Hydraulic ram analysis
Analyse du bélier hydraulique

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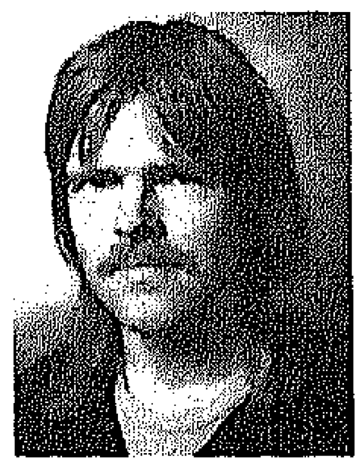

SUMMARY
A simple mathematical model describing the operation of a hydraulic ram is presented. Predictions of the model are compared with measurements done in an earlier stage of the project. The model is used to perform a parameter variation study.

RÉSUMÉ
Un modèle mathématique simple représentant le fonctionnement du bélier hydraulique est présenté. Les resultats de ce modèle sont comparés avec des mesures expérimentales obtenues à la première phase du projet. Ce modèle est destiné à l'étude de la variation des paramètres.

1 Introduction

Increasing interest in the performance characteristics of hydraulic rams made clear that there is a lack of simulation skills. Recently a computer model has been developed to investigate the effects of parameter variations. Such parameter variations are desired for a better understanding of the phenomena involved and for design purposes.

Hydraulic rams are self-operating water raising machines, which utilize the energy available in a flow of water to lift a portion of that water to a higher level. The components of a hydraulic ram installation (Fig. 1) are: supply reservoir - drive pipe - the ram itself - delivery pipe - storage tank. The ram itself consists mainly of a pump chamber with only two simple valves: waste valve (or impulse valve) and delivery valve.

The hydraulic ram operates on a flow of water falling under a supply head H_s from the supply reservoir down through the drive pipe and through the pump chamber (Fig. 1). This accelerating flow of water abruptly closes the waste valve when its velocity reaches a critical value (V_c) at which the dynamic drag on the valve exceeds a critical value. As a result the velocity is abruptly forced to decrease and a pressure wave is generated. The abruptly increased pressure opens the delivery valve and due to the high pressure the water is flowing into the surge tank with air cushion (in which the pressure is almost constant $P_d = \varrho g H_d$). During the retardation phase pressure waves propagates in upstream and downstream direction through the drive pipe cause a stepwise reduction of the flow velocity. After a short time (e.g. six times the length of the drive pipe over the wave celerity: $6L/c$) the momentum of the entire column of water in the drive pipe is exhausted and the velocity at the downstream end of the drive pipe is so low, that the delivery valve will be closed and (with a small back flow) the waste valve will be opened (almost instan-

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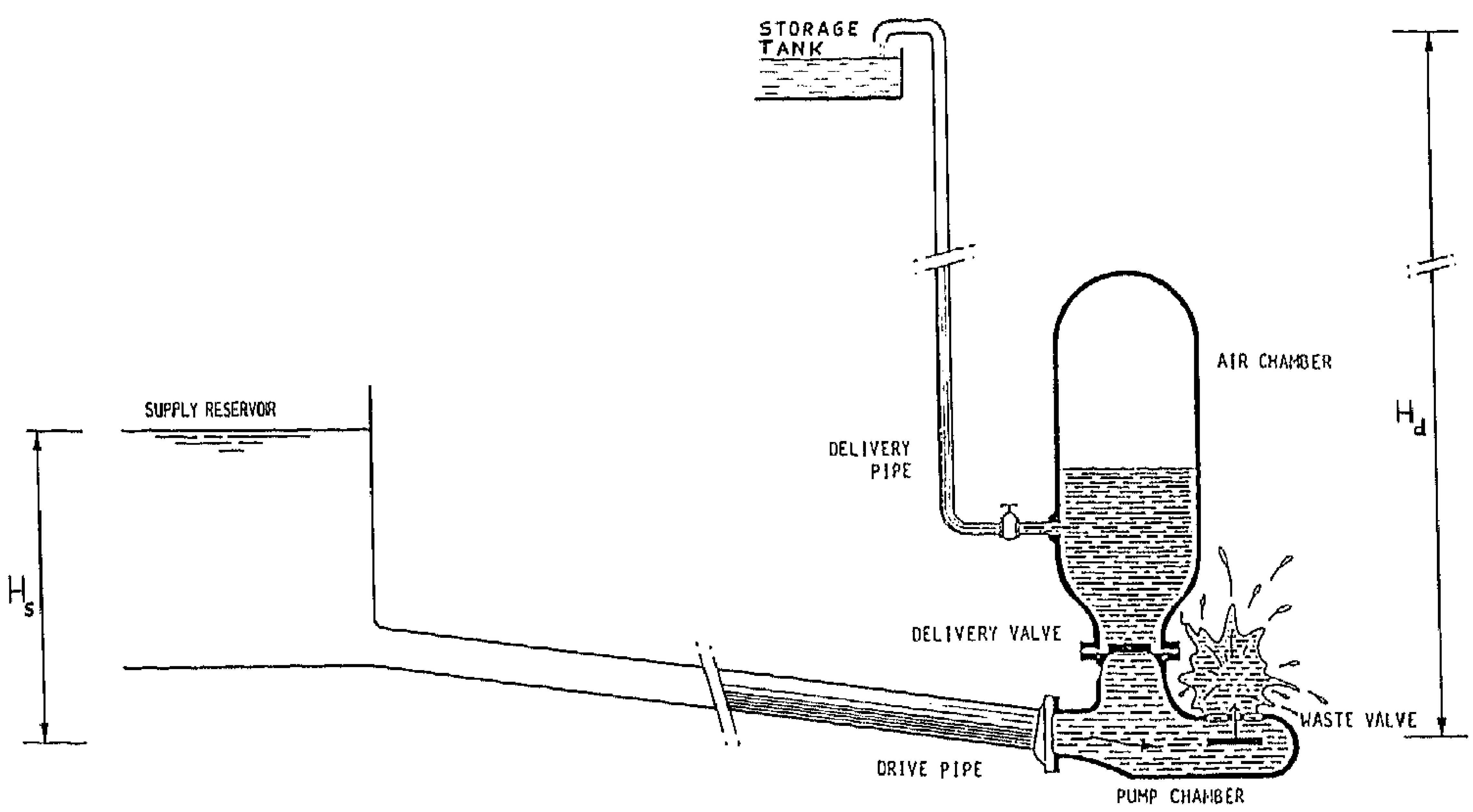

Fig. 1. Hydraulic ram installation.
L'installation du bélier hydraulique.

taneously). Due to the supply head H_s the column of water in the drive pipe is accelerating again after which the process repeats itself. A more detailed description can be found in [1], [2] and [3]. The division of this article is as follows. In section 2 most attention is paid to the numerical simulation by means of a model which was developed in 1989 using existing software [4] and to some details of the mode of operation in relation with boundary conditions. In section 4 the numerical results are compared with the experimental results described in section 3. Section 5 finally gives two examples of parameter variation.

