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**Abstract**

Liquid sloshing is a phenomenon encountered whenever a liquid in a container has an unrestrained surface and can be excited.
Liquid sloshing phenomena can be triggered e.g. by seismic effects in stationary containers (e.g. oil tanks) or can be initiated by movements of the container itself (e.g. liq. propellant rocket). Characteristically the sloshing in these systems is a wave motion from side to side within the container.

A specific type of sloshing can result during the core meltdown of a liquid metal reactor (LMR). After formation of a large molten fuel pool a pressure pulse in the pool leads to an outward slosh of the fuel to the core periphery followed by a gravity driven flow reversal and a compaction of the fuel in the center of the core. This type of "centralized sloshing" can lead to energetic nuclear power excursions. Fuel sloshing processes can also be found in LWR meltdown scenarios.
As no experimental information was available on the specific type of "centralized sloshing", it was decided to set up own simple experiments both to increase the phenomenological understanding and provide experimental data for benchmark exercises with fluiddynamics (accident simulation) codes.

A series of basic sloshing experiments were performed with highly symmetric conditions. It appeared that the centralized sloshing process exhibits inherent instabilities of the converging wave packages which can easily disturb an effective liquid compaction.
The influence of various intentionally introduced disturbances on sloshing (asymmetries, obstacles in the flow, particles) was investigated in an additional sequence of experiments.

It can be concluded from the experiments performed that the natural instability of the centralized sloshing will be excited by structures within the flow. An otherwise effective sloshing process can thereby be damped and disturbed.

Simulationsexperimente von zentralisierten Fluid-Schwappbewegungen

## Kurzfassung


Schwappbewegungen von Flüssigkeiten treten in Tanks auf, in denen die Flüssigkeit eine freie Oberfläche besitzt und angeregt werden kann.
Schwappbewegungen können z.B. durch seismische Effekte in stationären Behältern (z.B. in Öltanks) ausgelöst werden oder treten auf, wenn sich der Behälter selbst bewegt (z.B. bei Flüssigkeitsraketen). Charakteristisch schwappt hierbei die Flüssigkeit von Wand zu Wand.

Eine spezielle Form des Schwappens kann während des Zusammenschmelzens eines flüssigmetallgekühlten Reaktors auftreten. Nach der Ausbildung eines Brennstoff-Schmelzsees wird durch einen Druckpuls der Brennstoff an die Coreperipherie getrieben, um dann gravitationsbedingt zurückzuschwappen und im Kernzentrum zu kompaktieren. Diese Art des "Zentralisierten Schwappens" kann zu energetischen Leistungsexkursionen führen. Brennstoffschwappprozesse können auch während der Kernschmelzphase bei Leichtwasserreaktoren auftreten.
Da keine experimentelle Information zum "Zentralisierten Schwappen" vorhanden war, wurden eigene einfache Experimente durchgeführt, die sowohl das phänomenologische Verständnis erweitern sollten als auch experimentelle Daten zu Benchmarkzwecken für Fluiddynamikcodes (Unfallcodes) zur Verfügung stellen sollten.

In einem ersten Schritt wurde eine Folge von grundlegenden Schwappexperimenten unter symmetrischen Bedingungen durchgeführt. Es zeigte sich, daß der zentralisierte Schwappprozeß durch inhärente Instabilitäten der konvergierenden Wellenpakete leicht gestört wird.
Der Einfluß von verschiedenen absichtlich in die Strömung eingebrachten Störungen (Asymmetrien, Hindernisse in der Strömung, Partikel) wurde in weiteren experimentellen Serien untersucht.

Aus den Experimenten kann geschlossen werden, daß die natürlichen Instabilitäten des zentralisierten Schwappprozesses durch Störungen in der Strömung noch verstärkt werden. Ein effektives Schwappen der Flüssigkeit kann dadurch gedämpft und behindert werden.

Contents

## I. Introduction

The phenomenon of motion of liquids with unrestrained surfaces in containers, referred as "sloshing", has been a subject of investigation for many decades /1 - 5/.

