SEDIMENT PICK-UP FUNCTIONS

By Leo C. van Rijn

INTRODUCTION

At present, the application of mathematical models describing the sediment transport phenomena is becoming increasingly popular. An essential part of such models is the modeling of the exchange (pick-up and deposition) of sediment particles with the movable bed surface (bed-boundary condition). Usually, the particle pick-up and deposition are represented as separate subsystems, which can be combined by applying the equation of continuity to determine the sediment transport rate.

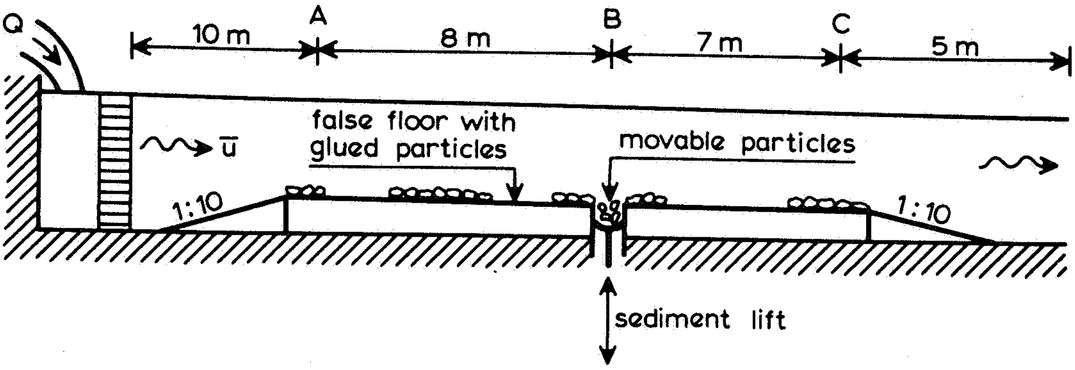

FIG. 1.—Experimental Set-Up

Because of the complexity of the phenomena involved, a complete theoretical description of the particle pick-up process is not yet feasible. Therefore, experimental research has been initiated at the Delft Hydraulics Laboratory to determine the pick-up rate experimentally by using a sediment lift installed in the center line of a flume (8).

Experimental Set-Up.—A sediment lift has been designed by which the sediment particles can be moved upwards at a constant rate through a circular opening in the flume bottom, as shown in Fig. 1.

The particles are pushed upwards by use of a piston connected to an electromotor. The upward piston speed can be set at different (constant) values by means of a mechanical drive system.

The sediment lift was installed in the center line of the test section of a small flume (length ≃ 30 m, width = 0.5 m and depth ≃ 0.7 m). To establish a uniform flow, the flume was equipped with a false floor supported by a jack system which was given (by trial and error) a pre-set slope equal to the expected water surface slope in each experiment. The false floor was covered with prefabricated wooden plates on which sediment particles of a size equal to those on the sediment lift were glued. In all, five types of almost uniform sand material were used. For each type of sand, a series of tests was performed with mean flow velocities in the range of 0.5–1.0 m/s. The flow depth was kept constant at a value of 0.25 m.

Experimental Procedure.—Prior to each run the sediment lift was filled with sediment particles by using a (perspex) tube with a length larger than the flow depth and placed in the opening of the sediment lift. Using this method, the lift could be filled without emptying the flume. The total mass to be poured into the lift tube was computed from the volume of the lift tube, assuming a porosity factor of 0.4. Some mechanical stirring was necessary to fill the tube with all available material.

At the beginning of a run, the opening of the sediment lift was covered to prevent initial pick-up of sediment particles. The (constant) piston speed of the lift was set at a value slightly higher than the expected pick-up rate of the flow (trial and error). Then the flow (constant discharge) was started. After an adjustment period of about 10 min to establish equilibrium flow conditions, the cover plate was removed and the sediment lift was started. When the surface of the movable particles was observed (visually) to rise above the surrounding surface of fixed particles, the lift was stopped for a short period and restarted when the over-height of particles had disappeared. The flow was stopped when all particles were removed. To reduce the subjective element in this procedure, different observers were used to operate the sediment lift. The experiments with a relatively large flow velocity, and therefore a relatively large pick-up rate, were repeated several times (Table 1) to increase the accuracy of the results. The maximum variation between similar tests using different observers was about 20%.