2 Hydraulic ram simulation

2.1 *Hydraulic ram model*

The operation of the hydraulic ram system is simulated using standard waterhammer theory [5]. The hydraulic ram is modelled as a three-position apparatus: in position 1 the waste valve is open and the delivery valve is closed, in position 2 the delivery valve is open and the waste valve is closed, and in position 3 both valves are closed. Starting from an initial situation in which both waste and delivery valve are closed (position 3), so that the fluid is at rest, the hydraulic ram is put in position 1. The waste valve is open now and pressure waves are travelling up and down the drive pipe, stepwise increasing the velocity of the fluid. When the velocity of the fluid reaches a critical value, V_c, the hydraulic ram switches instantaneously from position 1 to position 2. In this position severe pressure waves bring the fluid almost to rest in a relatively short time. Once the velocity of the fluid becomes less than zero (back flow), the hydraulic ram switches to position 1 again and the whole cycle repeats. Fig. 2 shows a typical cycle for the fluid velocity near the ram. The propagation of the pressure waves in the drive pipe, here described one-dimensionally, is governed by the continuity and momentum equation, together known as the waterhammer equations:

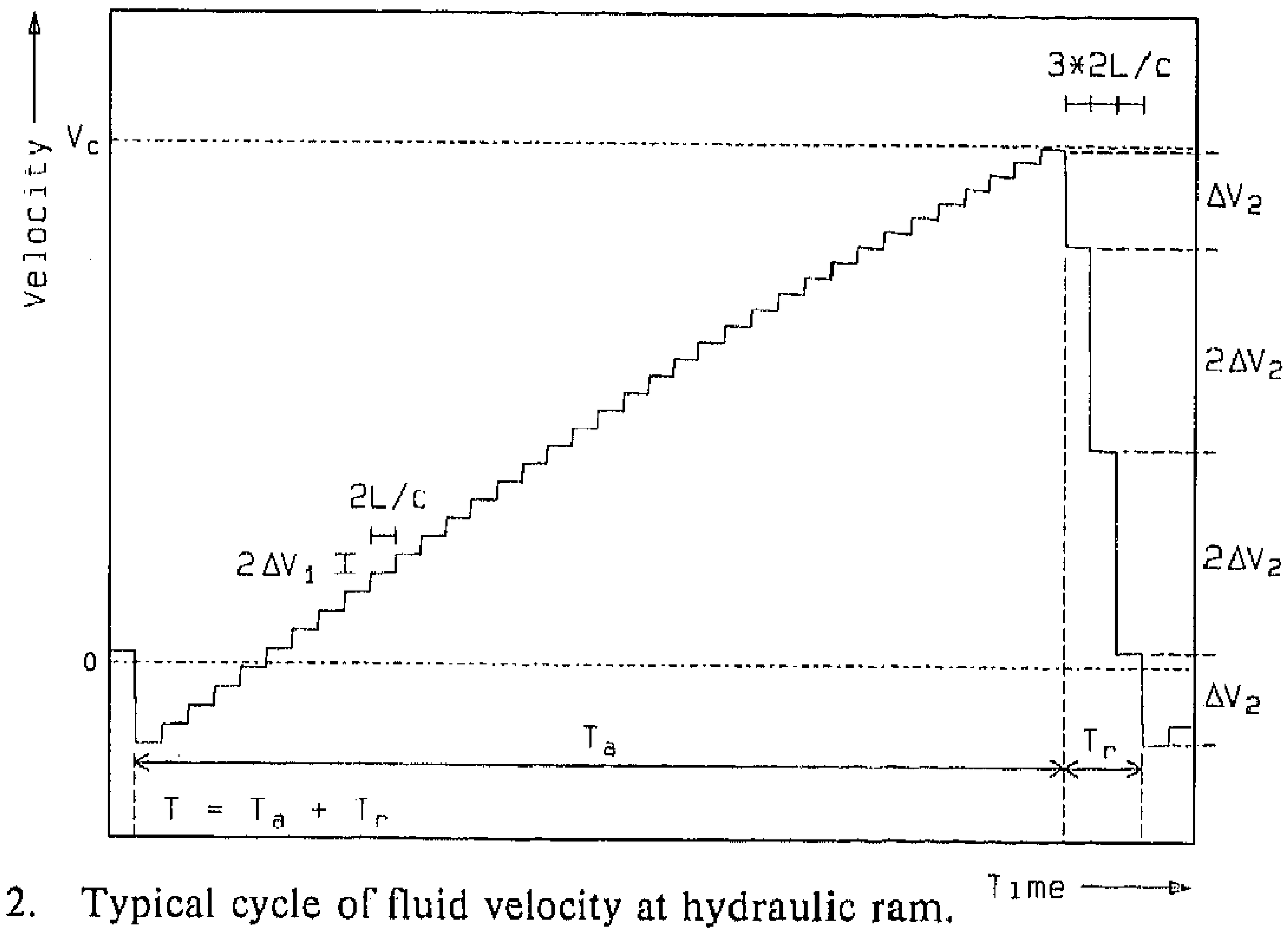

Fig. 2. Typical cycle of fluid velocity at hydraulic ram.
Un cycle typique des vitesses du fluide tout près du bélier hydraulique.

$$\frac{\partial V}{\partial x} + \frac{g}{c^2}\frac{\partial H}{\partial t} = 0 \tag{1}$$

$$\frac{\partial V}{\partial t} + g\frac{\partial H}{\partial x} = -\frac{f}{2D} V|V| \tag{2}$$

in which the pressure wave speed c is given by:

$$c = \frac{1}{\sqrt{\left(\frac{\varrho}{K} + \frac{D\varrho}{eE}\right)}} \tag{3}$$

The mathematical description of the problem is completed by initial and boundary conditions. As initial condition is taken fluid at rest:

$$V = 0 \tag{4a}$$

$$H = H_s \tag{4b}$$

The upstream boundary condition represents the constant head of the supply reservoir:

$$H = H_s \tag{5}$$

The hydraulic ram is modelled as a downstream boundary condition in the drive pipe:

$$\textit{position 1}: \; H = 0 \tag{6a}$$

$$\textit{position 2}: \; H = H_d \tag{6b}$$

$$\textit{position 3}: \; V = 0 \tag{6c}$$

plus "switch conditions" depending on the characteristics of the valves.
When the hydraulic ram is put in position 1, there suddenly exists a pressure head difference H_s over the fluid column in the drive pipe. The fluid column begins to accelerate. The acceleration is

brought about by pressure waves increasing the fluid velocity by an amount ΔV_1 every time that they reflect at the upstream or downstream boundary. See Fig. 2.
When the hydraulic ram is switched to position 2, there instantaneously exists a pressure head difference $H_s - H_d$ over the fluid column in the drive pipe. Severe pressure waves retard the fluid column, by decreasing the fluid velocity by an amount ΔV_2 every time that they reflect at a boundary. See again Fig. 2.
If friction is disregarded, the values of ΔV_1 and ΔV_2 are given by the Joukowsky formula [6]:

$$\Delta V_1 = \frac{g}{c} H_s \tag{7a}$$

$$\Delta V_2 = \frac{g}{c} (H_s - H_d) \tag{7b}$$

A complication occurs when in the last but one $2L/c$ seconds of the retardation phase, the fluid velocity at the ram is smaller than $2\Delta V_2$. In this special case, shown in Fig. 3, the last but one pressure wave in the retardation phase closes the delivery valve, but there is no back flow to open the waste valve. Both waste and delivery valve are closed now (position 3). The hydraulic ram remains in this position for $2L/c$ seconds, before it switches to position 1.

