DROPSHAFT CASCADES IN ROMAN AQUEDUCTS

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ABSTRACT

In Roman aqueducts, series of vertical dropshafts (i.e. dropshaft cascade) were used to dissipate the kinetic energy o the flow. Up to recently, it was thought that the dropshafts acted also as sediment traps. A new re-analysis of Roman dropshaft hydraulics was conducted with physical model tests performed at the University of Queensland. The results demonstrate that the vertical dropshafts could be very efficient energy dissipators and re-oxygenation structures, under appropriate flow conditions. The optimum operation of dropshaft is discussed and an analytical model is developed to predict these conditions. In addition, the performances of aqueduct dropshafts are compared with modern dropshaft designs. Dropshaft cascades were used successfully for centuries. The Roman engineers built sound dropshaft designs which were most efficient dissipators and aerators.

Keywords: dropshaft, Roman aqueduct, energy dissipation, flow aeration, engineering heritage, history of hydraulics

INTRODUCTION

The hydraulic expertise of Romans has contributed significantly to the advances of science and engineering in the Antiquity and up to the end of the Middle Age. The aqueducts at Rome, in France and North Africa, for example, left an indelible trace of this savoir-faire (e.g. ASHBY 1925, RAKOB 1974). The aqueduct construction was an enormous task conducted by the army and the cost was gigantic : i.e., around one to three millions sesterces per kilometre in average (e.g. LEVEAU 1991). The duration of the work was a function of the difficulties : i.e., tunnels, bridges, arcades, raised foundation, siphons, cascades. Although the Anio Vetus in Rome was built in 3 years only, it took 14 years to complete both the Anio Novus and Claudia aqueducts, and some provincial projects took longer. Roman aqueducts were designed with flat longitudinal slopes : i.e., 1 to 3 m/km in average typically. Short sections however had a steep-gradient : i.e., up to 78% (CHANSON 1998). Current knowledge and field observations suggest primarily three types of design : steep "smooth" chutes, stepped channel and the dropshaft cascade (Fig. 1). The stepped chute design was common also with dam spillways. The oldest stepped spillway was built around BC 1,300 in Greece (CHANSON 1997) and several stepped chutes were used prior to the Roman era (e.g. CHANSON 1995, pp. 23-37). Roman engineers built several significant stepped spillways : e.g., Kasserine dam, Tunisia AD 100?, Oued Guergour dam, Tunisia AD 100?, Qasr Khubbaz, Syria AD 100-200. There is however little information on the hydraulic performances of dropshaft cascades in aqueducts. In the paper, the hydraulics of Roman dropshafts is investigated using both physical and analytical models. The results provide new understanding of the dropshaft cascade operation. The performances are also compared with modern designs.

APPLICATIONS

Roman engineers built two types of dropshafts : dropshaft cascades along the main branch of aqueducts, in France and Algeria predominantly, and interconnection shafts from newer higher channels to older aqueducts (e.g. at Rome). The latter had a specific purpose (i.e. water redistribution) and their design was a concourse of circumstances (i.e. proximity of an older aqueduct) rather than a specific engineering feature of the newer aqueduct. Dropshaft cascades were used in steep topography predominantly : e.g., Recret, Vaugneray and Grézieu-la-Varenne, Yzeron aqueduct (Lyon, Fr.), Montjeu, Autun aqueduct (Fr.). Sometimes, combination of steep chutes and dropshaft were used : e.g., Chabet Ilelouine, Cherchell aqueduct (Alg.), Beaulieu aqueduct (Aix-en-P, Fr.). It is commonly accepted that dropshafts were built for energy dissipation purposes, and suggestions were brought forward that they were used for sediment trapping (Conseil Général du Rhône 1991, GAUCKLER 1902). From a sole hydraulic perspective, Roman dropshafts might have been used for : (1) a vertical drop in invert elevation, (2) kinetic energy dissipation, and (3) flow aeration. The sediment trapping function could NOT work, unless with very heavy particles that would damage the conduit mortar ! In the first application, a dropshaft allows the connection between two flat conduits, located at different elevations, along a very short distance : i.e., the shaft length. By contrast, a steep chute would require a horizontal distance equals to the drop height times the bed slope. The second application of dropshaft is the dissipation of the kinetic energy of the flow. Such a design is still used today (e.g. APELT 1984). It must however be optimised as a function of the drop height, shaft geometry and flow rate. With non-optimum flow conditions, scour and erosion may take place, and these are unacceptable. A third application is the aeration of the flow : e.g., re-oxygenation. Recent investigations of air bubble entrainment at vertical rectangular dropshaft highlighted the large rate of bubble entrainment in the shaft pool (e.g. ERVINE and AHMED 1982).