TABLE 1.—α-Constants

	α-CONSTANTS									
	Einstein		Yalin		De Ruiter		Nagakawa Tsujimoto		Fernandez Luque	
Sediment (1)	Best fitted (2)	Proposed (3)	Best fitted (4)	Proposed (5)	Best fitted (6)	Proposed (7)	Best fitted (8)	Proposed (9)	Best fitted (10)	Proposed (11)
130 μm	0.0077	—	0.0088	—	0.0092	0.016	0.0150	0.02	0.0121	0.02
190 μm	0.0077		0.0118		0.0089		0.0331		0.0224	
360 μm	0.0094		0.0167		0.0141		0.0642		0.0436	
790 μm	0.0067		0.0157		0.0182		0.144		0.0854	
1,500 μm	0.0050		0.0125		0.020		0.228		0.138	

The pick-up rate was determined as:

$$E = \frac{M}{A \Delta T} \quad \text{(1)}$$

in which E = pick-up rate in mass per unit area and time (kg/sm^2); M = total sediment mass (kg); A = area of movable surface (m^2); and ΔT = measuring period (s).

Measuring Equipment.—The flume system is equipped with a large reservoir from which the water is pumped to a small tank above the flume where the discharge is measured by means of a circular weir.

The flow velocities at the location of the sediment lift in the center of the flume were measured by use of an acoustical probe.

Bed-Shear Velocity.—As the pick-up rate is supposed to be related to the bed-shear velocity, this parameter must be determined from the measured flow variables. In an earlier study, it was found that the bed-shear velocity can be determined with an accuracy of about 10% from the flow velocities measured close to the bed. The method is based on the universal logarithmic velocity law:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \left(\frac{z}{z_0} \right) \quad \text{(2)}$$

in which u = flow velocity at height z above the origin; u_* = bed-shear velocity; κ = Von Karman constant (= 0.4); z_0 = zero-velocity level = $0.11\ (\nu/u_*) + 0.033k_s$; ν = kinematic viscosity coefficient; and k_s = effective roughness height.

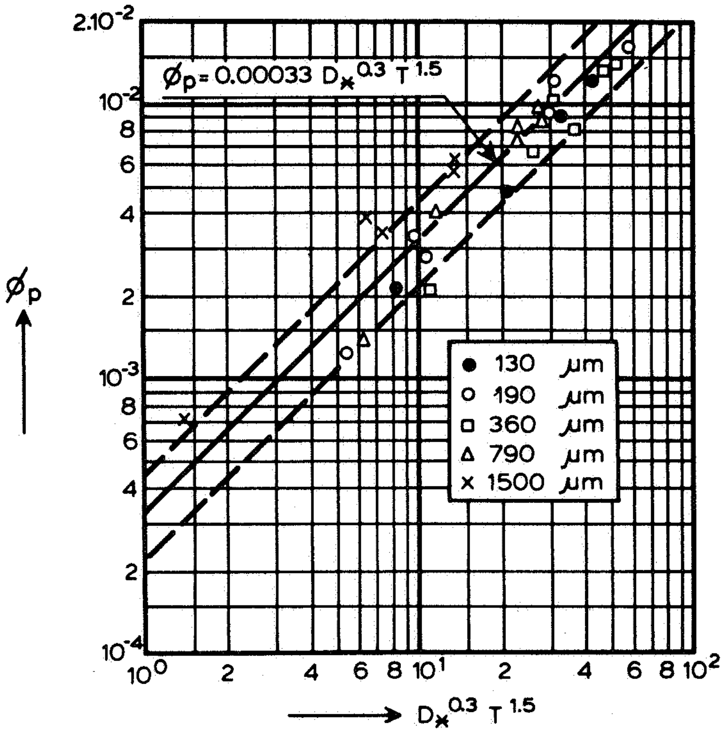

FIG. 2.—Empirical Pick-Up Function

The origin of the velocity profile is supposed to be located at a distance of $0.25D_{50}$ below the top of the particles. The effective roughness height is supposed to be equal to $k_s = 2D_{50}$.