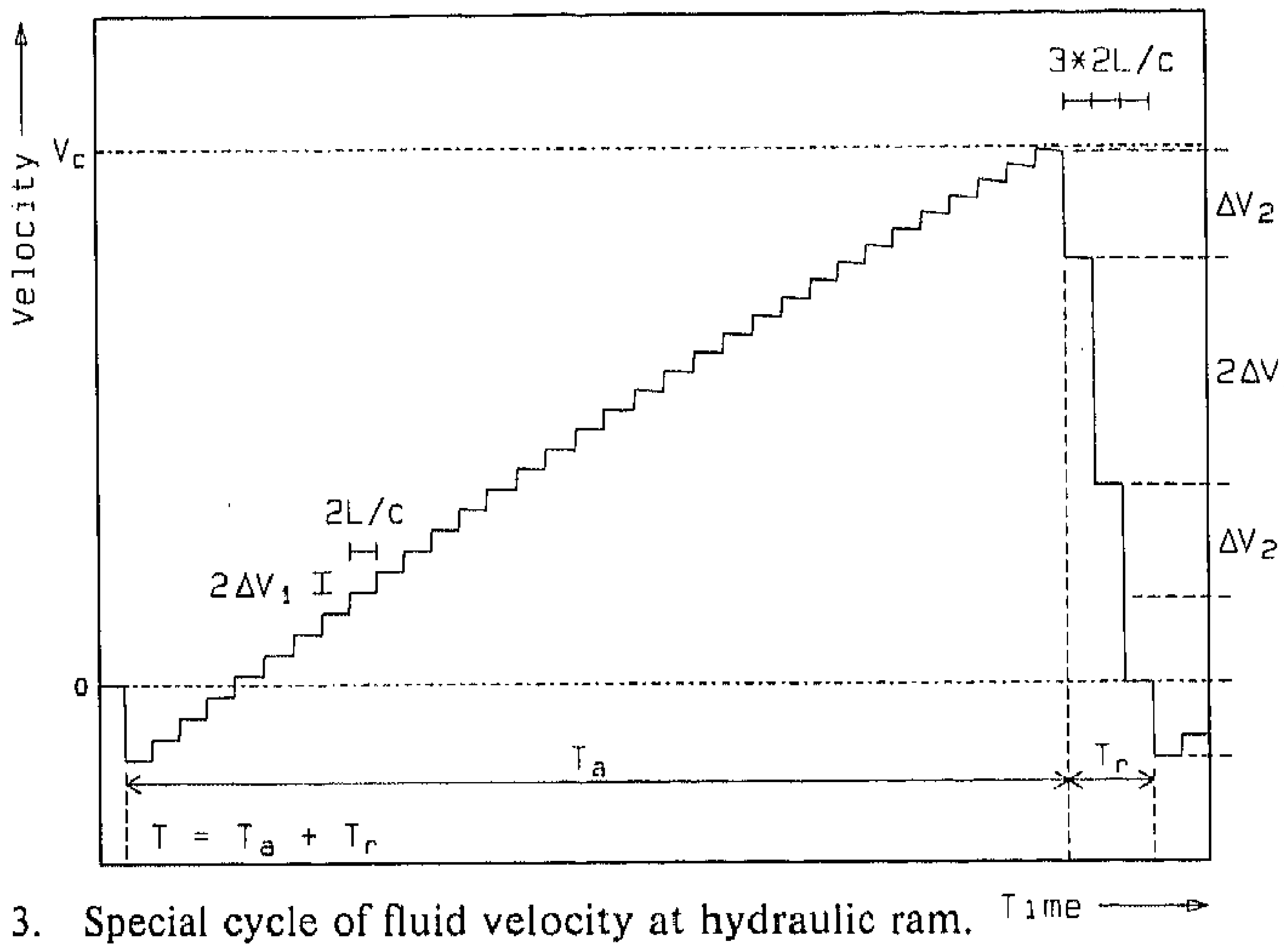

Fig. 3. Special cycle of fluid velocity at hydraulic ram.
Un cycle spécial des vitesses du fluide tout près du bélier hydraulique.

The waterhammer equations (1) and (2), together with the initial and boundary conditions (4)-(7), are solved by the method of characteristics. For this purpose the computer code FLUSTRIN was available.

2.2 *Computer program FLUSTRIN*

The computer program FLUSTRIN has been developed at Delft Hydraulics during a three phase research project on waterhammer with fluid-structure interaction [7]. Fluid-structure interaction refers to the interaction between pressure waves (waterhammer) and movement (vibration) of the fluid-transporting pipe system. During phase 1 of the project a prototype computer code has been used to study fluid-structure interaction phenomena in a single straight pipe [4]. This particular code has been extended in order to simulate the operation of a hydraulic ram. For the sake of simplicity fluid-structure interaction mechanisms are not taken into account in this article.

3 Some results of previous experiments

A large number of experimental results is described in detail in the publication "Hydraulic rams - a comparative investigation" [2]. From this publication the results of one particular ram working in one specific situation are chosen to be compared with the results of the numerical simulation. Details are discussed in chapter 4 but some headlines of the measurements are given here.
A graph of the ram system drawn in Fig. 4 shows the location of the four pressure transducers (1–4): one (4) is mounted in the surge tank and three (1–3) are mounted flush into the pipe wall of the drive pipe (downstream, in the middle and upstream close to the supply reservoir). The quartz pressure transducers (acceleration compensated and designed by "Kistler Instrumente AG, CH-8408 Winterthur/Switzerland") Kistler Type 7031 and the charge amplifiers Kistler Type 5006 have a typical accuracy of about 4%. The cut-off frequency is 80 kHz and only a bandwidth of about 1 kHz has been used. After filtering the charge amplifier signal a small damping with a delay time of only 0.2 ms (at 1 kHz) has been reached.

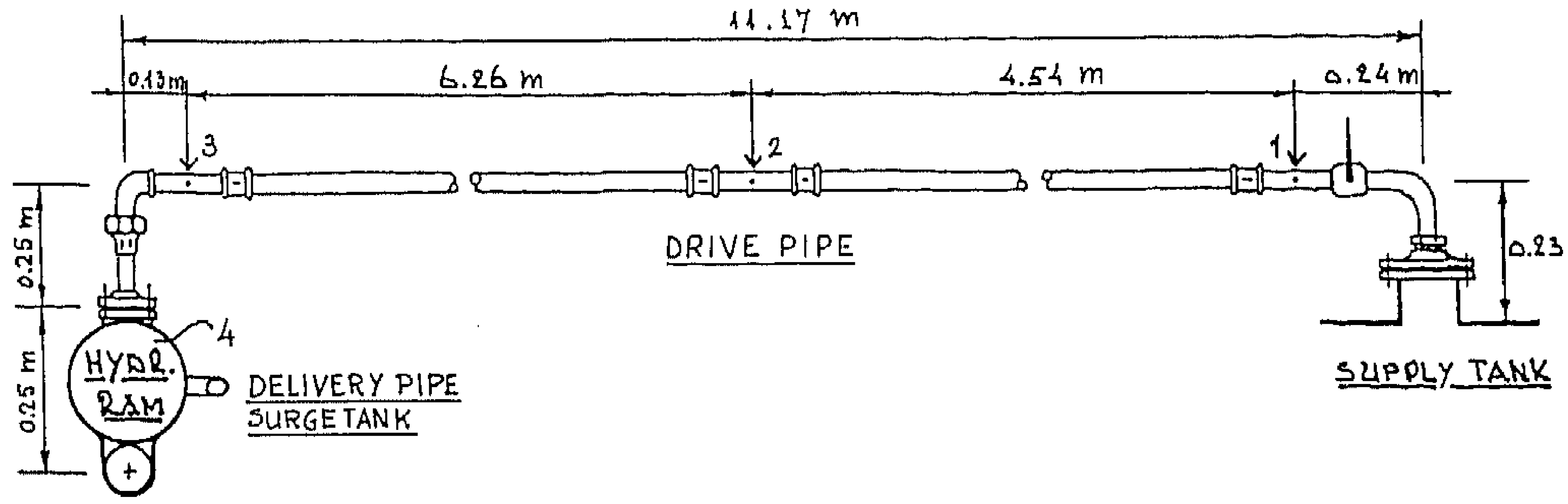

Fig. 4. Schematic of test rig.
Schéma de l'installation d'essai.