HYDRAULICS OF ROMAN DROPSHAFT

EXPERIMENTAL STUDY

A dropshaft model was built in the Hydraulics Laboratory at the University of Queensland, as basically a 1/4-th model of the Recret dropshafts on the Yzeron aqueduct. The model was a vertical square dropshaft ($B = L = 0.3$ m, $h/L = 1.68$, $P/h = 0.72$) (Fig. 2, Table 1). The upstream channel was uncovered while the downstream conduit was 0.15-m wide, 0.25-m high, 0.512-m long and ended with a free overfall. The discharge was deduced from the brink depth measurements, which were first calibrated with volume-per-time discharge data. Free-surface elevations were recorded with pointer gauges in the upstream and downstream channels, while the free-surface height in the dropshaft, being very-turbulent, was measured with rulers. The downstream head was measured with a total head tube ($\varnothing = 1$ mm). Full details of the experimental setup and data are presented in CHANSON (1998).

BASIC FLOW PATTERNS

Several flow patterns were observed, as functions of the flow rate. At low flow rates (i.e. $d_c/L \le 0.15$), the free-falling nappe impacts into the shaft pool (regime R1, Fig. 2). Substantial air bubble entrainment takes place and the entrained air bubbles occupy most of the dropshaft pool. For larger discharges (i.e. $0.15 \le d_c/L \le 0.30$), the upper nappe of the free-falling jet impacts into the downstream channel, flowing in between the inlet invert and obvert (regime R2). The pool free-surface level increases significantly, and lesser air bubble entrainment is observed in the pool. At large flow rates (i.e. $0.30 \le d_c/L \le 0.40$), the free-jet impacts onto the opposite wall, above the downstream conduit obvert (regime R3). The pool free-surface rises up to the downstream channel obvert and the water level (in the pool) fluctuates considerably. Significant water deflections take place in the shaft. During the present study, the impact angle of the nappe onto the wall was too shallow to produce a formed roller as observed by RAJARATNAM et al. (1997). For all the experiments, the flow in the downstream conduit was found to leave the dropshaft as a supercritical open channel flow. A similar observation was noted by RAJARATNAM et al. (1997).

HYDRAULIC PERFORMANCES OF ROMAN DROPSHAFTS

Pool free-surface height data are reported in Figure 3(A) where y_p is the free-surface height above downstream invert (Fig. 2). The observed flow regimes are clearly marked : i.e., R1, R2 and R3. The pool height rises with increasing discharges up to about $y_p/D \sim 1.2$, then remains stable with larger flow rates, until it rises again for $Q' \ge 1.2$, where $Q' = Q/\sqrt{g*b^2*D^3}$ and $Q' = Q/\sqrt{g*p^2*D^5/16}$ for rectangular and circular conduits respectively. The results are consistent with the observations of APELT (1984) and RAJARATNAM et al. (1997) (Table 1).

