamics and bed morphology up to now.

In this study, four types of depth-averaged 2D models without and with effect of secondary current are proposed and verified for both small scale (laboratory) and large scale (field) in order to investigate flow feature, bed morphology, and effect of vegetation on bed evolution at river confluences. Model 1 is a conventional depth-averaged 2D model, which does not consider secondary current; Model 2 is a depth-averaged 2D model, which includes effect of secondary current; Model 3 is a depth-averaged 2D model, which incorporates effect of both secondary current and a lag between a streamline curvature and secondary current; and Model 4 is a depth-averaged 2D model, which includes not only the factors as Model 3 does but also change in the downstream velocity profile. The main findings from the computational results obtained by these models are as follows. In general, for cases where secondary current is weak, such as where discharge ratio q*, which is defined by the flow of the main channel to that of the post-confluence channel, is high, all the models, except Model 2 which is realized to fail to simulate flow at open-channel confluences, are capable of quite reasonably simulating major flow features (e.g. water surface profile, flow field, and depth-averaged velocity profiles) at an open-channel confluence. However, for cases where secondary current is dominant, Model 3, and, particularly, Model 4 have certain advantages over Model 1. As these models (Model 1, Model 3, and Model 4) are used to simulate bed morphology at small channel confluences with a small junction angle, implying absence of separation zone, and flow mixing possibly occurring, Model 4 performed the results agreeing well with the measured ones, while Model 1 and Model 3 under-predicted much these results. This demonstrates high applicability of Model 4 to such junctions. However, as Model 1 and Model 4 are applied to a large river confluence with small confluence angle, where flow rate has dominant control on flow dynamics and bed morphology evolution, and discharge ratio between the confluent streams insignificantly changes over time, both these models are reasonably capable of

simulating flow feature and bed deformation as well as effects of vegetation on these characteristics. This suggest further studies needed to be conducted for various river confluences, such as for the cases where there is a transition of discharge ratio and/or where flow mixing is dominant, for more clearly indicating their applicability in practice.

In this study, a 3D model with the linear and nonlinear k-ε models is also developed in a moving boundary-fitted coordinate system for investigation of flow at open-channel confluences. Both the linear and nonlinear k -ε models well predicted water surface profile, planeform separation zone, and secondary circulation in the center-region cell in comparison to the experimental ones. However, the linear model, which uses the assumption of isotropic turbulence distribution, incorrectly predicted turbulence distribution, stream-wise velocity distribution, and secondary currents within and around separation zone, thus leading to under-prediction of distortion of separation zone boundary along water depth. In contrast, by considering anisotropy of turbulence, the nonlinear model overcomes the limitations of the linear one and performed very well in comparison to the experimental. This indicates powerful applicability of the nonlinear k - ε model and the important role of inclusion of anisotropy of turbulence in simulating complex flow patterns at open-channel confluences.

Effect of discharge ratio on secondary current, bed shear stress, and flow constriction at open-channel confluences is indicated by using the nonlinear k - ε model above. As discharge ratio increases, secondary current decreases in term of its strength and there is a change in the direction of the large vortex within the center-region cell as the lateral flow becomes less than the main one ($q^* > 0.5$).
The role of the small vortex within separation zone with its rotation direction is first discussed in this study, and this vortex is realized as one of the crucial features characterizing the open-channel confluence flow and may influence on flow mixing in the shear region and possible deposition of sediment.
Bed shear stress apparently decreases as discharge ratio increases. While sediment is possibly transported only toward the inner bank for $q^* < 0.5$, it diverges in the transport direction, that is, it is possibly transported toward both the inner and outer banks as $q^* > 0.5$ due to change in the direction of secondary current.

Flow constriction increases as discharge ratio decreases. The results obtained by the method based on the effective area of the channel cross-section, which uses the velocity isoline method to accurately determine the border of the separation, indicates under-estimation of that using the effective width of the channel commonly used in the previous studies.

Bed morphology at an unequal-width small channel confluence is also characterized by the features as those at an equal-width one, that is, by three distinct elements: avalanche faces at the mouth of each confluent channel, a deep central scour, and a bar within the separation zone formed at the downstream junction corner. Bed morphology at these regions seems to be strongly affected by secondary current which may be related to high flow mixing and instability of flow. As discharge ratio decreases, bed erosion substantially increases and the penetration of the main channel avalanche face into the confluence decreases, implying upstream development of the possible right bank erosion.
At a large river confluence where discharge ratio does not vary substantially over time (q^* is always more than 0.5) with a relative stability of the confluence bar position, bed morphology is substantially affected by flow rate rather than discharge/momentum ratio. Response of bed morphology here to different flow stages has a periodic tendency depending upon flow rate.

