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# Secondary Flow and Turbulence in a compound Meandering Channel

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**Synopsis**

Secondary flow structure and turbulence characteristics in meandering channels under flooding conditions are discussed. Detailed velocity data measured by a laser Doppler anemometer are used in the analyses. Spectrum analysis is carried out and it shows the contribution of secondary flow to energy dissipation in the whole channel system. Conditional sampling is applied to examine the stress production mechanism. The result shows that a strong shear stress produced at the interface is induced when the lower layer flow is going upward and accelerating along the streamwise direction. Velocity fluctuation also indicates that alternate occurrence of the interfacial shearing and the fluid exchange has close relation to the behaviour of secondary flow cell in the crossover.

**Keywords:** Compound Channel; Meandering Channel; Secondary flow; Turbulence

## 1. Introduction

Flow in a meandering channel during floods often inundates adjacent flood plains, which is so-called compound meandering flow. Since US Army Corps of Engineers (1956) for the first time investigated this sort of flow, compound meandering flow has been known to have a quite complicated nature. However quite a few research programmes for this sort of flow (Toebes and Sooky, 1967; Ervine and Ellis, 1987) have been conducted until quite recent because of the flow complexity itself and difficulty in its handling by primitive experimental devices. A large flood channel facility installed at HR Wallingford, UK (Knight and Sellin, 1987), enabled to give much better understanding of flow structure and resistance of compound meandering flow. Its output can be found elsewhere (Greenhill and Sellin, 1993; Willetts and Hardwick, 1993; Ervine et al., 1993).

Shiono and Muto (1993) carried out detailed velocity measurements in a trapezoidal meandering channel with flood plains in a small laboratory-scale flume using a 2 component fibre optic laser Doppler anemometer. They could successfully illustrate unique features of compound meandering flow as to secondary flow and shear layer instability. Muto et al. (1996) summarised flow features typically seen in compound meandering channels, i.e. vigorous secondary flow, large internal shearing and fluid exchange. In other words, with these features compound meandering flow has its uniqueness apart from another much simpler flow. They also indicated that these features could work as major additional factors for energy loss estimation. Fukuoka et al. (1997) also carried out an experimental study for compound meandering flow and sketched the internal structure of the flow, which is similar to that submitted by Willetts and Hardwick (1993).

Owing to these research outputs, flow characteristics in compound meandering channels, as a resultant sketch of the internal flow structure from some experimental results, has largely been clarified until now. However, mechanisms which originate and maintain such a unique structure are still not cleared yet. In order to identify these mechanisms investigation into time-dependent behaviour of the internal flow structure should be necessary. Such identification can be attained by a sophisticated flow visualisation or turbulence analyses for time-variable data obtained in a high frequency.

This paper deals with time-dependent behaviour of the internal flow structure in compound meandering channels. The production mechanisms of secondary flow and large shear stress at the interface are discussed. Fluctuating behaviour of the secondary flow and its influence to the whole flow system are also discussed. Time-variable velocity data measured by a 2 component fibre optic laser Doppler anemometer are used in the analyses. The sampling rate of the data was 100Hz. The hydraulic conditions, the experimental set-up as well as the parameters for meander geometries are the same as in the previous papers and can be referred to Muto et al. (1995).

## 2. Secondary Flow

As has been shown by Muto et al. (1995 & 1996), secondary flow is one of the most interesting topics in compound meandering flow. Its unique structure can be summarised in the following points:

1) The originating and developing mechanism for secondary flow in compound meandering channels is the internal interaction between the upper and lower layers, and this is totally different from that for inbank meandering cases, i.e. the centrifugal force brought by channel curvature.
2) The resultant secondary flow induced by the above mechanism is far more strong than in inbank cases.
3) The dominant secondary flow at the bend apex in overbank cases has the rotation whose direction is opposite to that in inbank cases.

These points strongly suggest that secondary flow plays an important role in determining both flow structure and energy expenditure mechanism of compound meandering flow.