Liquid sloshing phenomena can be triggered e.g. by seismic effects in stationary containers like water reservoirs (dams), partially filled oil tanks or large pool reactors. Other causes may be mixing processes of liquid and gas in tanks or piping systems during chemical engineering processes. Large damaging pressure impacts on the walls and internal structure of the containers can be the result of such fluid motions. Sloshing can also be initiated by moving of the liquid container itself as in the case of supertankers or liquified natural gas (LNG) ships and large liquid propellant rockets*. In these cases the sloshing liquid exerts excitation forces on the vehicle that can cause serious stability problems. A large number of literature is available on this widespread natural phenomenon "sloshing". The emphasis of the experimental and theoretical investigations is mainly put on the dynamic effects (pressure loads) of the moving and impacting waves and on stability questions (spacecraft). Characteristically the sloshing in these systems is a wave motion from one side of the container to the other or an azimuthal motion.

In the framework of core disruptive accident simulations in a liquid metal reactor (LMR) another type of sloshing manifests /6 - 10/. Under specific pessimistic assumptions the reactor core melts and a large whole core liquid fuel pool confined by blockages (consisting of frozen fuel and blanket structures) is build-up in the socalled transition phase /11/. A local fuel compaction may trigger a mild nuclear excursion in this pool. The following energy deposition leads to a pressure build-up in the core center which pushes the liquid fuel towards the core periphery. Driven by gravity the fuel sloshes back towards the core center and piles up in a neutronically critical or even supercritical configuration. This "centralized sloshing" /10/ which is schematically depicted in Fig. 1.1 can lead to energetic nuclear power excursions and the conditions and phenomena of these processes are therefore studied extensively.
The main interest in the transition phase area is not in the dynamic effects of the sloshing process (impact pressures) but more in its inherent structure characterized by the velocity of compaction, the shape of the wave front and the stability of the converging waves. These issues define the resulting neutronic reactivity ramp rates by the compacting fuel.

*) in everyday life this sort of sloshing excitation can be nicely observed with a glass of wine