The pressures $P(t)$ at points 1, 2, 3 and 4 were measured as gauge pressure relative to atmospheric pressure. The recordings are converted into pressure heads $H(t) = P(t)/(\varrho g) + h$, relative to datum $h = 0$ m at the level of the downstream end of the drive pipe. Pressure head recordings at points 3 and 4 are discussed here, whereas pressure head recordings at points 1, 2 and 3 are shown in section 4, together with predicted pressure heads.
Fig. 5 shows the pressure head variation versus time at the end of the drive pipe just upstream the waste valve and the delivery valve (point 3, see Fig. 1 and Fig. 4). The cycle period (T) is about 0.70 s. The opening and closing of the valves is observed to be almost instantaneous (within 1 ms). The duration (T_a) of the acceleration phase is about 0.64 s and the duration (T_r) of the retardation phase is about 0.05 s. In the specific situation considered here, one surge travels up and down the drive pipe (length L) in a time of 17.6 ms (see also Fig. 6). With $L = 11.9$ m and $2L/c = 17.6$ ms the wave speed c is 1352 m/s.

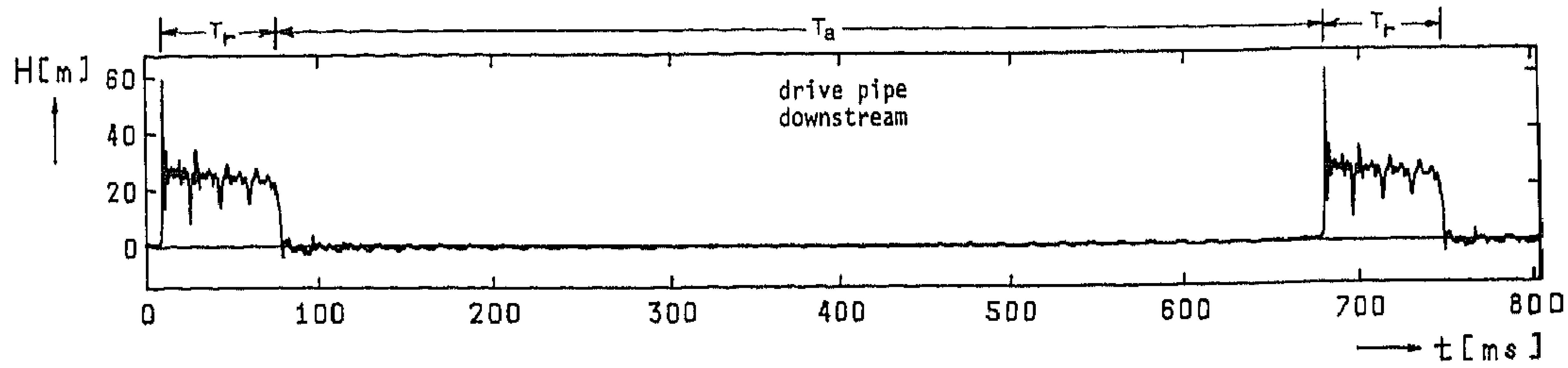

Fig. 5. Measured pressure head close to hydraulic ram.
Hauteur de pression mesurée près du bélier hydraulique.

Fig. 6 gives the pressure head variation during the retardation phase (in point 3). In this phase three surges travel up and down the drive pipe. However, depending on ram installation characteristics (H_s, H_d, ...) the number (N_r) of surges can be 1, 2, 3, 4, 5, ... (see [2]).
Fig. 7 shows the measured pressure head variation in the delivery tank (point 4) in some detail during the retardation phase (delivery valve open). The time scale of Fig. 6, showing the head in point 3, agrees with that of Fig. 7. This figure proves the delivery head to be almost constant in time if the pressure fluctuations with high frequency caused by the opening and closing of the delivery valve are ignored.

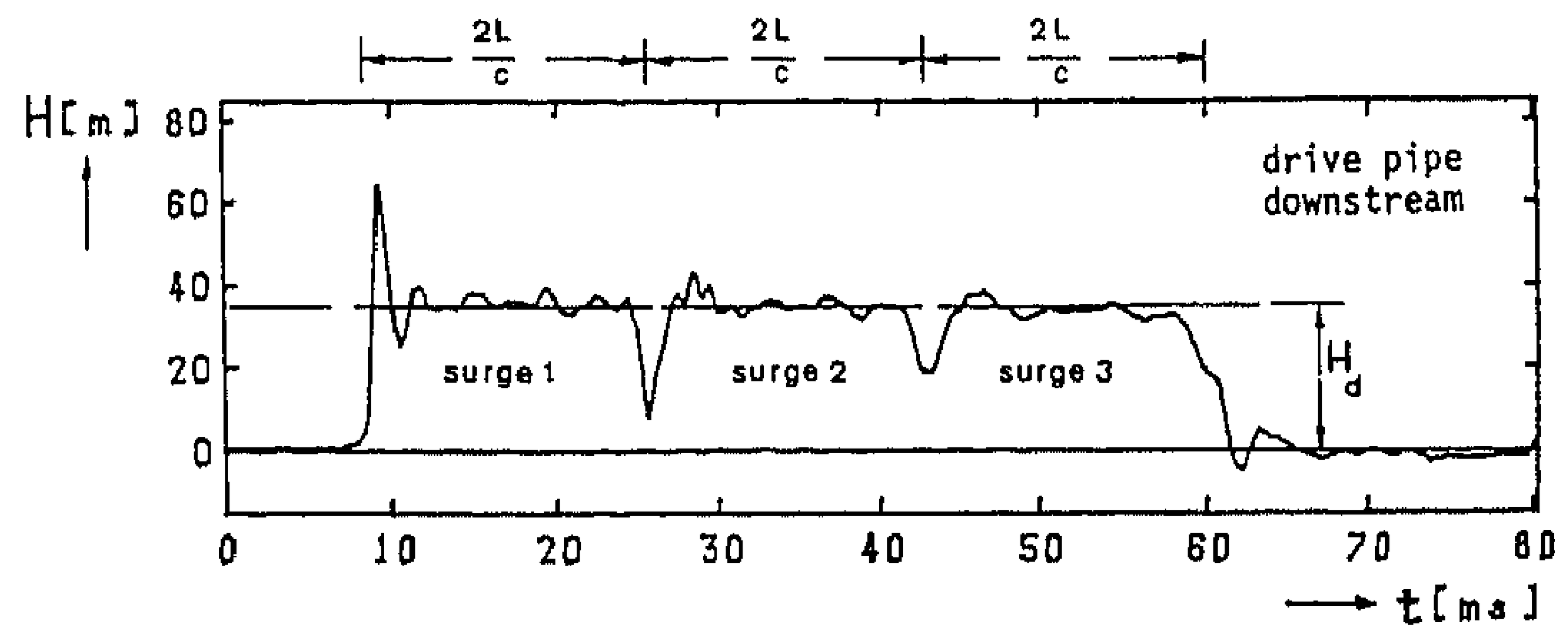

Fig. 6. Measured pressure head close to hydraulic ram during retardation period.
Hauteur de pression mesurée près du bélier hydraulique durant la période de retard.

