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Using COSSY (COBble Satellite SYstem) for measuring the effects of lift and drag forces

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ABSTRACT The COSSY system was developed in order to improve techniques on the measurement of fluid forces acting on a single particle during unsteady flows. This enables the shear stress at the point of sediment entrainment to be calculated from the COSSY pebble itself. The artificial pebble is distinct in that it has five pressure sensors. The first one measures the reference pressure. The other four sensors measure pressure differences in the direction of the lift and drag forces. This data is transmitted from the inbuilt sensors via a radio and antenna system directly into a computer. This enables the forces acting on the pebble to be measured nearly simultaneously. First results of flume experiments are described, showing the importance of lift forces at incipient motion.

NOTATIONS

A_p	projected area
C_D	drag coefficient
C_L	lift coefficient
F_D	drag force
F_G	gravitational force
F_L	lift force
g	acceleration of gravity
h	flow depth
Q	discharge
Re	Reynolds number
S	slope
v	flow velocity
v_m	average flow velocity
α	inclination of the river bed
ϱ	fluid mass density
ϱ_s	particle density
ν	kinematic viscosity
Φ	pivot angle

INTRODUCTION

The investigation of interactions between flowing water and loose individual particles is of great importance for many aspects of hydraulics, aerodynamics and geomorphology. The forces acting on particles at rest and in entrainment have long been theoretically defined and their relationships formulated. However, there is a shortage of empirical studies on lift and drag forces acting on coarse particles.

Under turbulent conditions the lift and drag forces can be expressed as (Scheidegger, 1991):

$$F_L = C_L \, Ap \, \rho \, v^2/2 \text{ and } F_D = C_D \, Ap \, \rho \, v^2/2 \qquad (1)$$

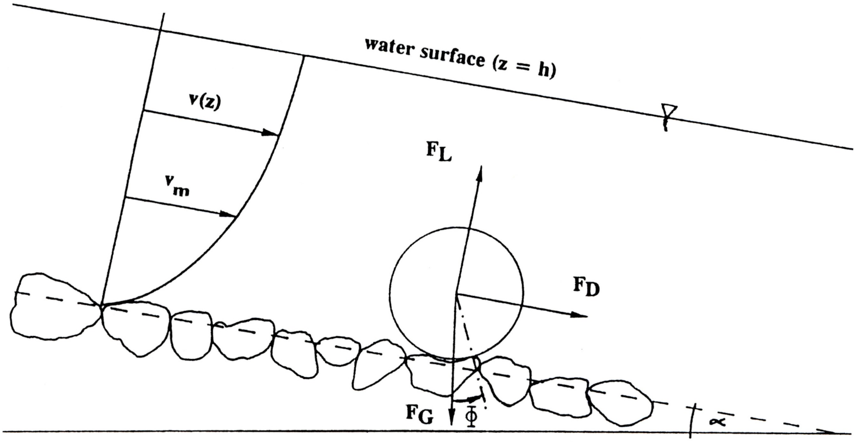

FIG. 1 Hydrodynamic forces acting on a grain at the river bed (Komar & Li, 1986).

In the case of a resting sphere, the coefficients C_L and C_D are dependent on the following parameters:

$$C_{L,D} = f(v\,D/\nu\,;\; h/D;\; \Phi) \qquad (2)$$

where vD/ν = Reynolds number,
h/D = relative roughness,
Φ = pivot angle.

The hydrodynamic forces exerted on a freely moving particle have not yet been measured with adequate precision. Measurements of forces acting on fixed objects of varying size (e.g. Einstein & El-Samni, 1949; Coleman, 1967; Cheng & Clyde, 1972; Aksoy, 1973; Bagnold, 1974; Sumer, 1984; Davies & Sanad, 1979; Willets & Naddeh, 1986) are only an unsatisfactory substitute for continuous measurements at a movable particle.

One of the first attempts to study the hydrodynamic forces acting on bed load particles was made by Jeffreys

(1929). Using the theory of ideal flow, he studied the forces acting on a cylinder placed normal to the stream on the stream bed.