### 2.1 Contribution to energy expenditure

In order to estimate energy expenditure by secondary flow, spectrum analysis was carried out. The wavenumber spectrum should be used in the analysis. However direct measurement for the spectrum is in practice extremely difficult. Moreover the transformation from the frequency spectrum into the wavenumber spectrum applying Taylor's frozen turbulence hypothesis is questionable in such a complex flow case. Thus the following discussion is made based on the frequency spectrum. The spectrum was calculated using a FFT technique. The number of data points was $2^{12} = 4096$.

Figure 1 shows spatial distributions of spectra for the streamwise component at the bankfull level in the

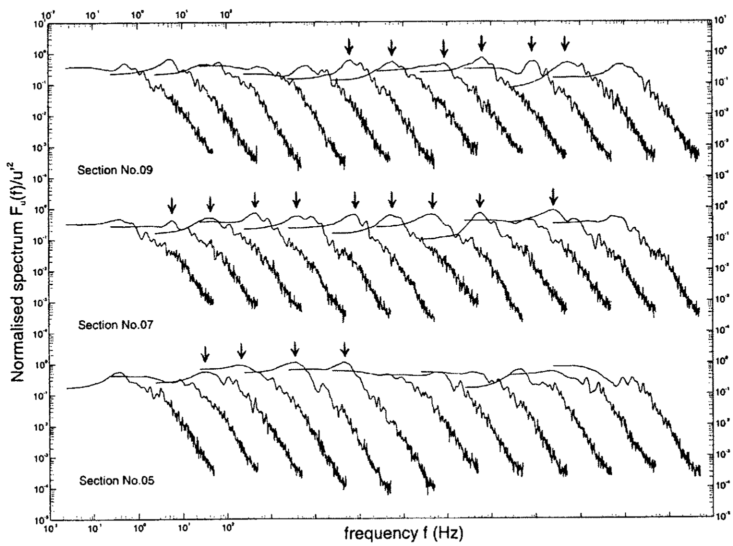



Fig. 1 Normalised spectrum for the streamwise component at the interface (s=1.370, Dr=0.50)

crossover region for the s=1.370, Dr=0.50 flow. The figure shows that the positions of a clear peak in the productive subrange of spectra change from one section to the other, as indicated by arrows in the figure. That is, such spectra as having a clear peak mainly appear near the left hand side wall in Section 5, and they distribute over the whole channel width in Section 7, and then surge toward the right hand side in Section 9. These peak appearances can be closely related to the position of secondary flow, which is induced near the left wall and developed towards the right hand side through these sections. The spectral peak mainly appears in the frequency range from 0.3Hz to 1.0Hz. If Taylor's hypothesis of Eq. (1) can be applied,

$$E(k) = \frac{U_c}{2\pi}F(f), \quad k = 2\pi\frac{f}{U_c} \qquad (1)$$

(where E(k) = wavenumber spactrum, F(f) = frequency spectrum, $U_c$ = convection velocity), the corresponding length scale (the reciprocal of wavenumber) is from 2cm to 8cm, which is about the order of the main channel depth. This is evidence that secondary flow of the channel depth scale takes an important role in energy expenditure.

To see the contribution of the spectral distribution to the total energy, the cumulative spectrum is considered. The cumulative spectrum K(f) defined for the streamwise component, for example, is written as follows:

$$K_u(f) = \frac{1}{u'^2}\int_0^f F_u(f')df' \qquad (2)$$

Figure 2 shows the cumulative spectra together with their corresponding frequency spectra for the streamwise component in Section 9, s=1.370 and Dr=0.50. The frequency range which is within the secondary flow scale is assessed as follows. According to Imamoto et al. (1989), the diameter of cell generally distributes around its mean $d_m$ from $0.4d_m$ to $1.6d_m$. If this distribution can also be applied to the case being considered, using Eq. (1), the frequency range governed by the secondary flow scale can be estimated as $0.625f_p$ to $2.5f_p$, where $f_p$ is the peak frequency. The length scale which corresponds to the peak frequency can be considered as the mean size of the secondary flow cell, as was examined above. Figure 2 also shows the estimated

