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泥砂顆粒啟動之滾動與抬起機率研究

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Rolling and lifting probabilities for sediment entrainment

中文摘要

泥砂顆粒之啟動機率為序率輸砂模式中不可或缺之要素，其精確與否影響輸砂率推估之準確性，進而影響河川整治之成效。過去之研究並未有系統地探討泥砂顆粒啟動之機制，亦未明確界定泥砂顆粒滾動與抬起之門檻條件，甚或採用不一致之啟動機率推導輸砂模式，致使預測結果與實測資料差距甚大。本研究之目的即有系統地探討泥砂顆粒滾動與抬起之門檻條件，並推估在不同流況下泥砂顆粒之啟動機率，進而將其應用於序率輸砂模式推估礫砂河床之分區輸砂率。

關鍵詞：滾動與抬起機率，泥砂啟動，亂流跳動，河床幾何。

ABSTRACT

This study addresses the rolling and lifting probabilities for sediment entrainment by incorporating the probabilistic features of the turbulent fluctuation and bed grain geometry. The two threshold conditions identified herein enable us to precisely define the probabilities of entrainment in the rolling and lifting modes. The lifting probability increases monotonously with the dimensionless shear stress θ, consistent with the earlier results yet displaying improved agreement with the experimental data. The maximum value of rolling probability, with a magnitude of 0.25, occurs at $\theta \approx 0.15$. For $\theta < 0.05$ (or $\theta > 0.6$), the rolling (or lifting) probability makes up more than 90% of the total entrainment probability and thus can be used as an approximation to the total entrainment probability. The rolling and lifting probabilities are further linked to two separate criteria for incipient motion. The results reveal that a consistent probability corresponding to the critical state of sediment entrainment cannot be found.

Keywords: Rolling and lifting probabilities, sediment entrainment, turbulent fluctuation, bed geometry.

1. Introduction

The purpose of this study is to develop theoretical components for evaluating two types of entrainment probability, i.e., the rolling and lifting probabilities, in hydraulically smooth-bed and transitional open-channel flows. The thresholds for two different entrainment modes are identified, which lead to a more precise definition of the rolling and lifting probabilities. Both the fluctuation of turbulent flow and the randomness of bed grain geometry are considered in the derivation of rolling and lifting probabilities. The lifting and rolling probabilities are verified with the published data. These two probabilities are further linked to the rolling and lifting thresholds to demonstrate the inconsistency involved in the calculation of critical shear stress.

2. Results and Discussion

2.1 Verification of Results

The relationships between the computed results and the dimensionless shear stress θ are shown in Fig. 1, where a distinct difference between the lifting and rolling probabilities is demonstrated. The lifting probability PL increases monotonously with θ, whereas the rolling probability PR increases with θ in the region of $\theta < 0.15$ but then reduces for larger values of θ. Firstly, the lifting probabilities reported by Guy et al. (1966), Luque (1974), Jain (1992), and Papanicolaou (1999) are used for comparison with the calculated PL. Fig. 1 reveals that the computed result of PL agrees well with the published data. The discrepancies present at the upper end are probably due to the observed flow-retardation (or drag-reduction) effect caused by the impact on the near-bed flow of the increasing particles in motion at higher θ values. The lifting probability from Wu and Lin (2002) is also presented in Fig. 1 to demonstrate the improvement made in this study. The earlier result of Wu and Lin (2002) displays a substantial overestimation of lifting probability for $\theta \approx 1$. The magnitudes of the Euclidean norm $\|e\|_2$ and the coefficient of determination R^2 for the result of Wu and Lin (2002) and the present result are compared. The values of $\|e\|_2$ and R^2 for the result of Wu and Lin are 0.266 and 0.966, respectively, whereas the corresponding values for the present result are 0.245 and 0.971. The percentages of reduced $\|e\|_2$ and increased R^2 are 8% and 0.5%, respectively. In contrast to the work of Wu and Lin (2002), the present study incorporates the probabilistic feature of the initial bed geometry (in addition to the turbulent velocity fluctuation) and also the dependence of lift coefficient on flow condition (whereas a constant lift coefficient $C_L = 0.21$ was used by Wu and Lin). The improvement is believed to originate from these additional considerations.

