Study on Solitary Wave Boundary Layer

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論文内容要旨

Understanding of sea bottom boundary layer characteristics, especially bottom shear stress acting on the sea bed, is an important step needed in sediment transport modeling for practical application purposes. Because of this important reason, both laboratory and numerical experiments of bottom boundary layer under periodical non-linear waves have been done by many researchers (e.g. Lee and Cheungk, 1999; Lin and Zhang, 2008; Suntoyo et al., 2008; Suntoyo and Tanaka, 2009a). However, only several researchers have conducted experimental and theoretical studies to describe the wave boundary layer under solitary wave motion.

Bottom boundary layer under wave motion has crucial importance in the analyses and modeling of nearshore sediment transport. Solitary wave with narrow crests without trough has been often used as an approximation of surface profile of ocean water waves propagating in shoaling water area. Moreover, a tsunami wave approaching shallow water can also be frequently replaced with a solitary wave to a first approximation. In past five years, investigation of boundary layer characteristics under a solitary wave becomes trending topics after many large tsunamis. Theoretical study on damping solitary wave was introduced by Keulegan (1948) and then, it has been followed by some researchers in both laboratory experiment and numerical approach (e.g., Ippen and Kulin, 1957; Naheer, 1977, 1978; Tanaka et al., 1998; Liu et al., 2006, 2007; Suntoyo and Tanaka, 2009b Sumer et al., 2010; Vitori and Blondeaux, 2008, 2011). In case of laboratory experiment, facilities or generation set up used in the previous experiments can be classified into two groups: a wave flume with free surface (e.g., Ippen and Kulin, 1957; Naheer, 1977, 1978; Liu et al., 2006, 2007) and an oscillating water tunnel (Sumer et al., 2010).

In the past, many problems and inconveniences had been faced during conducting the laboratory experiment. As an example: Liu et al. (2006, 2007) had carried out experiments by using a wave flume facilitated Particle Image Velocimetry (PIV). Their generation system just able to investigate boundary layer characteristics in a laminar flow regime and it could not do experiments in the higher Reynolds number / in transition and turbulent flow regimes. In contrast to the wave flume data, U-shaped oscillating water tunnel which has been used by Sumer et al. (2010) enable conducting experiment in higher Reynolds number. However, it will be practically difficult in a U-shaped oscillating tunnel to generate boundary layer flow exactly corresponds to solitary wave motion because of restorative force in a tunnel, which may induce oscillating motion with flow reversal. Indeed in Sumer et al.'s (2010) analysis of the experimental result, the portion of the data with negative velocities at the trailing of the fluid motion was disregarded. In an experiment using a wave flume or U-shaped tunnel, another difficulty arises in a great number of realizations required to obtain a reliable ensemble averaged quantities. It is reported that under oscillatory motion, 50 samples are necessary to achieve convergence of turbulent statistics such as turbulence intensity and mean velocity (Sleath, 1987; Jensen et al., 1989).

The overall aim of the present study is to enhance our understanding in the boundary layer characteristics under a solitary wave by development an appropriate generation system and conducting solitary wave motion experiments for all regimes (laminar, transition and turbulent regime), doing comprehensive investigation in order to identify the flow characteristics in each regime and identifying the main criterion of a solitary wave cases (stability diagram, wave friction factor, phase difference and boundary layer thickness).