The dimensionless bubble penetration depth is plotted in Figure 3(B) as a function of the dimensionless flow rate d_c/h. In flow regimes R1 and R3, substantial flow aeration takes place in the shaft : the bubble cloud occupies more than half of the shaft pool volume. The entrained bubbles enhance the air-water interface area and the air-water gas transfer : i.e., re-aeration (e.g. re-oxygenation), nitrogen removal and removal of volatile organic compounds (e.g. chlorine). The flow regime R2 is less efficient in entraining air because the nappe impact interacts with the downstream conduit inlet, and the entrained bubbles do not have enough downward momentum to reach the shaft bottom. Residual energy data are presented in Figure 3(C). The results are compared with the data of RAJARATNAM et al. (1997) (Table 1). Low residual heads are associated with efficient energy dissipators and Figure 3(C) demonstrates the poor dissipation performances of regime R2. The best rates of energy dissipation, associated with the lowest residual heads, are achieved for $d_c/L < 0.15$ (for $h/L = 1.683$). Further comparison with drop structures and vortex shafts suggest that Roman dropshafts operating at low flow rates (i.e. flow regime R1) were most efficient energy dissipators, by modern standards (CHANSON 1998).

DISCUSSION

SHAPE & DESIGN

Compared with modern designs, Roman dropshafts exhibited unusual shapes : i.e., a deep wide shaft pool. Modern dropshafts do not include a pool, the shaft bottom being at the same elevation as the downstream channel bed, to minimise construction costs. At Roman aqueducts, the pool of water acted as a cushion at the nappe impact, and the disposition contributed to prevent scour of the shaft bottom. The shaft pool facilitated further the entrainment (by plunging jet) of air bubbles deep down, maximising the bubble residence time and hence the air-water gas transfer. The design contributed successfully to an enhancement of the DO content (dissolved oxygen content). The Roman dropshafts were designed with a wide shaft : i.e., the ratio B/b was greater than 2. By comparison, modern dropshafts are designed with a ratio B/b typically unity or not greater than 1.5. Additionally, the dimensionless drop height h/L is today larger than that at Roman structures. It is believed that the wider design of aqueduct shaft was unnecessary from a hydraulic perspective but it might have been selected for an easier construction. Two dropshaft shapes were used : rectangular at Vaugneray, Recret en bas and Puit Gouttenoire (Yzeron, Fr.), and circular at Cherchell (Alg.), Gunudu (Alg.) and Rusicade (Alg.). It is possible that the latter shape was a design evolution. However the circular design involved a construction technique well known and used by the Romans : i.e., artesian wells, wells used to collect streams for aqueduct supply and to harness springs (e.g. Beaulieu).

OPERATION OF ROMAN DROPSHAFT

The experimental investigation has highlighted that the best dropshaft performances, in terms of energy dissipation and flow aeration, were achieved with a flow regime R1. The study shows also that the flow regime R2 was associated with high risks of scour and erosion at the lower conduit inlet and obvert, and it was unsuitable for the dropshaft operation. Roman aqueducts had to be designed for a flow regime R1 for long-lasting operation. Based on analytical calculations of the nappe trajectory and impact conditions, the optimum operation of well-documented dropshafts was investigated (CHANSON 1998). In the particular case of dropshafts operating with subcritical inflow, optimum flow conditions must satisfy :

$$Q < 0.1292 * \sqrt{g} * b * \frac{L^3}{h^{3/2}} \qquad \text{Regime R1} \quad (1)$$

where b is the dropshaft inflow width, L is the shaft length and h is the invert drop (Fig. 2) (CHANSON 1998). For dropshafts operating with supercritical inflow, the inflow conditions must satisfy :

$$\frac{V_b}{\sqrt{g * L}} < \frac{1}{2} * \frac{h}{L} * \left(\sqrt{8 * \frac{L}{h} + \frac{Q^2}{g * b^2 * h^2 * L}} - \frac{Q}{\sqrt{g * b^2 * h^2 * L}} \right) \qquad \text{Regime R1} \quad (2)$$

where V_b is the inflow velocity.

At Chabet Ilelouine (Cherchell aqueduct, Alg.), only flow rates less than 6,600 m^3/day could provide optimum performances (i.e. regime R1). This result challenges the accepted discharge of 40,000 m^3/s (LEVEAU and PAILLET 1976). For the Yzeron aqueduct (Lyon, Fr.), optimum operation (i.e. regime R1) was achieved for flow rates up to 7,500 m^3/day in the Recret section (i.e. main branch) and 22,000 m^3/day in the Vaugneray branch. It is reasonable however to assume that the Vaugneray branch could not receive more than 5,000 m^3/day. These figures are consistent with an overall discharge of 10,000 to 13,000 m^3/day in the Yzeron aqueduct (Conseil Général du Rhône 1991).