Einstein & El-Samni (1949) were the first to conduct experiments to measure the lift and drag forces acting on a particle resting on the sediment bed (a hemisphere surrounded by similar hemispheres) using strain gauges. The lift force was measured as the pressure difference between the top and bottom of the hemispheres, and drag force was derived from the vertical velocity distribution. The theoretical bed was assumed to be 0.2D below the hemisphere top (cf. Benedict & Christensen, 1972). The pressure difference Δp is a function of the lift coefficient and the flow velocity v:

$$\Delta p = C_L \varrho /2\ v^2 \qquad (3)$$

The lift coefficient was found to be a constant 0.178 when the flow velocity was measured at a distance of 0.35D from the theoretical bed. Further experiments using natural gravel of about the same size yielded very similar results. According to Einstein & El-Samni (1949), lift force is the primary force in bed load transport. The results obtained show that it is normally distributed and fluctuates around an average.

Using indirect experiments, Cheng & Clyde (1972) measured the forces acting on a large sphere (about 30.5 cm in diameter) in an artificial bed of roughness elements of similar sizes and shapes. A loose sphere was placed slightly downstream of a fixed instrumented sphere. After incipient motion of the loose sphere, the critical forces acting on the instrumented sphere were measured using strain gauges. This indirect measurement undoubtedly limits the validity of the results. The theoretical bed level was determined as 0.15D below the top of the spheres. The Manning and de Chezy coefficients as well as the coefficients C_D and C_L were calculated. As in Einstein & El-Samni (1949), the fluctuations of lift and drag had normal distributions; the particle Reynolds numbers ranged between 20800 and 36300.

The forces acting on particles resting on the stream bed have not yet been described in detail. There are no adequate descriptive models (Naden, 1986; James, 1990), nor do reliable data exist to verify theoretical concepts. In addition, important parameters such as flow conditions in the interstitial zone have been neglected. In order to address some of these problems, a new measurement technique has been developed: the Cobble Satellite System (COSSY).

INSTRUMENTATION

In 1988 the Ergenzinger/Schmidt team introduced a new radio tracer technique known as PETSY (PEbble Transmitter

SYstem) to study coarse bed load transport. (A similar technique was evolved contemporaneously and independently by Emmett and his co-workers at the USGS in Denver.) Radio-implanted cobbles can be tracked during transport using a receiver and directional antenna. The mini-transmitters send continuous signals at a frequency of about 150 MHz. The signals are transmitted via antenna to a receiver and on-line data processor (Ergenzinger, Schmidt & Bußkamp, 1989).

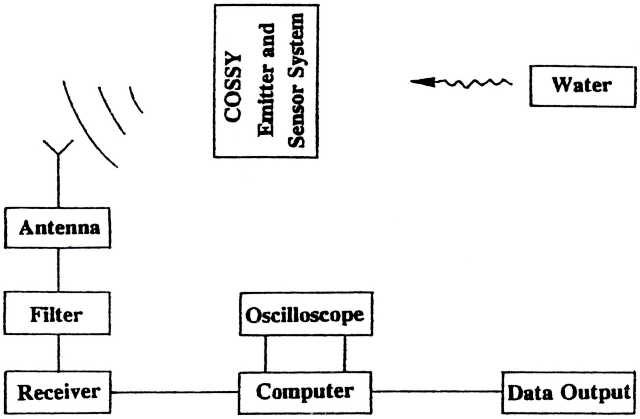

FIG. 2 Schematic diagram of the COSSY system.

This tracer system has been further refined by a combination of emitter and sensors. The new telemetric device measures lift and drag forces directly. The COBble Satellite SYstem (COSSY) comprises an artificial cobble with differential pressure sensors built in along the B and C axes. Pressure is measured by sensors at an interval of 7.2 cm along both axes. Signals are transmitted at a frequency of 144 MHz to a receiver, processed and stored in a computer (see Fig. 2). The electronic instrumentation is cased in a small watertight cylinder, 65 mm high and 80 mm in diameter. The cylinder can be built into variously shaped casings in order to study different particle geometries. Approximately 65 ms are required to record the data of each sensor. In order to measure incipient motion accurately COSSY is also equipped with an acceleration sensor. The system is switched on and off by means of an external magnetic switch.