By considering the inconveniences of facilities applied in the previous experimental study, in this current study, a closed conduit water tunnel with a downstream gate has been newly proposed to investigate boundary layer characteristics under a solitary wave over a smooth bed. The experimental set up consists of an overflow head tank, a conduit water tunnel, a downstream gate and a flow velocity measurement device. The conduit has length of 400 cm, width of 15 cm and height of 10 cm. The overflow head tank keeps a constant pressure head and then, water flows into measurement section intermittently along the conduit in response to opening and closing of the gate at the downstream end which is controlled by rotating disk. Firstly, Disk 1 which consists of semicircle and half ellipse has been used in the generation system. The elevation of the gate is adjusted to generating such a movement that the gate is completely closed during attachment of the bearing to semicircle portion, whereas it gradually opens and subsequently closes when it attaches to half ellipse of the disk. By using Disk 1, it can be observed a negative value of velocity during early stage of oscillatory motion. It is an indication that a tranquil period between two peaks of oscillatory motion is not sufficient. A tranquil period is too short to release instantaneous velocity from the previous oscillatory motion in a relatively small of quantity when the next oscillatory motion coming. Secondly, after considering the deficit of the prior generation method which uses Disk 1, a new design of rotating disk is designed by reflecting the exact theory of free stream velocity under solitary. Next, it is call as Disk 2. A new set up has accomplished a series of experiment with a various value of Reynolds number (R_e). It should be noted here that the flow motion generated by the present mechanism is not purely "solitary", but periodical consists of solitary-wave-like positive peaks and tranquil period in between two peaks. Because of this characteristic, the present generation system facilitates measurements of statistical properties obtained by phase ensemble averaging, whereas the previous generation methods such as wave flume and oscillating tunnel require a great number of realizations to obtain reliable ensemble averaged quantities.

As mentioned previously, a series of experiments has been carried out by a closed conduit generation system over the Reynolds number (R_e) range $2.25 \times 10^5 - 7.34 \times 10^5$. As an addition, the instantaneous velocities are measured by using a Laser Doppler Veloci-meter (LDV) over 50 wave numbers and at 17 to 22 measurement points in the vertical direction under single and periodical/continuous measurement methods. The reason of conducting measurement under single method is to evaluate the sufficiency of tranquil period between two peaks of oscillatory motions. From the comparison of measured free stream velocity and the exact solution of solitary wave, it can be concluded that good agreement can be achieved among them. Furthermore, it should be here emphasized that the negative velocity at the trailing of fluid motion inherent in a U-shape oscillating tunnel as reported by Sumer et al. (2010) can be definitely avoided. In periodically measured data, 24th and 25th samples are depicted out of continuous 50 wave cycles and it is compared with a result under single measurement methods. A similar characteristic can be observed between two measurement methods. Then, a vertical velocity distribution is also depicted in order to get detail information under two measurement methods. And the result informs that it is needed a certain wave number to achieved convergence of measurement. To check the convergence of the statistics, a sensitivity analysis is carried out for Case 2-4 as the highest Reynolds number (R_e) = 7.34×10^5 at $z = 0.029$ cm and $t = 0.70$s where the turbulence is largest. And a minimum wave number (n) to achieve convergence is 40. In order to check a sufficiency of tranquil period between two peaks of oscillatory motion, a vertical velocity distribution at the end of oscillatory motion is also analyzed and drawn. The result of analysis shows a velocity value in the end of oscillatory motion is almost closed to zero, this fact is different with the result of experiment by using Disk 1 that a negative value of velocity distribution can be observed in the end of oscillatory motion. It apparently confirms that tranquil period between two peaks of oscillatory motions is sufficient and or it can satisfy an inherent requirement of solitary wave as single wave generation.

Investigation on transitional flow characteristics under a solitary wave has been done based on the present experiment data with Reynolds number (R_e) = 2.25×10^5 and 5.64×10^5. The investigation consists of spike intermittency, velocity distribution and bottom shear stress. From comprehensive analyses in terms of intermittency and velocity distribution, Case 2-2, $R_e = 5.64 \times 10^5$

can be classified in transition flow. As a tentative demarcation, Case 2-2, $R_e = 5.64 \times 10^5$ can be regarded as critical Reynolds number for transition to turbulence. This case shows a fairly agreement with the finding of previous studies as critical Reynolds number (Sumer et al., 2010; Vittori and Blondeaux, 2011).