CONCLUSION

Roman engineers built dams, spillways and hydraulic structures all around the Mediterranean sea. Despite recent progresses, there is still little information on the hydraulic design of aqueducts and dropshaft cascades. Roman dropshaft hydraulics was investigated on a 1/4-th laboratory model of a Recret shaft. The results are compared with an analytical model. Three flow regimes were observed. Optimum dropshaft operation occurred for the flow regime R1, characterised by low flows and nappe impact into the shaft pool. In flow regime R1, the dropshaft design was most efficient in terms of energy dissipation and air bubble entrainment, in particular compared to modern designs. History shows also that such a flow regime operated for centuries and required (likely) little maintenance. The issues of re-aeration should also be considered. Most aqueducts were covered along their entire length, limiting the gas transfer at the free-surface and the downstream waters were low in dissolved oxygen (DO) content, unless re-oxygenation devices were installed. The writer suggests that dropshafts might have been introduced, in place of steep chutes, to enhance the water quality and to re-oxygenate the water.

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Table 1 - Experimental studies of vertical dropshafts

Study (1)	Upstream conduit (2)	Shaft (3)	Downstream conduit (4)	Flow conditions (5)	Remarks (6)
Present Study	Rectangular b = 0.144 m	Square B = L = 0.30 m h = 0.505 m P = 0.365 m	Rectangular b = 0.15 m D = 0.25 m	$0.0002 \le Q \le 0.018$ m^3/s	Open upstream conduit. Roman aqueduct dropshaft model.
APELT (1984)	Circular ∅ = 0.152 m	Square B = L = 0.152 m h = 0.325 m, P=0	Circular ∅ = 0.152 m	$0.0022 \le Q \le 0.026$ m^3/s	Energy dissipation downstream of culverts.
	Circular ∅ = 0.152 m	Square B = L = 0.203 m h = 0.325 m, P=0	Circular ∅ = 0.152 m	$0.0022 \le Q \le 0.026$ m^3/s	
RAJARATNAM et al. (1997)	Circular ∅ = 0.154 m	Vertical plate L = 0.5 m, h = 2.9 m	N/A	$Q \le 0.042$ m^3/s	Series 3. Sewer dropshaft models.
	Circular ∅ = 0.154 m	Circular ∅ = 0.29 m h = 2.11 m, P=0	Circular ∅ = 0.29 m	$0.0021 \le Q \le 0.042$ m^3/s	Series 4.
	Circular ∅ = 0.154 m	Circular ∅ = 0.29 m h = 2.11 m, P=0	Circular ∅ = 0.29 m	$0.0021 \le Q \le 0.042$ m^3/s	Series 5. Curved inlet radius.
	Circular ∅ = 0.154 m	Circular ∅ = 0.152 m, P=0	Circular ∅ = 0.152 m	$0.0021 \le Q \le 0.042$ m^3/s	Series 6. Curved inlet radius.