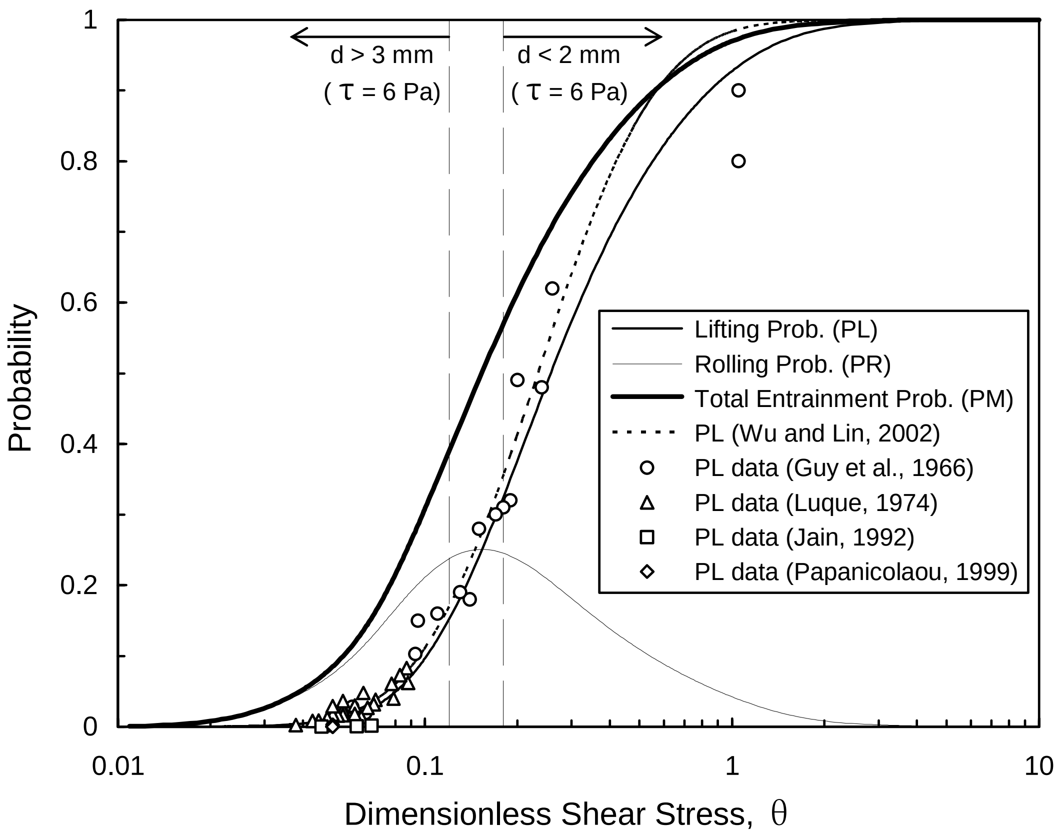

Figure 1. Relationships between entrainment probabilities and dimensionless shear stress

Secondly, the rolling and lifting probabilities are compared with the observations made by Drake et al. (1988). Bed shear stress was approximately 6 Pa. The streambed is hydraulically transitional, consisting of fine gravels with a median diameter = 4 mm. The transport of sediment was almost entirely as bedload. The recorded plan and side views of the motion of individual bedload particles indicated that rolling was the commonest mode of entrainment for particles larger than about 3 mm, whereas lifting was the mode of entrainment for most bedload particles smaller than about 2 mm. The bed shear stress (i.e., 6 Pa) and particle diameters correspond to the values of $\theta = 0.12$ (for $d = 3$ mm) and $\theta = 0.18$ (for $d = 2$ mm), respectively. In other words, when $\theta < 0.12$, rolling is the commonest mode of entrainment, whereas for $\theta > 0.18$, lifting is the dominant mode of entrainment. Clearly demonstrated in Fig. 1 is that the rolling probability is greater than the lifting probability in the region of $\theta < 0.12$; however, the lifting probability becomes much greater than the rolling probability for $\theta > 0.18$. The results obtained in this study coincide very well with the observations made by Drake et al. (1988) and are physically meaningful. In fact, such a coincidence can be reasonably interpreted because when the values of θ are sufficiently high (i.e., for very large τ values or very small d values), there is a strong tendency that particles will be entrained in the lifting (i.e., rolling-lifting) mode rather than the pure rolling mode. On the other hand, when the magnitudes of θ are appreciably low (i.e., for negligible τ values or extremely large d values), the particles will most likely stay in repose rather than move. As such, the probability of entrainment in the rolling mode becomes vanishing small at both very high and low values of θ.