Pick-Up Rate.—In earlier studies (6,7) it has been shown that the movement of bed-load particles can be described in terms of a dimensionless particle parameter (D_*) and a dimensionless transport-stage parameter (T). The particle parameter (D_*) is defined as:

$$D_* = D_{50} \left[\frac{\Delta g}{\nu^2} \right]^{1/3} \quad \text{(3)}$$

in which $\Delta = (\rho_s - \rho)/\rho$; ρ_s = sediment density; ρ = fluid density; and g = acceleration of gravity.

The transport-stage parameter (T) is defined as:

$$T = \frac{(u_*)^2 - (u_{*,\mathrm{cr}})^2}{(u_{*,\mathrm{cr}})^2} \qquad (4)$$

in which $u_{*,\mathrm{cr}}$ = critical bed-shear velocity according to Shields. The dimensionless pick-up rate is defined according to Einstein (1):

$$\phi_p = \frac{E}{\rho_s(\Delta g D_{50})^{0.5}} \qquad (5)$$

A detailed examination of the experimental results yielded the following simple pick-up function:

$$\phi_p = 0.00033\, D_*^{0.3}\, T^{1.5} \qquad (6)$$

Eq. 6, shown in Fig. 2, gives a reasonable representation of the measured pick-up rates. The relative standard error is about 30% (dashed lines).

EXISTING PICK-UP FUNCTIONS

Various researchers have studied the pick-up of sediment particles. It is, however, not always clear what is meant by the various researchers by "pick-up," i.e., which events contribute to the pick-up rate and which do not. Einstein (1950) assumed that a particle can only be picked up after a period of rest which is large compared to the pick-up time scale (1). In his approach, the total travel distance between two successive periods of rest may consist of several jumps or saltations. Yalin (1977) assumes that a particle is picked up whenever it leaves the bed surface to perform a jump (9). Therefore, each particle jump involves a pick-up and a deposit event. It must be stated that the pick-up rate according to the definition of Yalin may be about 10 times as large as that according to the definition of Einstein (assuming an average travel distance equal to about 10 jump lengths).

In the opinion of the present writer, the definition of Yalin should be preferred.

Einstein (1950).—The approach of Einstein is stochastic. The sediment pick-up rate in mass per unit area and time can be expressed as:

$$E = \alpha\rho_s(\Delta g D)^{0.5}P \qquad (7)$$

in which α = universal constant; and P = fraction of time during which a sediment particle is picked up by the flow. Einstein did not determine the α-constant explicitly because the pick-up theory was an integral part of a bed-load theory.

Yalin (1977): $E = \alpha\rho_s u_* P$ (8)

De Ruiter (1982,1983): $E = \alpha\rho_s F\left[\left(\frac{\rho_s - \rho}{\rho_s}\right)\left(\frac{\sigma}{\tau_{\mathrm{cr}}^{o}}\right)(gD\tan\phi)\right]^{0.5}$ (9)

in which F = pick-up probability function (4,5); τ_{cr}^{o} = critical instantaneous bed-shear stress at a horizontal bed; ϕ = angle of repose; and σ = standard deviation of instantaneous bed-shear stress.

According to De Ruiter, the α-constant is 0.016.

Nagakawa-Tsujimoto (1980): $$E = \alpha\rho_s(\Delta g D)^{0.5}\left[1 - \frac{0.035}{\Theta}\right]^3 \Theta \ldots\ldots\ldots \quad (10)$$

in which $\alpha = 0.02$ for spherical particles, and $\Theta = u_*^2/(\Delta g D)$.