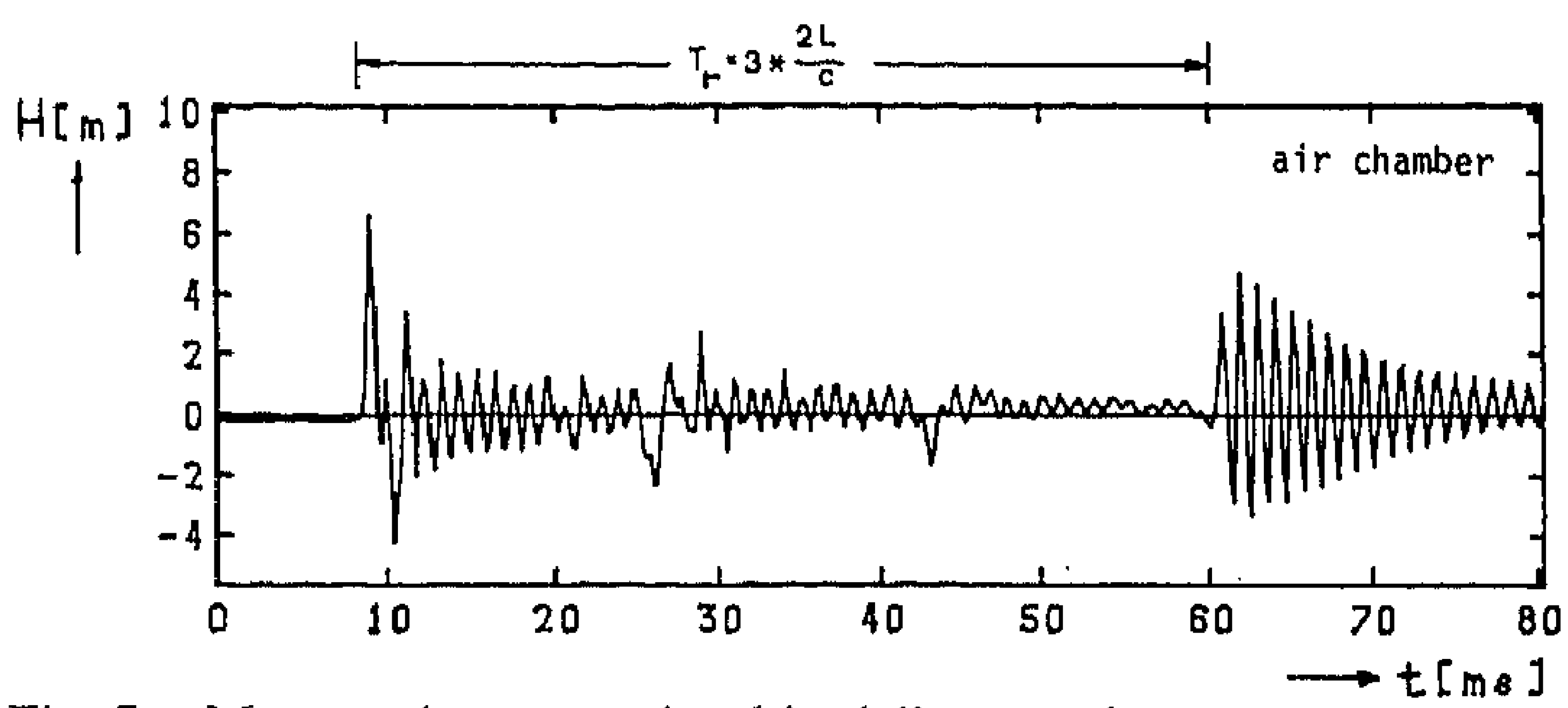

Fig. 7. Measured pressure head in delivery tank.
Hauteur de pression mesurée dans le réservoir de refoulement.

With these three figures part of the ram operation is visualized, more details are discussed in the next section.

4 Comparison measurements are calculations

In order to validate the mathematical model described in section 2.1, a representative experiment from Tacke's comprehensive work on hydraulic rams [2] is chosen for further investigation. The experimental results as shown in [2] on p. 88 will be compared with calculated results. For this purpose the experiment was simulated with the following data ([2], p. 36, p. 73):

$$\begin{array}{ll} H_s = 3 \text{ m} & \varrho = 1000 \text{ kg/m}^3 \\ H_d = 35 \text{ m} & K = 2.15 * 10^9 \text{ N/m}^2 \\ V_c = 1.2 \text{ m/s} & E = 2.10 * 10^{11} \text{ N/m}^2 \\ L = 11.9 \text{ m} & f = 0.03 \\ D = 0.038 \text{ m} & g = 9.813 \text{ m/s}^2 \\ e = 0.0035 \text{ m} & \end{array} \quad (8)$$

From these data the pressure wave speed is calculated as $c = 1391$ m/s by means of formula (3), which compares reasonably well with a measured wave speed of 1352 m/s. (The wave speed was measured by counting from Fig. 9 the number (N_a) of pressure waves during one period of acceleration: $c = N_a * 2L/T_a$). Simulations, using data (8), predict a too short duration (T_a) of the acceleration phase, in comparison with the experiment. By using the measured value $c = 1352$ m/s in the calculations, and furthermore a friction factor $f = 0.04$, T_a in simulation and experiment agree, and it is these results that are shown in the next figures. A parameter variation study with respect to c and f can be found in section 5.
Tacke measured pressures at three locations along the 11.9 m long drive pipe of the hydraulic ram system. The locations were at 0.47 m, 5.01 m and 11.27 m distance from the supply reservoir, as indicated in Fig. 4. The measured pressures, converted into heads, at the location nearest to the hydraulic ram, are shown in Fig. 8 together with calculated results.