DISCUSSION

To date, the COSSY telemetric device has undergone only preliminary testing. Initial experiments were conducted under natural conditions at Lainbach (Upper Bavaria) in

TABLE 1 Technical data of the COSSY system.

Cylinder size	diameter 80 mm; height 65 mm
Sensors	4 differential pressure sensors (type 16PC05DF) 1 absolute pressure sensor (type 136PC15A1, both Micro-Switch Honeywell) 1 acceleration sensor (type JTF-AG111 Sensotec)
Data transfer	high frequency, 144 MHz
Measuring time	65 ms for all sensors
Power supply	9 V battery

summer 1991. Tests are being continued in the coarse bed load flume at the Institute of Geographical Sciences, Free University Berlin. Two of these experiments are presented here.

To obtain the simplest boundary conditions possible, all the following statements refer to experiments using a sphere 12 cm in diameter with a density of $\varrho_s = 2.85$ g/cm^3 (Table 2). During the runs the sphere was placed on a rough bed (D_{50} = 5 cm) and, at constant discharge (Q = 0.22 m^3/s), the slope was constantly increased until entrainment set in. The hydrodynamic forces (pressure differences) were measured 15 times per second. In Figs 3 and 5 these values have been averaged per second.

During the first run the sphere lay relatively loosely on the bed, with a pivot angle of 15°. The lift forces were obtained from the pressure difference between the top and bottom of the sphere and therefore include static water pressure. This has a constant value of 7.2 cm and corresponds to the distance between the two sensor

TABLE 2 Parameters of Tests 1 and 2.

Test situation		Q $m^3\ s^{-1}$	Φ °	S $m\ m^{-1}$	h m	Re $x\ 10^5$	v_m $m\ s^{-1}$
A	pre-run	0.22	15	0	0.335	2.09	0.82
A	post-run	0.22		1.23	0.245	2.09	1.12
B	pre-run	0.22	45	0	0.315	2.09	0.87
B	post-run	0.22		4.07	0.150	2.09	1.83

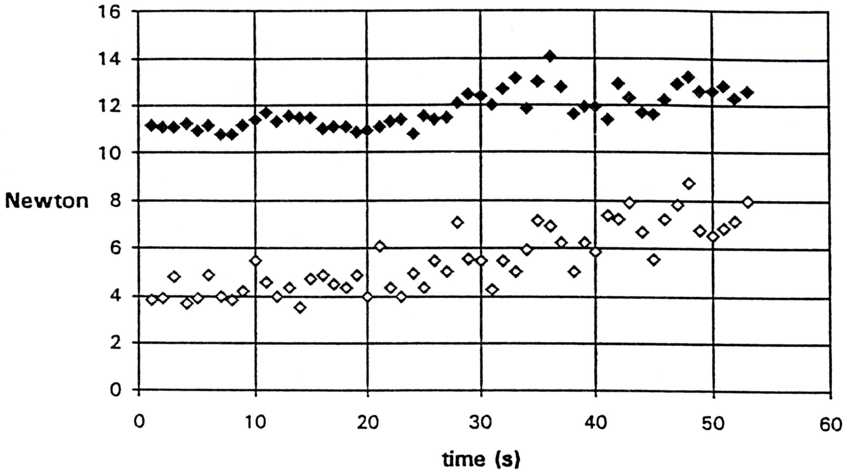

FIG.3 Lift and drag forces ($\Phi = 15°$).

membranes. Incipient motion or the point of erosion was reached only 53 seconds after the start of the experiment (slope = 1.2%) (Fig. 3).

Lift force has the same magnitude as drag force; however, the lift force values trend less steeply than those of drag force. The ratio of lift force (minus the constant value of static water pressure) to drag force is decreasing. The relationship is displayed in Fig. 4.