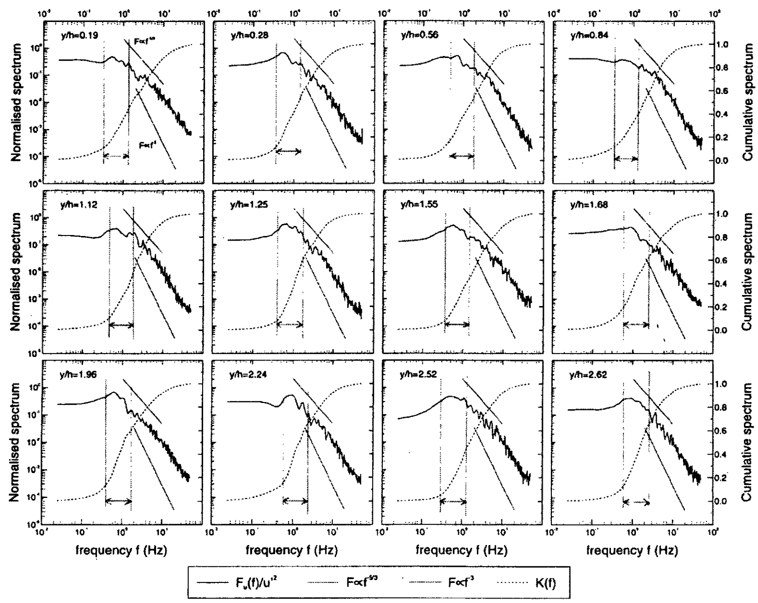



Fig.2 Normalised and cumulative spectra for the streanmwise component (Section 9, s=1.370, Dr=0.50)

range of secondary flow. The estimated contribution to energy expenditure due to secondary flow is 35% to 50%. On the other hand, the turbulence contribution is mostly over 50%. It can be said that the effect of secondary flow on energy expenditure is quite large and it dissipates as much energy as turbulence does.

## 2.2 Cell behaviour

Secondary flow structure illustrated from averaged velocity distributions, shown e.g. in Muto et al. (1995), can indicate that the dominant secondary flow cell, once it attains full development in the crossover region, maintains its size and position in a quite stable condition until it starts to decay. Velocity fluctuations measured at a typical point at the kernel of a secondary flow cell, however, shows somewhat different nature of the cell (Fig. 3). It can be recognised in the figure that V and W have a strong negative correlation, i.e. V<0 and W>0 (indicated by short arrows in the figure) whereas V>0 and W<0 (long arrows), and these two conditions occur almost alternately in some periodic nature. This will show fluctuating behaviour of the secondary flow cell.

Considering the rotation direction of the cell and the correlating conditions, the relationship between the cell behaviour and the interaction processes at the interfacial boundary can be illustrated as Fig. 4. That is, 1) When V>0 and W<0, the cell is depressed towards the bed by the upper layer flow and the interaction of expansion contraction type (fluid exchange) is predominant: 2) When the condition is reversed, the cell extends its size and the interaction mechanism changes to the interfacial shearing.