Hino et al. (1976) classified turbulent flow regime in three types: weakly turbulent flow, conditionally turbulent flow and fully turbulent flow. They defined conditionally turbulent flow when turbulence is generated suddenly in the decelerating phases while the flow recovers to laminar in the accelerating phases. As a result of investigations in terms of turbulence intermittency and velocity distribution, Case 2-3, $R_e = 6.06 \times 10^5$ and Case 2-4, $R_e = 7.34 \times 10^5$ can be classified in turbulent regime with conditionally turbulent flow type. And then, turbulence flow characteristic under solitary wave is probed based on experimental data of both cases (Case 2-3, $R_e = 6.06 \times 10^5$; Case 2-4, $R_e = 7.34 \times 10^5$) and it is also supported by Sumer et al.'s (2010) experiment data. An interesting phenomenon can be observed during investigation, a discontinue velocity distribution is found in both cases, this interesting phenomenon occurs in connection with turbulent fluctuation in the measured instantaneous velocity at certain sequent elevations. A similar flow velocity behaviour in case of discontinue velocity profile is also observed in the experimental study of Sumer et al. (2010). Then, the phase difference, wave friction factor and boundary layer thickness have been analyzed based on experimental data and also it has been confirmed by laboratory experimental data (Sumer et al., 2010) and DNS (Vittori and Blondeaux, 2011). Furthermore, the wave friction factor for higher Reynolds number ($R_e > 2 \times 10^6$) have been predicted by applying the heuristics law of Blondeaux and Vittori (2012) based on the result of RANS modeling. Note that so far no data are available for solitary motion / wave boundary layers which have Reynolds number (R_e) above of 2×10^6.

After completing an investigation and analysis of boundary layer characteristic under a solitary wave in laminar, transitional and turbulent flow regime, an important finding can be stated in this present study. Inconsistency of critical Reynolds number is found in a solitary wave case for wave friction factor, phase difference and boundary layer thickness. This observable fact is distinct different with sinusoidal wave case which has a consistency in critical Reynolds number at $\approx 1.5 \times 10^5$.

Validation in some criteria (velocity measurement methods, Critical Reynolds number, flow velocity distribution behaviour) of a closed conduit generation system have been done and as conclusions, validation results show a good agreement with the finding of previous studies (Sumer et al., 2010; Vittori and Blondeaux, 2011). The most important finding that we want to highlight in here is a closed conduit generation system proposed in the present study can overcome some difficulties of the facilities applied in the previous experimental studies (Liu et al., 2007; Sumer et al., 2010), particularly in achieving a reliable ensemble averaging with ease and also in conducting the sediment transport experiment.

論文審査結果の要旨

孤立波は津波を近似する波動として多用され，孤立波の遡上やそれに伴う土砂移動に関する研究がなされている．これらの取り扱いの際，抵抗則として定常流のマニングの粗度係数などを援用することが多い．ただし，そのような簡便な底面摩擦算定法の精度に関する十分な検討はなされていない．本論文では孤立波動下における底面境界層に関する検討を行っている．さらに，定常流抵抗則を援用した時の精度についても検討を行った．

第1章では，「序論」として本論文の目的と構成について述べている．

第2章においては，孤立波に関する既往の研究を紹介し，特に，これまでの実験的研究において用いられた実験装置が有する問題点を明らかにしている．

第3章においては，第2章で指摘された問題点を受け，十分な数のアンサンブルを取得することの困難さを伴っていた従来の実験装置の難点を克服する装置の提案を行っている．層流時の実験結果は解析解と極めて良好な一致を示し，開発された装置の妥当性が示された．これは，きわめて重要な成果である．

第4章においては，層流から乱流への遷移域に関する実験を行い，減速期における乱れの発生など，定常流では見られない非定常流特有の境界層特性を確認した．また，限界レイノルズ数はSumer(2011)によるU字管振動流装置による結果と一致するものであった．これは，流体力学上，有益な知見である．

第5章においては，限界レイノルズ数を越えた乱流域における流速分布・乱れ特性・底面せん断力について実験的検討を行っており，減速期の乱れによる運動量輸送により，層流時に見られた負流速の発生が見られないことを示した．また，マニングの粗度係数による手法では，底面せん断力を過大評価することを示している．これは，これまで実験的には報告されていない知見であり，重要な成果である．

第6章は総括及び今後の課題を述べたものである．

以上要するに，孤立波に伴う底面境界層の実験を行うための装置を提案すると共に，同装置により遷移域及び乱流域における境界層特性を明らかにしており，今後，津波による土砂移動実験の高精度化など多岐にわたる実験的研究への応用の可能性を有している．したがって，海岸・海洋工学分野の発展に寄与するところが少なくない．

よって，本論文は博士(工学)の学位論文として合格と認める．