Fig. 5 shows the results of a similar experiment. The run lasted longer (105 s) since the pivot angle was almost 45°. At incipient motion slope of bed was 4.1%. The

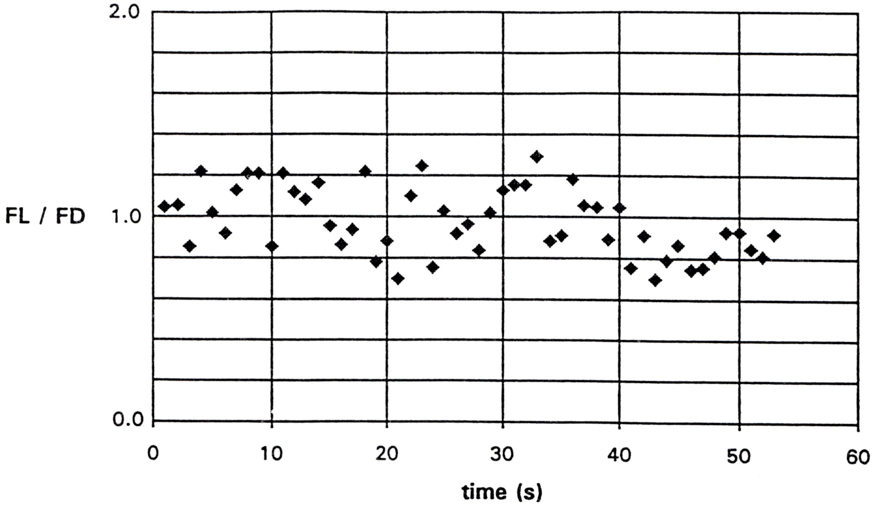

FIG. 4 Relationship between lift force and drag force.

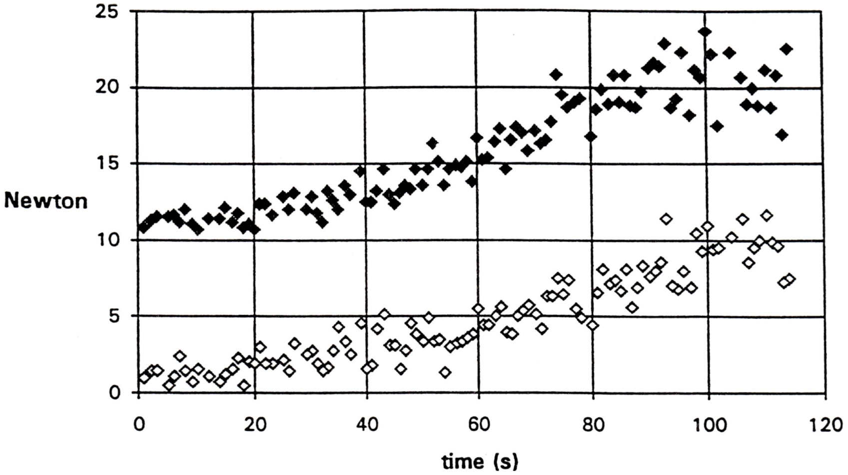

FIG. 5 Lift and drag forces (Φ = 45°).

boundary and hydraulic conditions were similar to the first experiment. The results are also similar: again, both drag and lift forces increase. Close to the critical point, the data start to scatter more widely.

The relationship between the forces is depicted in Fig. 5. As in Fig. 6, the FL/FD ratio decreases from about 2 to 1.7.

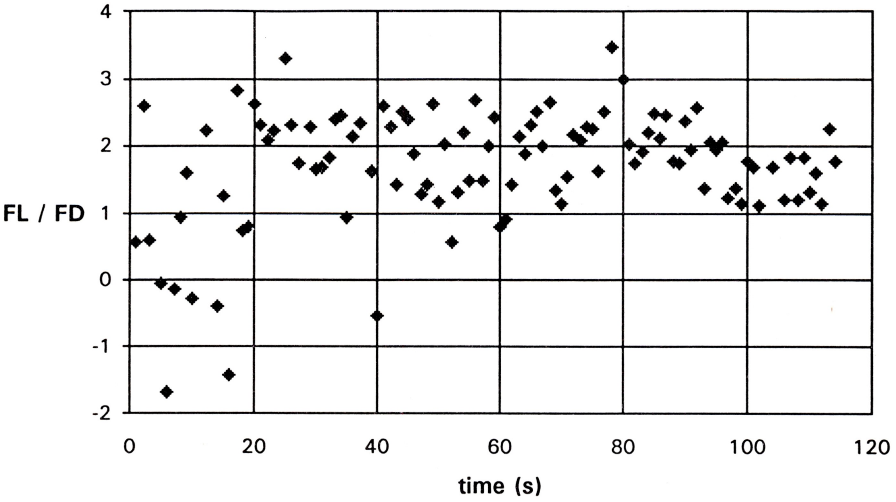

FIG. 6 Ratio of lift force (minus static pressure difference) and drag force (Φ = 45°).