Fernandez Luque (1974): $$E = \alpha\rho_s(\Delta g D)^{0.5}(\Theta - \Theta_{cr})^{1.5} \ldots\ldots\ldots\ldots\ldots \quad (11)$$

in which $\alpha = 0.02$ for spherical particles, $\Theta_{cr} = (u_{*,cr})^2/(\Delta g D_{50})$.

Evaluation.—The evaluation of the existing pick-up functions implied the determination of the α-constant by using the experimental results. The "best-fitted" α-constants and the originally proposed (by the authors) α-constants are presented in Table 1. Einstein and Yalin did not propose an α-constant for the pick-up function, because their "pick-up" theories were integrated in a bed-load theory for which only the overall constant was determined.

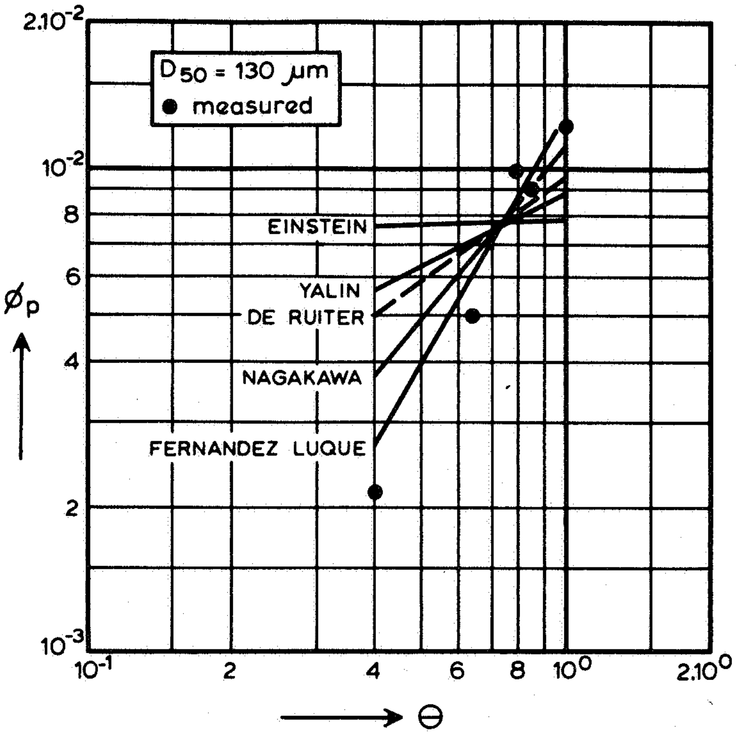

FIG. 3.—Measured and Predicted Pick-Up Rates for 130 μm-Sediment

The "best-fitted" α-constants of Einstein and Yalin are not very much dependent on the particle size. The "best-fitted" α-constant of De Ruiter is weakly dependent on the sediment size, and is in good agreement with the proposed α-constant, particularly for the larger particle sizes.