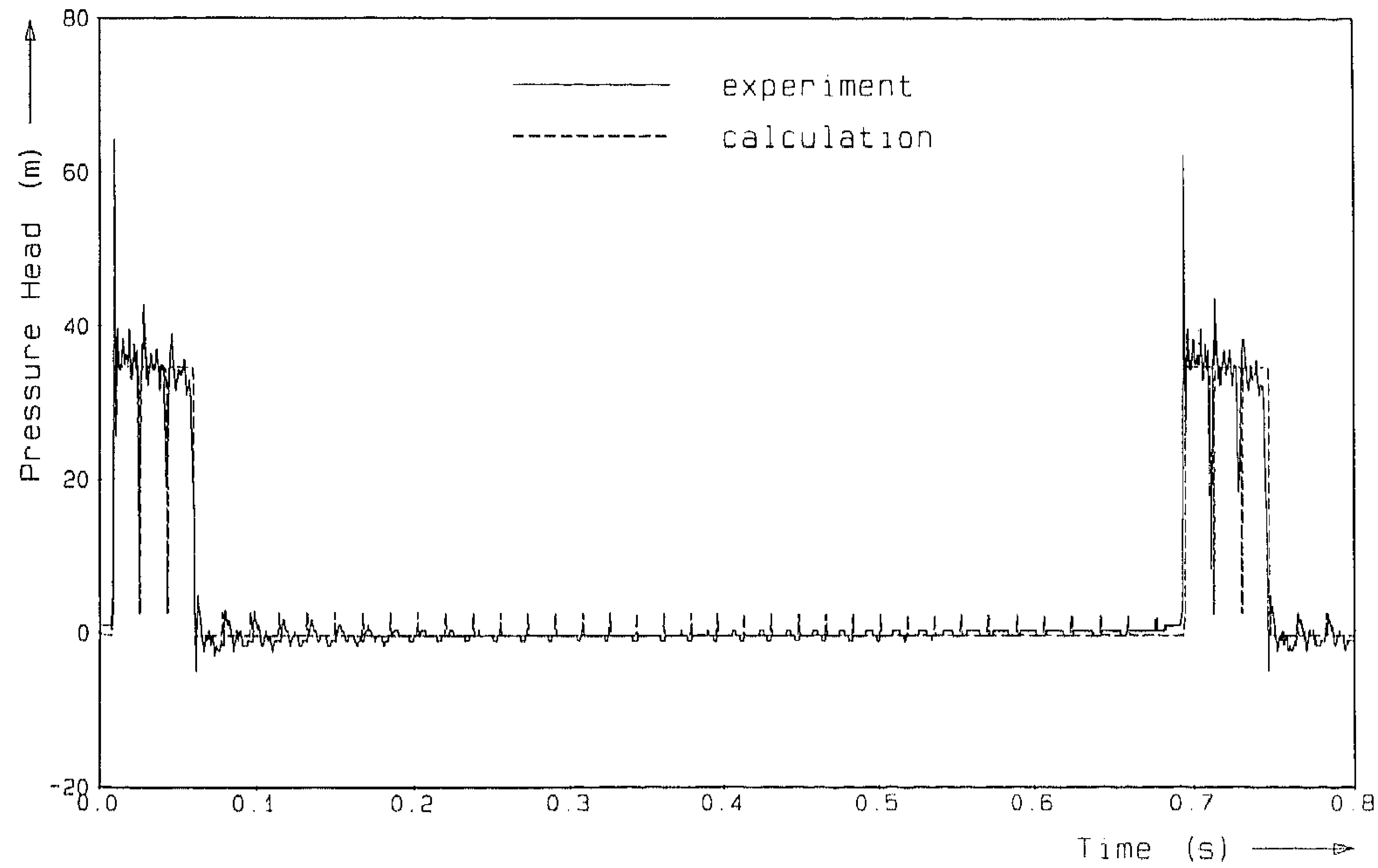

Fig. 8. Measured and calculated pressure heads close to hydraulic ram.
Hauteur de pression mesurée et calculée près du bélier hydraulique.

It is seen that the delivery valve is open for a period of $3 * 2L/c$ seconds. During this period of retardation, the average pressure head is 35 m in both calculation and experiment. The period of acceleration lasts 12 times the period of retardation. During this period weak pressure waves are travelling up and down the drive pipe. Except for the number of waves, no resemblance exists between measured and calculated *weak* pressure waves.

The enormous pressure spike recorded at the beginning of each period of retardation is caused by the closure of the waste valve. The waste valve closes when the fluid velocity is V_c, so that according to Joukowsky the pressure head rise equals $(c/g)V_c = 165$ m. This huge rise in pressure head opens the delivery valve almost instantaneously, resulting in a local pressure head of 35 m. Due to delay effects, however, part of the huge pressure head rise passes the delivery valve and can be observed in the drive pipe.

At points of time $2L/c$ and $2 * 2L/c$ after beginning of the retardation period, pressure head drops of short duration appear in measurement and calculation. These drops are due to the pressure waves reflected at the supply reservoir. It is noted that the pressure was measured and calculated 0.63 m away from the waste valve.

The pressure heads as measured and calculated at the middle of the drive pipe and near to the supply reservoir are given in Figs. 9 and 10 respectively. The agreement between measurement and calculation is reasonable, except for the short duration pressure spikes measured. The enormous pressure spike, which is not essential for the performance of the ram, attenuates by physical dispersion when it travels up and down the drive pipe.

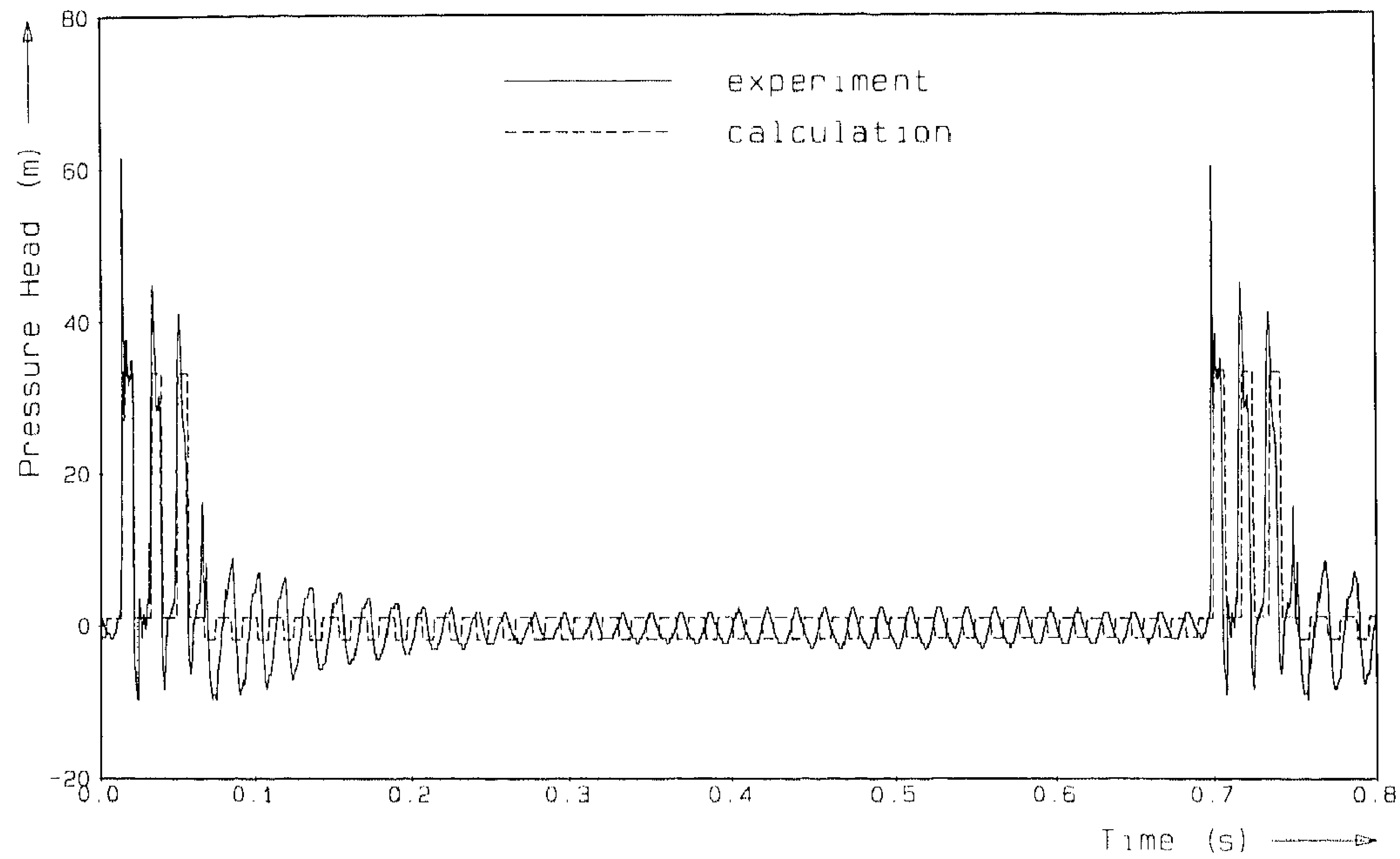

Fig. 9. Measured and calculated pressure heads at middle of drive pipe.
Hauteur de pression mesurée et calculée au milieu du tuyau d'alimentation.