2.2 Total Entrainment Probability

Because rolling and lifting are mutually independent modes, the total entrainment probability (P_M) is the summation of rolling and lifting probabilities, i.e., $P_M = P_R + P_L$. Taking the expected value of P_M over the entire range of δ yields $PM = PR + PL$, where $PM =$ mean total entrainment probability. The PM curve resulting from the superimposition of PR and PL curves is shown in Fig. 1. It is found that the rolling probability makes up more than 90% of the total entrainment probability for any θ value less than about 0.05, while the lifting probability occupies more than 90% of the total entrainment probability for any θ value greater than about 0.6. Hence, for the regions of $\theta < 0.05$ and $\theta > 0.6$, PR and PL can be used respectively as the approximations to PM. However, for the θ values in the range between 0.05 and 0.6, the contributions of both probabilities to the total probability of entrainment should be equally weighted.

2.3 Critical Entrainment Probabilities

We are also interested in the probability of entrainment corresponding to the condition that the applied shear stress equals to the threshold shear stress for incipient motion, i.e., $\theta = \theta_c$, where $\theta_c =$dimensionless critical shear stress. Gessler (1971) reported a 50% probability of movement in rough turbulent flow when θ_c (based on d_{50}) was applied to the bed particles. The entrainment probabilities at the critical conditions can be evaluated with the aid of the rolling and lifting thresholds developed by Ling (1995). His criteria for incipient motion can be presented in a graphical format similar to Shields diagram, i.e., θ_c versus critical boundary Reynolds number R_c^* (shown in Fig. 2). He found that the Shields' curve for the most part lies between the two theoretical thresholds. For a given value of R_c^*, the corresponding rolling and lifting thresholds (i.e., θ_{cR} and θ_{cL}) can be determined from the two separate criteria for incipient motion. The values of θ_{cR} and θ_{cL} are then liked to the proposed $PR-\theta$ and $PL-\theta$ relations (or Fig. 1) to evaluate the critical rolling and lifting probabilities, respectively. The results so obtained are shown in Fig. 2, where the entrainment probabilities corresponding to the critical conditions demonstrate considerable variations in the magnitude, especially for the critical lifting probability. The maximum and minimum values of the critical lifting probability are 1.0 and 0.05, respectively, while the critical rolling probability ranges from 0.008 to 0.2. The critical lifting probability drops drastically from about 0.8 to 0.05 as R_c^* increases from 1 to 10. For $\mathrm{R}_c^* > 10$, the critical lifting probability increases modestly from 0.05 to 0.16. On the other hand, the critical rolling probability remains approximately constant within the range between 0.01 and 0.04 for $\mathrm{R}_c^* < 10$, but then increases to about 0.2 as R_c^* increases from 10 to 500. For smooth boundaries ($R_c^* < 2$), both of the critical entrainment probabilities display decreasing trends with the increasing R_c^*. However, in the transitional regime ($2 < R_c^* < 500$), both of the critical entrainment probabilities demonstrate transitions from descending to ascending trends. These trends of variation appear to correlate with the criteria for incipient motion. In summary, the probabilities of entrainment corresponding to the critical rolling and lifting conditions are neither constant values nor monotonous functions of R_c^*. Their variation trends agree with those of the entrainment thresholds.