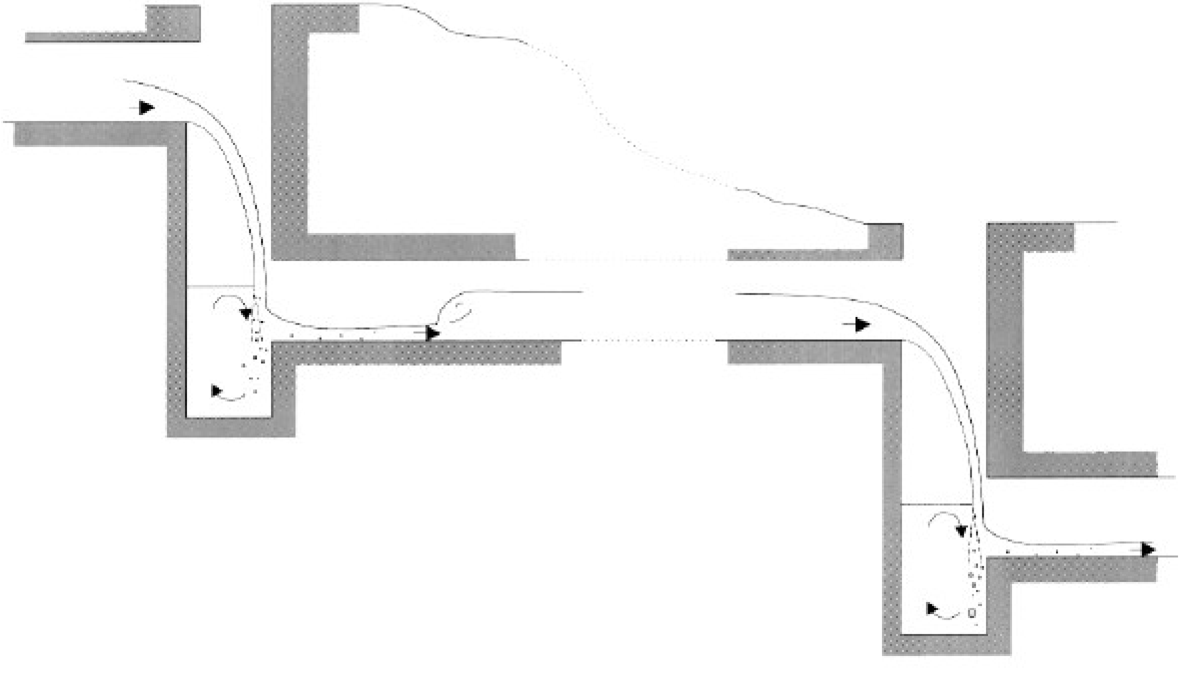

Figure 1 - Dropshaft cascade in Roman aqueduct

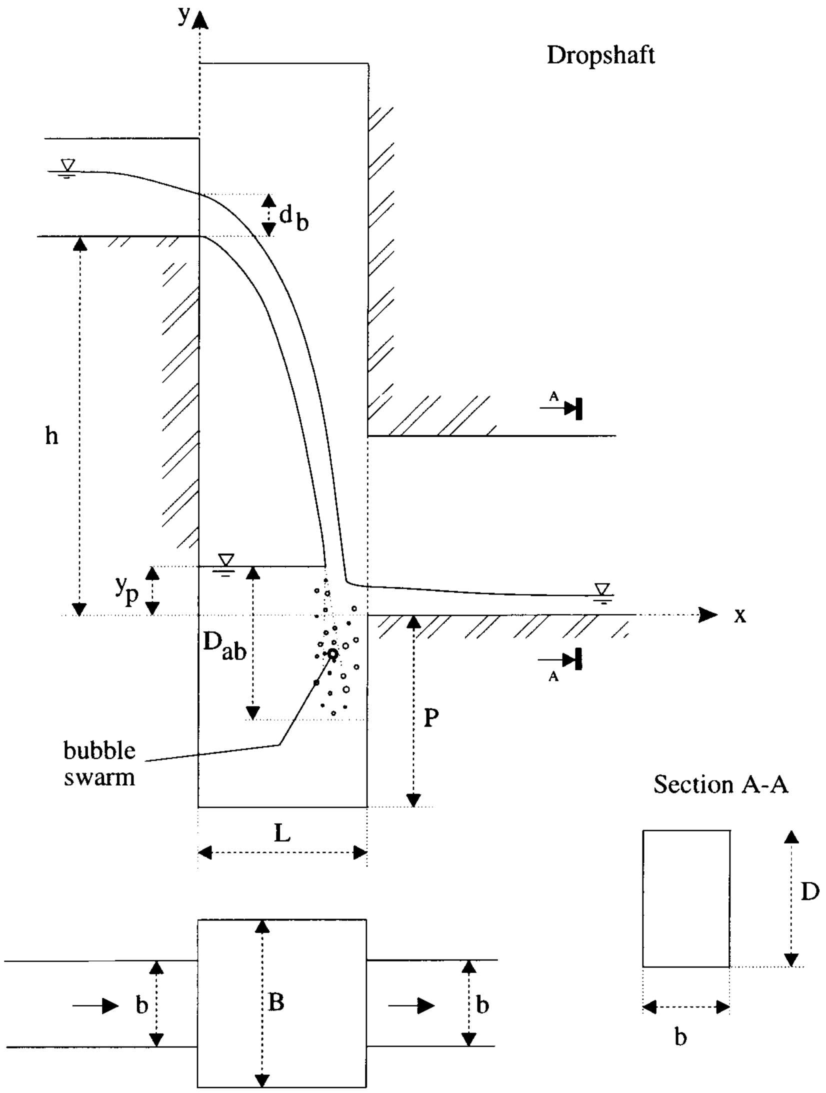

Figure 2 - Dropshaft operation in regime R1 : sketch and notation