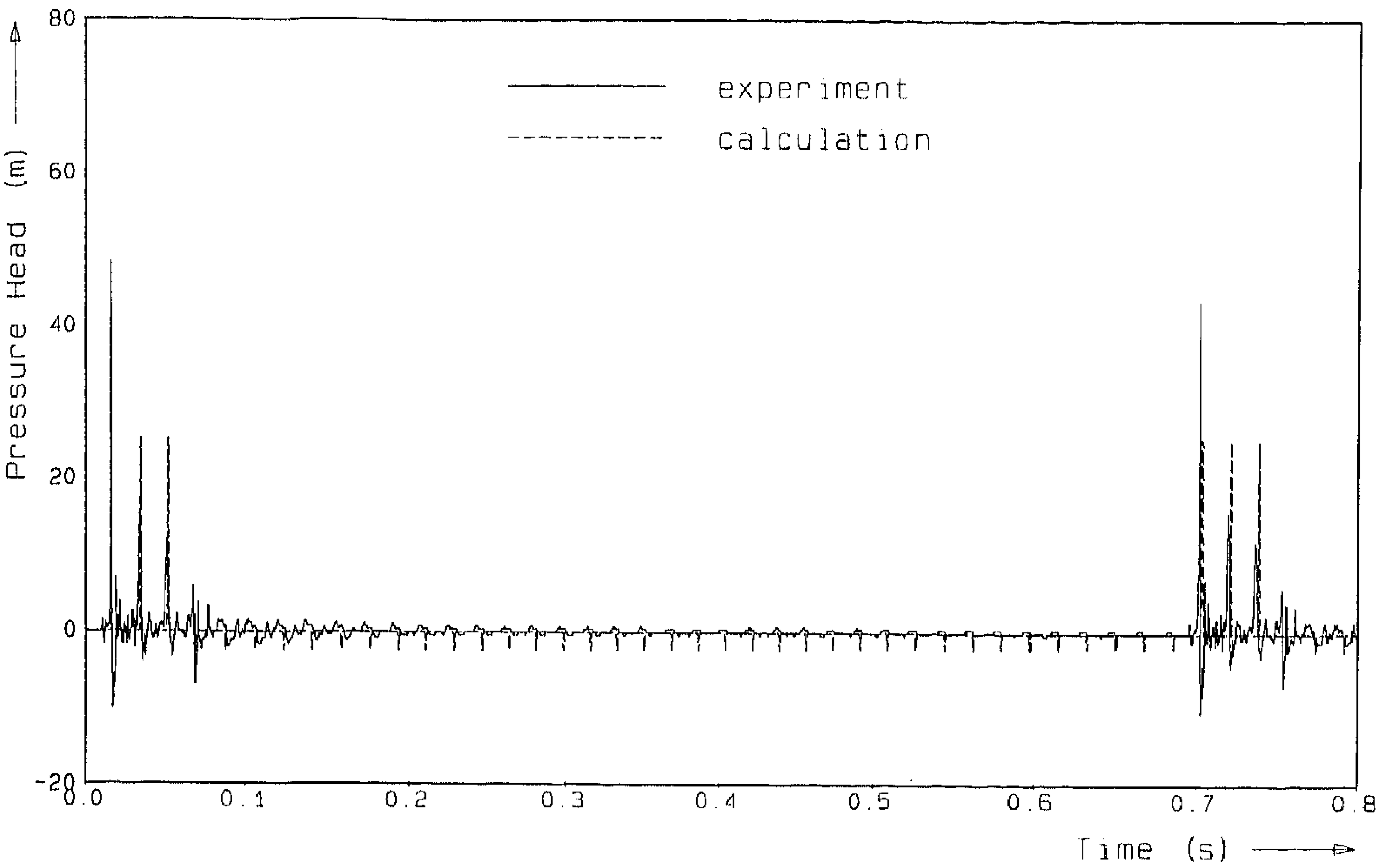

Fig. 10. Measured and calculated pressure close to supply reservoir.
Hauteur de pression mesurée et calculée près du réservoir d'alimentation.

5 Illustration parameter variation

The numerical results presented in section 4 were obtained after changing in the initial data (8) the values of K to 2.02 GPA, and hence c to 1352 m/s, and f to 0.04. The wave speed c can be changed via K, but also via E or e for given D (imposed by ram size) and ϱ, see formula (3). The effects of changing the wave speed c and the friction factor f are investigated in this section. Both c and f are parameters which are mostly not accurately known beforehand. For example, the wave speed c becomes considerably lower when there is a small amount of free gas present in the water. The friction factor f, the value of which is based on steady state situations, is often used as a parameter accounting for all dissipative mechanisms. Velocity-time diagrams are employed to illustrate the influence of the parameter variations.

In Fig. 11 calculated flow velocity histories at the hydraulic ram are shown for three different wave speeds: $c = 1450$ m/s ($K = 2.36$ GPa), $c = 1350$ m/s ($K = 2.01$ GPa) and $c = 1250$ m/s ($K = 1.70$ GPa). As can be expected, the wave speed hardly influences the acceleration phase, since this phase of the cycle can be well described by rigid column theory. Differences are encountered in the retardation phase. The velocity change ΔV_2, as given by formula (7b), is the smallest when the wave speed is the highest. For $c = 1450$ m/s the small value of ΔV_2 leads to a relatively small negative flow velocity at which the acceleration phase begins. Hence, the critical velocity V_c is reached in a shorter time, so that the period T of the whole cycle is shorter than in the other two cases.

For $c = 1350$ m/s and $c = 1250$ m/s the period T is almost the same. This is a consequence of the fact that for $c = 1250$ m/s the hydraulic ram remains $2L/c$ seconds in position 3, at the end of each retardation phase. This is the special case described in section 2.1.