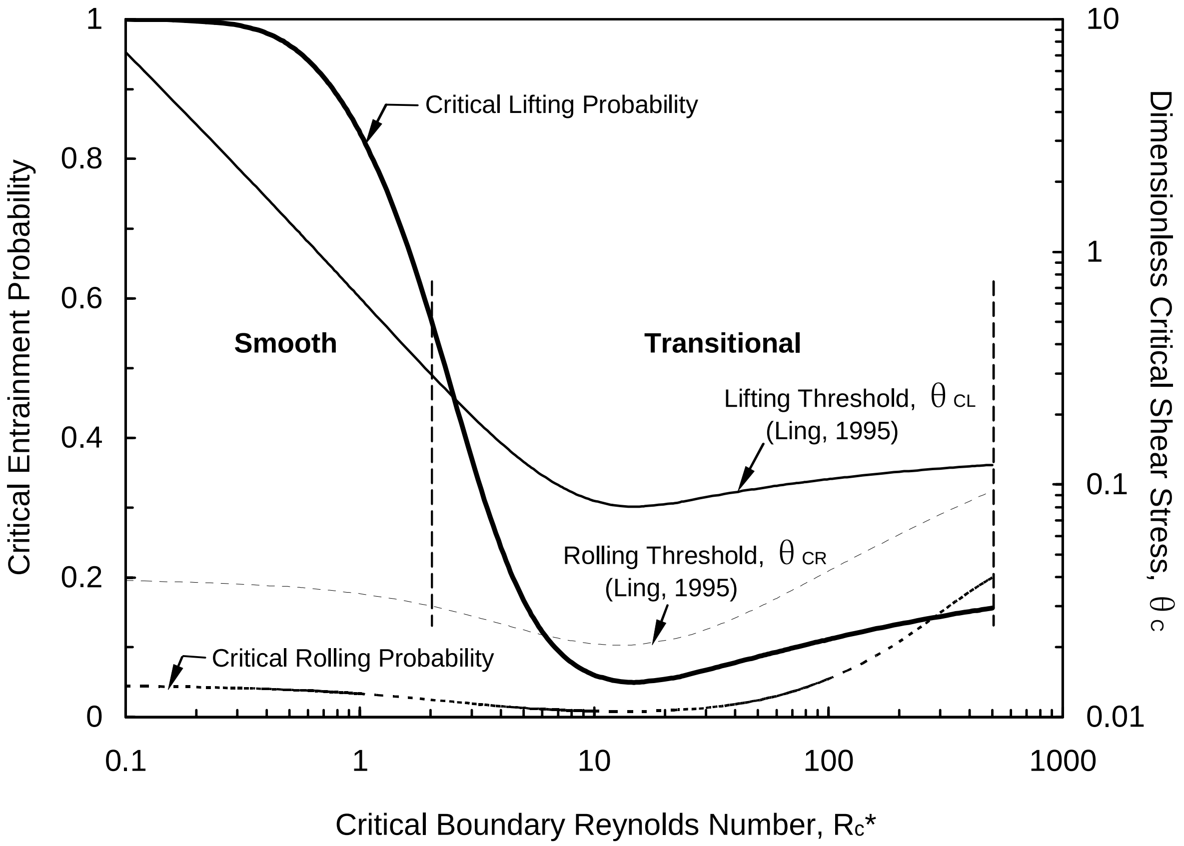

Figure 2. Variations of dimensionless critical shear stress and critical entrainment probabilities with critical boundary Reynolds number

If the critical shear stress is a distinct threshold for incipient motion of the sediment, there must be a consistent probability of entrainment corresponding to such a critical condition. For example, a 50% probability of movement at the critical conditions as proposed by Gessler (1971). However, the results gained in the present study do not support such an argument, in terms of both rolling and lifting modes of entrainment. It is revealed that even when the threshold shear stress is applied to the sediment particle, the entrainment probability is a highly variable function of the hydrodynamic boundary condition, rather than a meaningful value representing the critical state of particle entrainment. Since the probabilities of entrainment corresponding to the so called "critical conditions" vary over such a wide range, a possible explanation would be that there is no such thing as "critical shear stress", as pointed out by many investigators. The results of this study appear to imply the inconsistency embedded in the conventional definition of the critical shear stress for incipient motion, thus probably provide a different aspect worth further investigations.

3. Conclusions

The results show that the lifting probability (ranging from 0 to 1) increases monotonously with the dimensionless shear stress θ, whereas the rolling probability (ranging from 0 to 0.25) displays an increasing trend for $\theta < 0.15$ yet a decreasing trend for larger θ values. Both of the rolling and lifting probabilities coincide well with the published data, quantitatively and qualitatively. Moreover, the lifting probability gained in this study demonstrates an improved agreement with the experimental data. For $0.05 < \theta < 0.6$, the summation of rolling and lifting probabilities is recommended for use as the total probability of incipient motion. However, for θ less than 0.05 (or greater than 0.6), the rolling (or lifting) probability can be used as the approximation to the total entrainment probability. The critical entrainment probabilities are highly variable functions of the boundary Reynolds number, thus no consistent probability corresponding to the critical state of particle entrainment can be found. The results of this study appear to imply the inconsistency involved in the conventional definition of critical shear stress.

4. References

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計畫成果自評

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