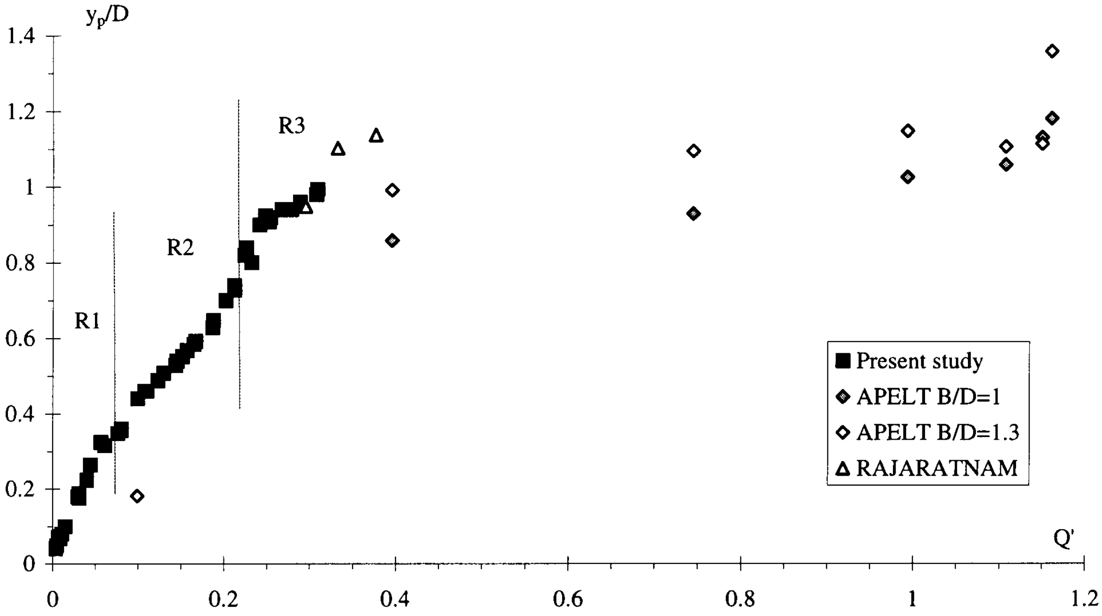

Fig. 3 - Hydraulic performances of the dropshaft model
(A) Dimensionless shaft pool free-surface height y_p/D