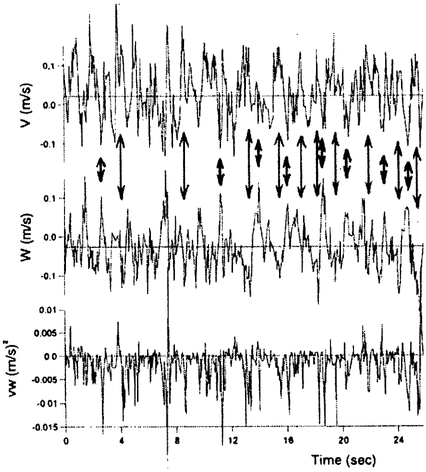
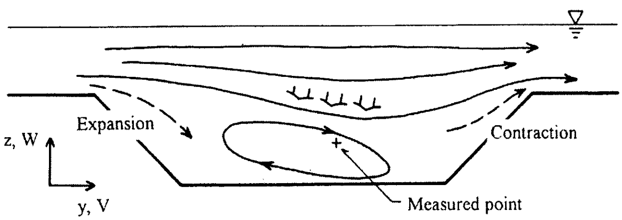
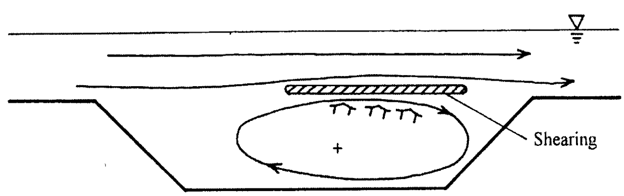



Fig. 3 Temporal variation of velocity V and W at a point within secondary flow cell




(a) Flow expansion and contraction is dominant, a secondary flow cell is depressed towards the bed.




(b) Secondary flow cell extends the size up to the interface, shearing at the interface is dominant.

Fig. 4 Secondary flow fluctuation and interaction processes

## 3. Interfacial Shear

Muto et al. (1995 & 1996) discussed turbulence structure of compound meandering flow based on the distributions of turbulent kinetic energy and Reynolds stresses. Their distributions, especially for Reynolds stresses, are highly distorted owing to vigorous secondary flow and a complex turbulence nature, which can never be seen in simple flow cases. Turbulence characteristics as to shear stresses can be summarised as follows:

1) A large vertical shear stresses $-\overline{uw}$ and $-\overline{vw}$ are produces in the crossover region, whose magnitude can be 2 to 5 times larger than that of the bed shear stress along the main stream direction in the main channel.
2) Such large stresses can be seen within a rather limited area, its peak being at around the bankfull level, i.e. the boundary between the upper layer flow and the lower layer flow, thus these stresses are presumably induced by interaction between these two layer flows.
3) Vertical distributions of these stresses show strong non-linear nature, however the effectiveness of two layer model for compound meandering flow, dividing the channel system at the interface between the upper and lower layers, is also suggested in their distributions.

In order to examine producing mechanism of such a large shear stress, temporal variations of velocity fluctuations measured at a point suffering from a strong interaction are shown in Fig. 5. Intermittent production of extremely large shear stress $vw$ can be seen in the figure. A large negative stress is produced in a rather rapid manner when the vertical component W is accelerated but the lateral component V is decelerated (indicated by arrows in the figure). Figure 6 shows conditional sampling of fluctuating $vw$ measured at another point but in a similar condition. As is indicated in Fig. 5 the negative correlation between V and W, i.e. Quadrant 2 (v<0, w>0) and Quadrant 4 (v>0, w<0) in Fig. 6, is responsible for the stress production. It can be seen that time fraction of Q2 and Q4 is nearly the same irrespective of the hole size H'. Whereas contribution of Q4 is larger than that of Q2 in a small hole size. However this relation is reversed in the range H'>3.

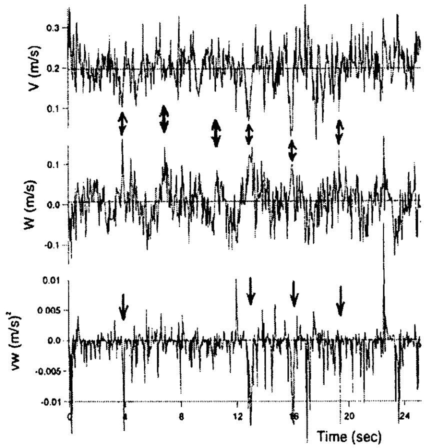



Fig. 5 Temporal variation of velocity V and W at a point within the interfacial boundary