CONCLUSION

The COBble Satellite SYstem is a promising method of obtaining high temporal resolution measurements of the drag

and lift forces acting on loose coarse particles. It offers a first opportunity to verify theoretical concepts using reliable flume and field data on hydrodynamic forces.
The flume experiments investigating the hydrodynamic forces acting on cobbles confirm the resuts of Einstein & El-Samni (1949) that the lift force is far more important than the drag force for the entrainment of bed load. For this reason, the relationship of forces at incipient motion should be studied in detail, with respect to both cobble shape and bed conditions.

Further experiments will be performed to determine individual parameters such as pivoting angle, bed configuration etc. for various particle geometries. The limited data presently available permit the following conclusions:

(a) Lift force and drag force have similar magnitudes (1-20 Newton).
(b) Given a constant increase of slope, the changing forces are best expressed by an exponential function.
(c) In the present tests the drag force increased slightly more than the lift force; the lift/drag ratio tends to decrease.
(d) The position of the test cobble on the flume bed, expressed by the pivoting angle, is of great importance for the onset of erosion.
(e) The experiments using a sphere represent specially selected cases; however, this does not affect the general validity of the results described above.
(f) The lift force can be measured at the point of erosion, which can be exactly determined.

Further data will be available by the start of the symposium.

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REFERENCES

Aksoy, S. (1973) Fluid forces acting on a sphere near boundaries. Proc. 15th Congr. IAHR, no. 1, 217-224.
Bagnold, R. A. (1974) Fluid forces on a body in shear flow: experimental use of "stationary flow". Proc. Roy. Soc., London Ser. A 340, 147-171.
Benedict, B. A. & Christensen, B. A. (1972) Hydrodynamic lift on a stream bed. In: Sedimentation - Symposium to Honor Professor H.A.Einstein (ed. by H.W.Shen) 5-1 - 5-17.
Cheng, E. D. H. & Clyde, C. G. (1972) Instantaneous lift and drag force on large roughness elements in turbulent open channel flow. In: Sedimentation - Symposium to

Honor Professor H.A.Einstein (ed. by H.W.Shen) 3-1 - 3-20.

Coleman, N. L. A. (1967) A theoretical and experimental study of drag and lift forces acting on a sphere resting on a hypothetical stream bed. Proc. 12th Congr. IAHR, Fort Collins, 185-192.

Davies, T. R. H. & Sanad, M. F. A. (1978) Fluid dynamic lift on a bed particle. J. Hydraul. Div.ASCE, 104, HY8, 1171-1182.

Einstein, H. A. & El-Samni, E. A. (1949) Hydrodynamic forces on a rough wall. Review of Modern Physics 21 (3), 520-524.

Ergenzinger, P., Schmidt, K.-H. & Bußkamp, R. (1989) The Pebble Transmitter System (PETSY): first results of a technique for studying coarse material erosion, transport and deposition. Z. Geomorphol. 33, 503-508.

James, C. S. (1990) Prediction of entrainment conditions for nonuniform, noncohesive material. J. Hydraul. Res. 28 (1), 25-41.

Jeffreys, H. (1929) On the transportation of sediment by streams. Proc. Camb. Phil. Soc. 25, 272-276.

Komar, P. D. & Li, Z. (1986) Pivoting analysis of the selective entrainment of sediments by shape and size with application to gravel threshold. Sedimentology 33, 425-436.

Naden, P. S. (1987) An erosion criterion for gravel-bed rivers. Earth Surf. Processes 12, 83-93.

Scheidegger, A. (1991) Theoretical Geomorphology. Springer, Heidelberg, Berlin.

Sumer, B. M. (1984) Lift forces on particles near boundaries. J. Hydraul. Engineering 110 (9), 1272-1278.

Willets, B. B. & Naddeh, K. F. (1986) Measurements on lift on spheres fixed in a low Reynolds number flow. J. Hydraul. Res. 24 (5).