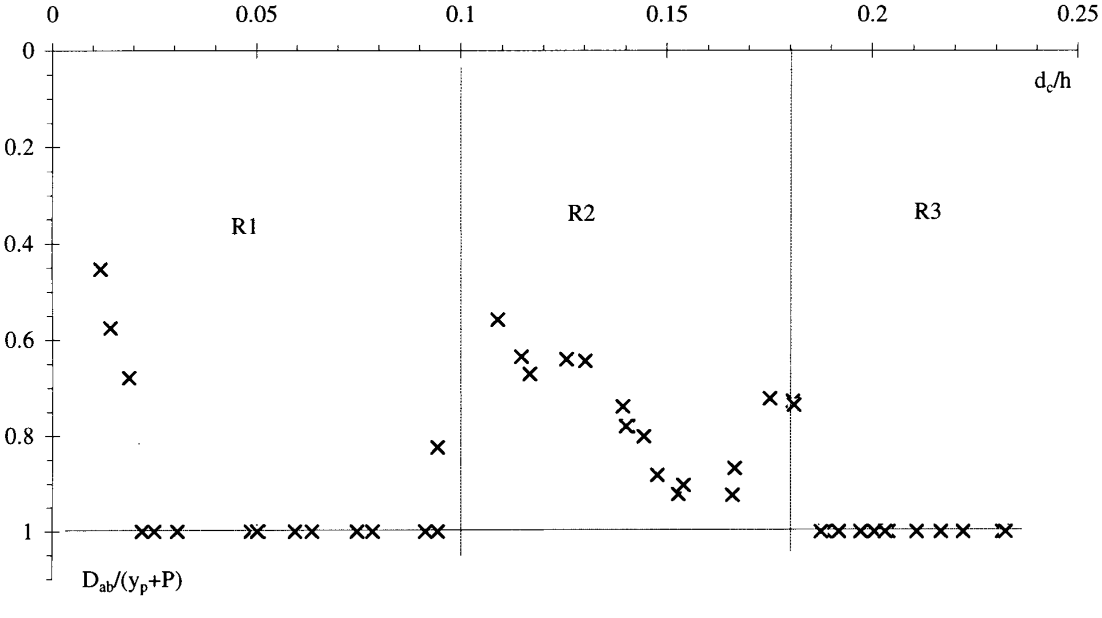

Fig. 3 - Hydraulic performances of the dropshaft model
(B) Dimensionless bubble swarm depth $D_{ab}/(y_p+P)$

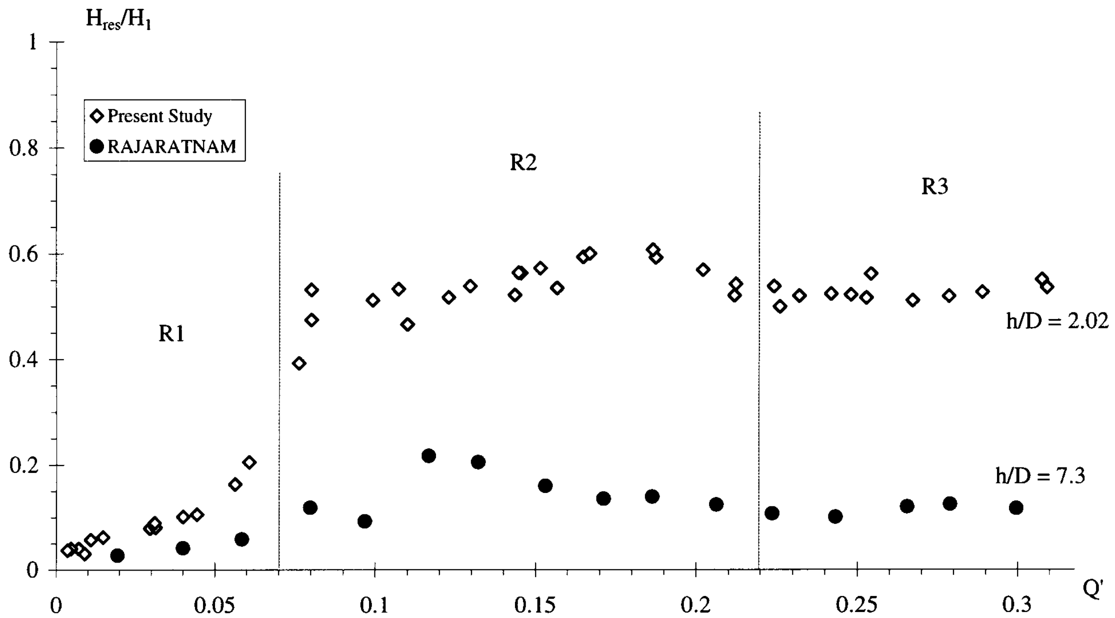

Fig. 3 - Hydraulic performances of the dropshaft model

(C) Dimensionless residual head H_{res}/H_1 as a function of the dimensionless flow rate

$$Q' = Q/\sqrt{g*b^2*D^3}$$