The role of local configuration of the confluent river mouths at river confluences is first identified through the numerical simulation. The presence of small side bar or bars and bank-vegetation within these river mouths may promote development of the confluence bar (the origin of this bar is attributed to flow deceleration), thus influencing bed morphology evolution. Besides, confluence-bar vegetation possibly has substantial influences on bed morphology within and downstream the confluence; thus re-meandering process may occur.

学位論文審査の要旨

主　査	准教授	木　村　一　郎
副　査	教　授	清　水　康　行
副　査	特任教授	鈴　木　英　一

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（河川合流部における流れと河床変動に関する数値解析的研究）

河川合流部においては，複雑な乱流構造が生じ，疎通能力の予測を困難なものとしている．さらには，合流部の砂州や蛇行などの河床変動特性についても未解明な点が数多く残されている．これは，河川合流部における水理量の支配パラメータが単流に比べて多いという単純な理由のみならず，合流部の現象の非線形性に起因するものであるため，数学的な理論式や，単純化した簡易式などにより記述できるものではないことは明らかである．従って，合流部の流動特性や河床変動特性の予測には，数値解析モデルによらざるを得ない．しかし，従来の河川流，河床変動解析において一般に用いられている平面二次元モデルは，河川合流部においてはその精度が著しく低下する可能性が従来から指摘されている．この原因の一つは合流部の二次流（断面内の循環流）の発生に伴う強い三次元性が存在するためである．従って，三次元モデルによる解析が望ましいが，実河川スケールの三次元解析は計算機負荷が課題となり，実務においては現実的選択とは言えない．近年提案されつつある二次流を伴う流れの三次元性を考慮した平面二次元モデルは，これらの問題点を克服できる可能性が指摘されてきたが，河川合流部での検証はこれまで行われていない．

本研究では，実験スケールおよび実河川スケールにおける水路流れ合流部の流れ構造と河床変動の解明に向けて，数値解析的アプローチを試みたものである．流れの数値解析モデルとしては，二次流の効果を考慮した平面二次元モデル，および三次元モデルを用いている．前者のアプローチは比較的新しいものであり，第一種二次流による断面内循環流の発生について，二次流と主流の曲がりのラグや，主流流速分布の変化をも考慮したモデルが最近提案されおり，これらを採用した．後者の三次元解析においては，第二種二次流の再現も鑑み，非線形 k-ε モデルが用いられている．一方，河床変動の解析については，単粒径の掃流砂のみを考慮するものとし，実河川への適用性と経済性にも配慮し，主流方向の河床勾配を考慮した平衡流砂モデルを採用した．

数値解析モデルの検証は Weber らの水理模型実験を用いて行われている．流れ構造についての検討は，特に合流部の直下流に形成される剥離循環流とその周囲に形成される二次流の構造に着目し

て, モデルの比較がなされた. この結果, 平面二次元モデルについては, 主流流速分布の変形と二次流成長ラグを考慮したモデルが実験結果を極めて良好に再現することが示された. しかし, 合流部の二次流が流線の曲がりと, 支流の流速分布の二つの複合的要因により生成されるものであり, 後者の効果については数値解析モデルに十分反映されておらず, モデルの限界も指摘された. 一方, 三次元モデルについては, 標準型 k- ε モデルに比べて非線形 k- ε モデルの再現性が格段に良好であることが示された. 一方, 合流部の河床変動の再現性については, 重枝らの水理模型実験結果を対象に行われ, 二次流を適切に考慮した平面二次元モデルと河床変動モデルの組み合わせにより, 河床変動特性を適切に再現することが示さるとともに, 二次流を考慮しないモデルは河床変動を過小評価する可能性も指摘された.

実河川の合流部における検討は, 十勝川水系, 十勝川と利別川の合流部を対象に行われた. 合流部の直下流には砂州が存在し, これが洪水の発生とともに, フラッシュと成長を繰り返すという周期的構造が数値解析モデルの適用結果から指摘された. また, 現在の砂州は植生がほとんど存在しないが, 植生が一旦発生すると, 砂州が洪水によりフラッシュされなくなり, 陸地化する可能性が指摘された. この結果は, 合流部の砂州と植生の管理において, 重要な示唆を与えるものといえる.

以上に述べたように, 本研究は河川合流部の流れ構造と河床変動の予測という困難かつ重要な課題の解決に向けて, 数値解析的アプローチの有用性を多角的視点から示したものである. 本研究の成果は合流部の水理特性解明に資するのみならず, 実河川の管理にも貢献するものといえる. よって著者は, 北海道大学博士 (工学) の学位を授与される資格があるものと認める.