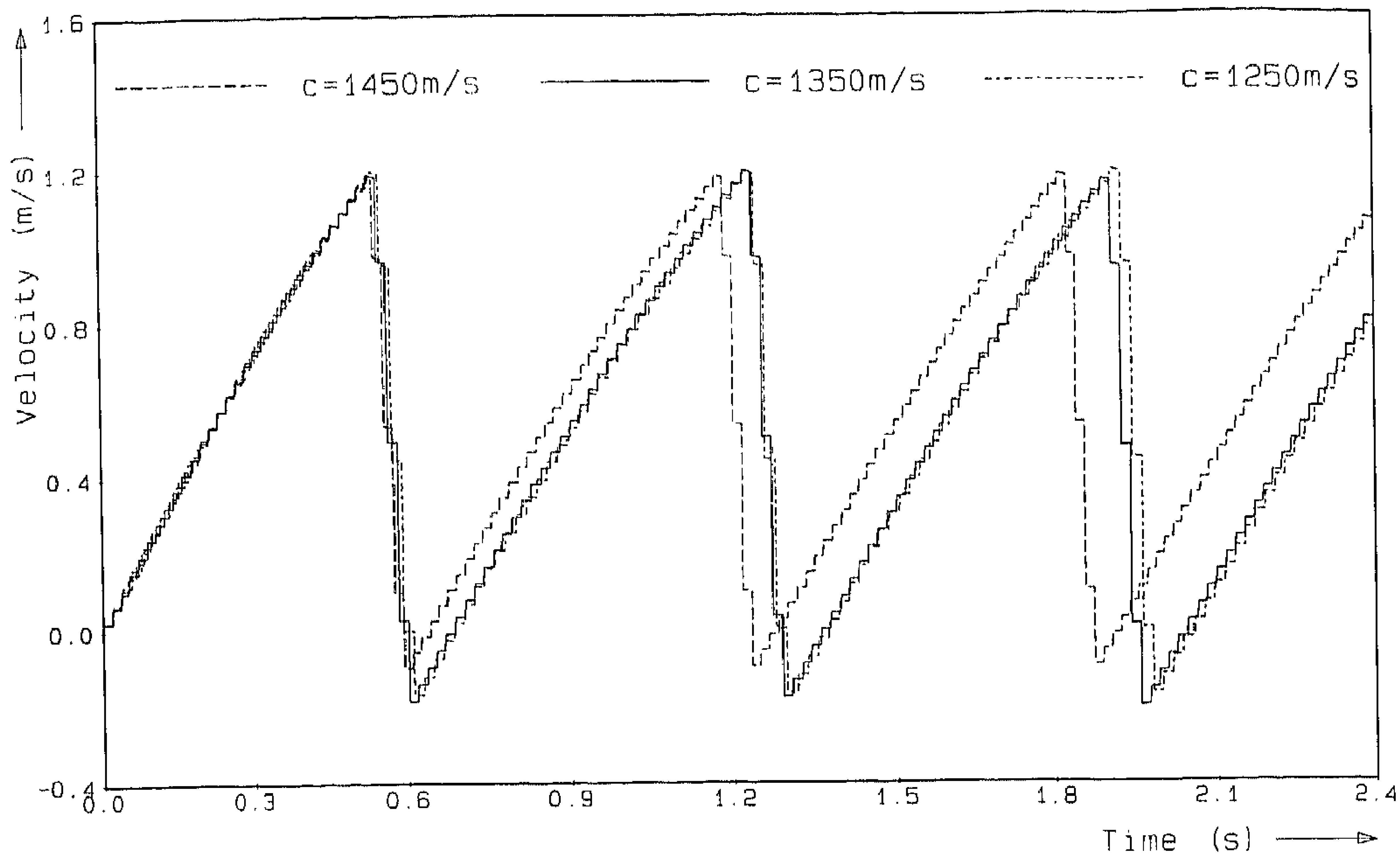

Fig. 11. Fluid velocity at hydraulic ram, calculated for three different wave speeds.
Vitesses du fluide tout près du bélier hydraulique, calculées pour trois vitesses d'onde différentes.

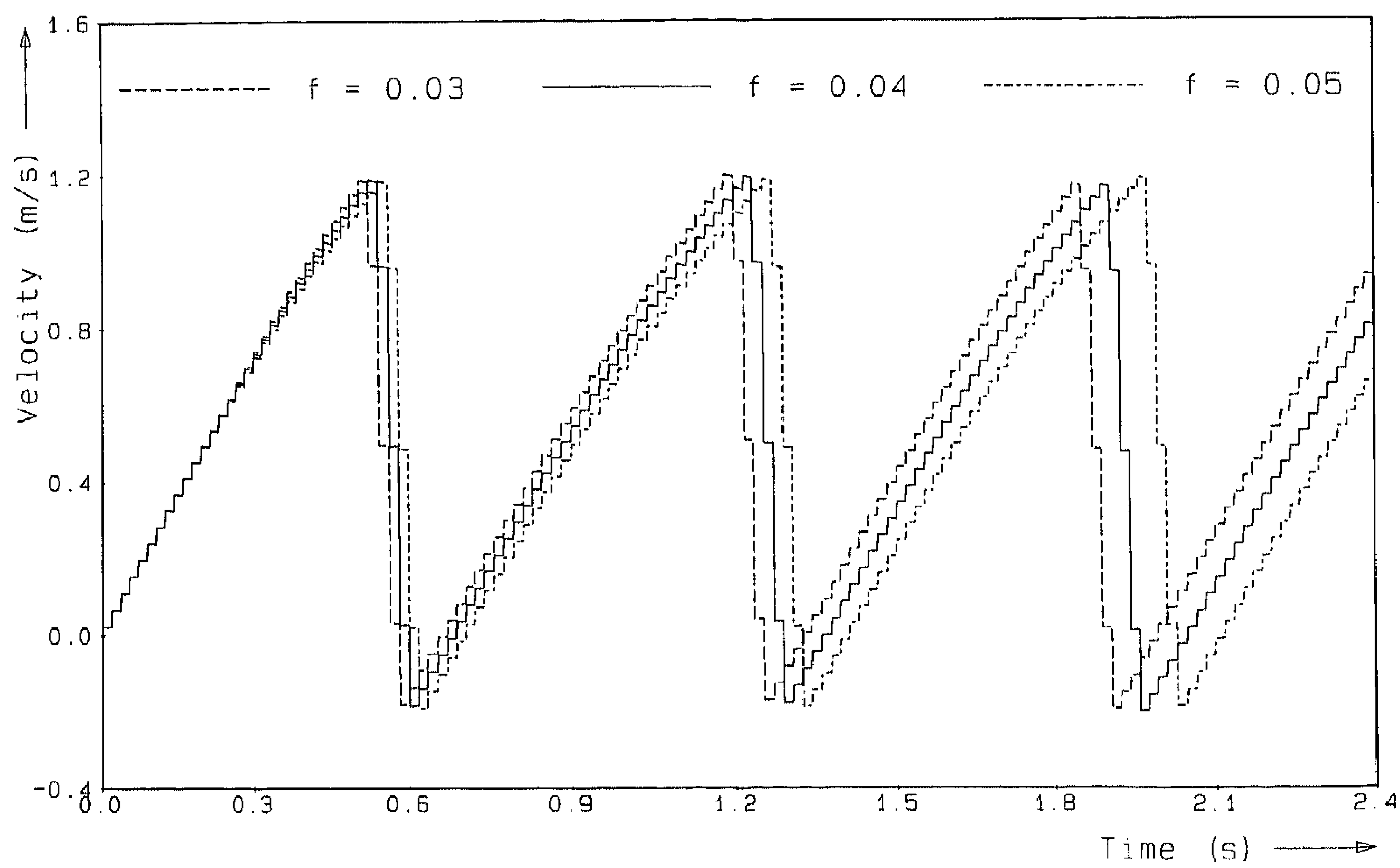

Fig. 12. Fluid velocities at hydraulic ram, calculated for three different friction factors.
Vitesses du fluide tout près du bélier hydraulique, calculées pour trois coefficients de friction différents.

Fig. 12 shows the influence of variations in the value of the friction factor. The velocity histories at the hydraulic ram are shown for friction factors $f = 0.03$, $f = 0.04$ and $f = 0.05$. In this case the period of acceleration is affected and not the period of retardation. The more friction, the slower the acceleration, and consequently the longer the cycle period T. From the figure it can also nicely be seen that the value of ΔV_1 diminishes for increasing values of the velocity. It may be concluded that formula (7a) is not valid any more if the velocity becomes larger than 1 m/s.

6 Conclusions and additional remarks

The operation of a hydraulic ram installation is analysed by considering the pressure waves occurring in the drive pipe. A model is presented in which the pressure waves are described by standard waterhammer theory. The hydraulic ram, being the source of the pressure waves, is modelled as an instantaneous opening and closing of two massless valves. This most simple model gives a good agreement when compared with a representative set of the many experimental results obtained by Tacke [2]. The model shows its usefulness in a parameter variation study. In this article pressure wave speed and friction factor were varied. The main effect of both variations is in the duration of the pumping cycle, which is of importance for the performance of the ram.

In improving the presented model emphasis should be placed on the dynamic behaviour of the fast-acting valves, which are the essential parts of a hydraulic ram. In this context it is remarked that there exist unconventional hydraulic rams without moving parts at all, see [8]. At present Glover et al. [9], [10] are working on a more sophisticated model of a hydraulic ram system.

Acknowledgement

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Notations

c	pressure wave speed
D	internal diameter of drive pipe
E	Young's modulus of drive pipe material
e	thickness of drive pipe wall
f	Darcy-Weisbach friction factor
g	acceleration due to gravity
H	pressure head
H_d	delivery head
H_s	supply head
h	elevation of drive pipe
K	bulk modulus of water
L	length of drive pipe (measured from supply tank to waste valve)
N_a	number of surges in acceleration phase
N_r	number of surges in retardation phase
P	pressure
P_d	delivery pressure

T duration of a complete cycle of operation

T_a duration of acceleration phase

T_r duration of retardation phase

t time

V velocity of water in drive pipe

V_c velocity of water in drive pipe at waste valve closure

ΔV_1 change in velocity (acceleration phase)

ΔV_2 change in velocity (retardation phase)

x distance along drive pipe

ϱ mass density of water

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