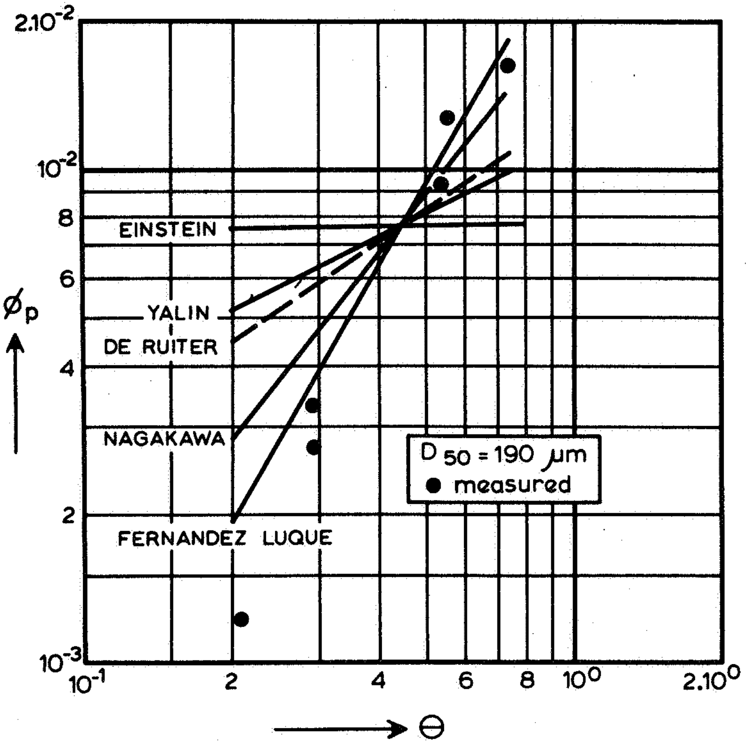

FIG. 4.—Measured and Predicted Pick-Up Rates for 190 µm-Sediment

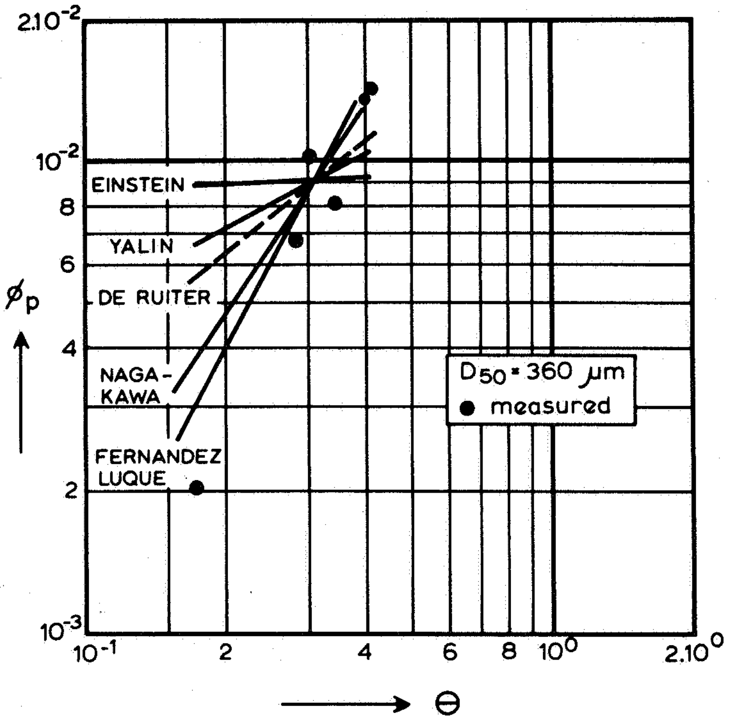

FIG. 5.—Measured and Predicted Pick-Up Rates for 360 µm-Sediment

The "best-fitted" α-constants of Nagakawa-Tsujimoto and Fernandez Luque are strongly dependent on the particle size. As regards the largest particle sizes, the "best-fitted" α-constants are about 10 times too large. For the smaller particles sizes the "best-fitted" α-constants are in relatively good agreement with the proposed values, which is a remarkable result because the proposed constants are based on experiments with rather coarse bed material particles.

Figs. 3, 4, 5, 6 and 7 show that the variation (trend) of the measured pick-up rates (ϕ_p) with the dimensionless particle mobility parameter (Θ)