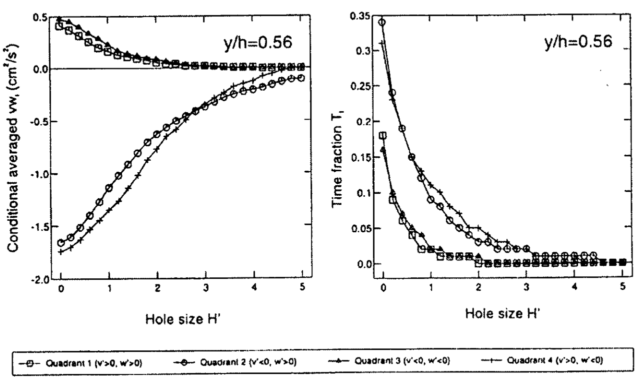



Fig. 6 Conditional sampling for vw at the interface

This implies that the main contribution to producing $-\overline{vw}$ is in Q4, but distinct instantaneous peak of product $vw$ in Q2 also has a large contribution.

In addition to the unique V-W relation on producing large shear stress as examined above, it is also seen from the u-v measurements at the same point that accelerating U and decelerating V have a strong correlation (Fig. 7). Consequently when large $-\overline{vw}$ is produced, the lower layer flow is going upward (W accelerated) and accelerating along the streamwise direction (U accelerated and V decelerated). At this condition secondary flow doesn't develop so much since energy from the upper layer flow is used to accelerate the lower layer flow in the main direction, not to induce secondary flow whose movement is perpendicular to the streamwise direction. This fact well supports the theoretical consideration by Nezu and Nakagawa (1993) about the origin of secondary currents.

## 4. Conclusions

1) Energy expenditure due to secondary flow was estimated by energy spectra. The applicability of Taylor's frozen turbulence hypothesis to complex compound meandering flow and the analogy of the distributions between cell size of secondary flow and spectra around its peak were assumed in the analysis. The estimated contribution to energy expenditure due to secondary flow is 35% to 50%. Consequently secondary flow dissipates as much energy as turbulence does.

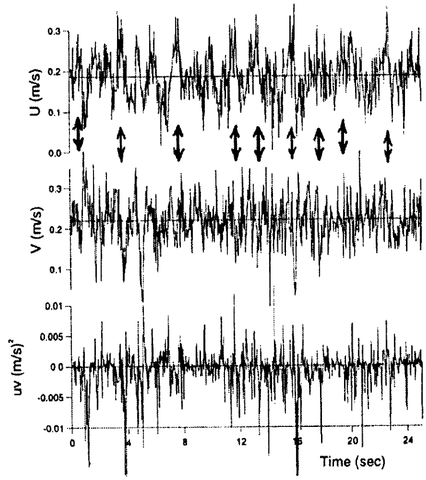



Fig. 7 Temporal variation of velocity U and V at a point within the interfacial boundary

2) Within the fully-developed secondary flow cell, V and W have a strong negative correlation. The cell is thus thought to have a fluctuating behaviour even after its full development. This fluctuation largely influences interaction mechanism between the upper and lower layer flows, as being alternate occurrence of the interfacial shearing and the fluid exchange.
3) Conditional sampling clearly shows the mechanism of inducing shear stress at the interface. An instantaneous large shear is produced when the lower layer flow is going upward and accelerating along the streamwise direction. Such a condition could strongly interact with the upper layer flow whose main way is in the valley direction. It is deemed that in this condition secondary flow is not induced but the mean flow energy is transformed mainly to stress production.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## 要旨

本報告では，既報に示された統計理論に基づく複断面蛇行開水路流れの構造を基礎とし，流速変動の時系列データに乱流解析手法を適用し，二次流と内部せん断層の組織的構造に関して検討を行った．その結果，エネルギー損失に関する二次流の寄与率が算定されるとともに，二次流のゆらぎと高水敷・低水路間の流体干渉機構との関連が指摘された．また，境界部におけるせん断力の発生時に卓越する，流れの干渉構造が明らかとなった．

**キーワード**：複断面流れ，蛇行水路，二次流，乱流