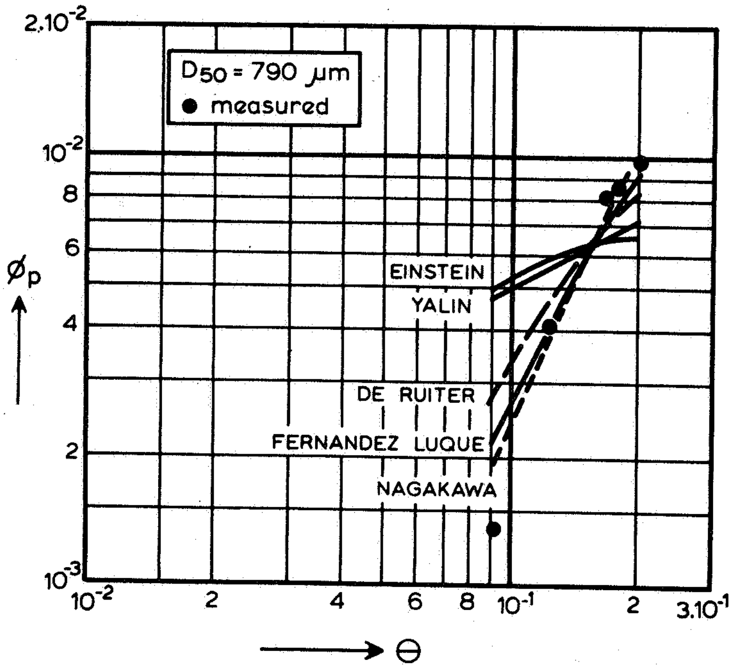

FIG. 6.—Measured and Predicted Pick-Up Rates for 790 µm-Sediment

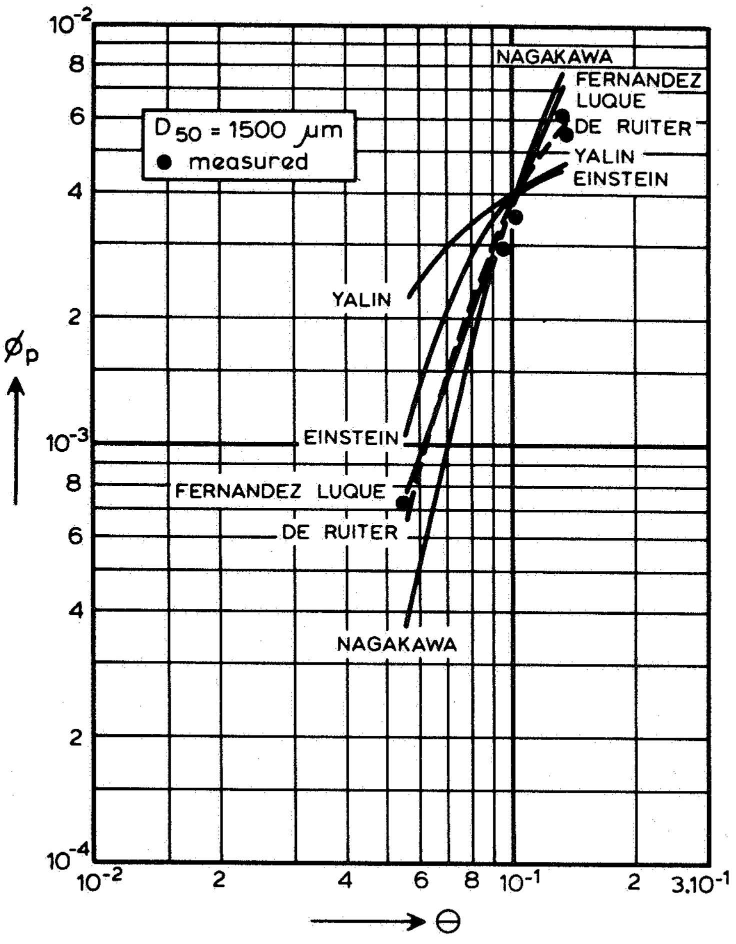

FIG. 7.—Measured and Predicted Pick-Up Rates for 1,500 µm-Sediment

is best represented by the curves of Fernandez Luque and Nagakawa-Tsujimoto, while also the curve of De Ruiter shows good results for the larger particle sizes (790 and 1,500 μm).

CONCLUSIONS

The main findings of the study can be summarized in the following conclusions:

1. The experimentally determined pick-up rate can be represented by a simple pick-up function for particles in the range 130–1,500 μm.
2. The predictive ability of the pick-up functions of Einstein and Yalin is rather poor; the theory of De Ruiter produces the best results for the larger particles sizes (>1,000 μm), while the theories of Nagakawa-Tsujimoto and Fernandez Luque yield the best results for the smaller particle sizes (<200 μm).

APPENDIX.—REFERENCES

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