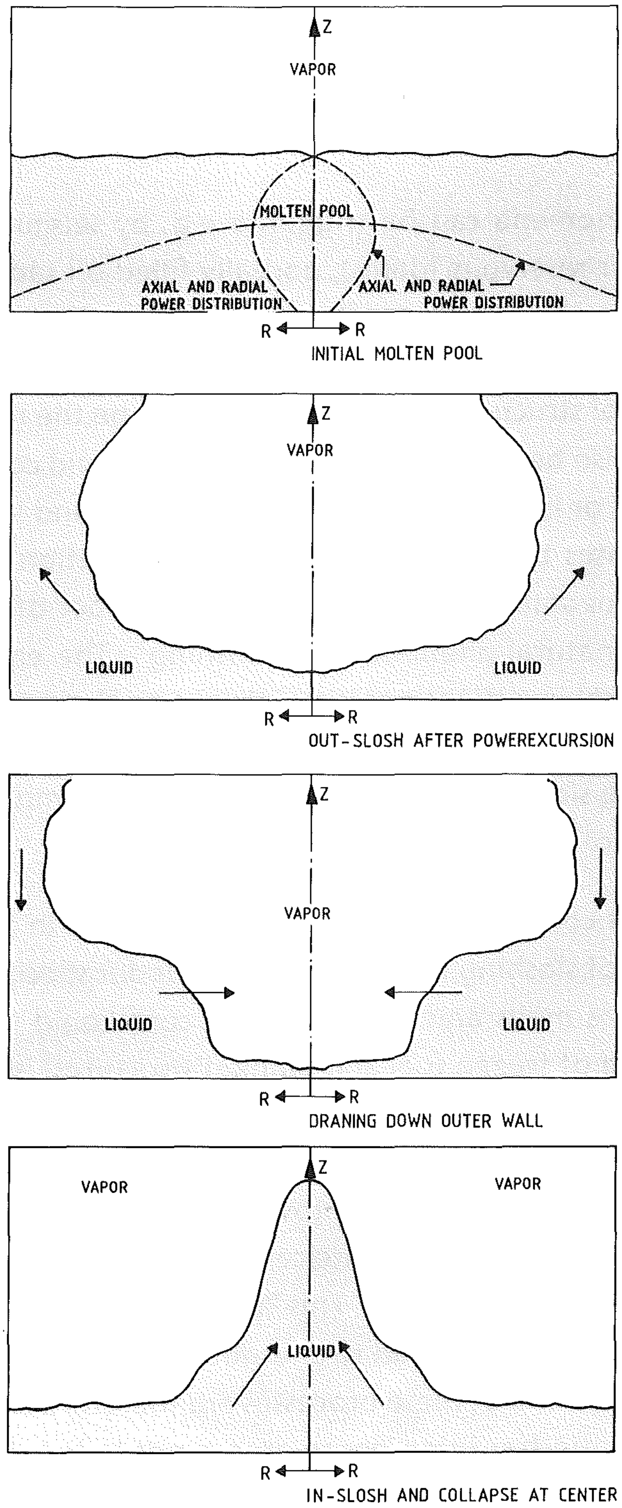


Figure I.1: Schematic representation of liquid fuel sloshing in an ideal cylindrical pool

Sloshing phenomena of liquid fuel may also occur during accident scenarios in a light water reactor e.g. when the fuel melts down into the reactor cavity /12/. Here, the actual location of the melt front is of interest while the neutronic effects of the fuel are of minor importance.

An extensive literature research showed that no experimental information was available on the specific type of "centralized sloshing".

Therefore it was decided to set up simple experiments with two aims:

- to increase the phenomenological understanding of centralized sloshing processes

- to provide experimental data for benchmark exercises with fluiddynamics codes (specifically the fluiddynamics part of accident codes).

The first purpose of the experiments was to get a better phenomenological insight into the sloshing process itself. It is well known that converging waves exhibit an inherent instability /13/. So we were also looking for these instabilities which would disturbe the sloshing process. Any disturbance of the coherence or symmetry of sloshing would mean a reduction of e.g. reactivity ramp rates in a pool slosh in the transition phase.
Besides the inherent instability of the sloshing process additional disturbances caused by asymmetries, obstacles and particles may exist in the system. To give some insight how and how much sloshing is influenced by such disturbances, asymmetries and obstacles were intentionally introduced into the flow.
Where possible the basic frequencies of the sloshing water waves in the container were measured. This gives further insight into the acting damping processes.

The second purpose of these experiments was to provide data for a benchmark exercise for accident analysis codes. For the code simulation with Eulerian schemes the movement of sloshing interfaces across the grid is difficult to describe and can lead to unwanted effects like smearing. Because of the importance of the sloshing phenomenon in accident analyses the simulation codes should be able to describe this process adequately. Precalculations with the SIMMER-II /14/ and with the AFDM code /15/ had shown marked differences in the results when using first order or second order differencing in the numerics of the fluiddynamic equations. The experiments were planned in a way to be sufficiently accurate to discriminate between the code results. The description of sloshing motions basically means the simulation of free surfaces or interfaces between phases. Waves develop accompanied by complex phenomea as wave braking and atomisation of the liquid. The centralized sloshing of fluids can be regarded as a good test for numerical schemes as e.g. smooth but compact wave packages, various shapes of interfaces and sharp fluid peaks characterize the flow.

To simulate the centralized sloshing phenomenon the sloshing problem was casted in two simple geometries and two typical configurations have been set up called a "(cylindrical) dam break problem" and a "cylindrical water step problem*".

For both configurations, a cylindrical container is divided into two concentric parts by a cylindrical diaphragm. In the first case only the inner cylinder contains water of a certain depth, the outer cylinder contains air. In the water step problem both - the inner and outer cylinder - contain water. The depth of the water in the inner cylinder is higher than in the outer one. A (r,z)-diagram of both configurations is shown in Figure I.2.

The general event sequence is that at time $t = 0$ the diaphragm is suddenly broken and the water and air are set in motion. A water wave flows outwards and finally reaches the outer cylinder, it is reflected and the reversal wave travels towards the center. This cylindrical water wave converges and produces a high water peak in the center. By this collapse at the axis the water wave is again reflected and moves outwards and after contacting the outer vessel wall, inward again. The amplitude of this follow-up wave is smaller due to the viscous forces.

* Related problems with such initial conditions can be found with the phenomenon of base surges caused e.g. by phreatomagmatic eruptions or shallow underwater explosions /16, 17/.

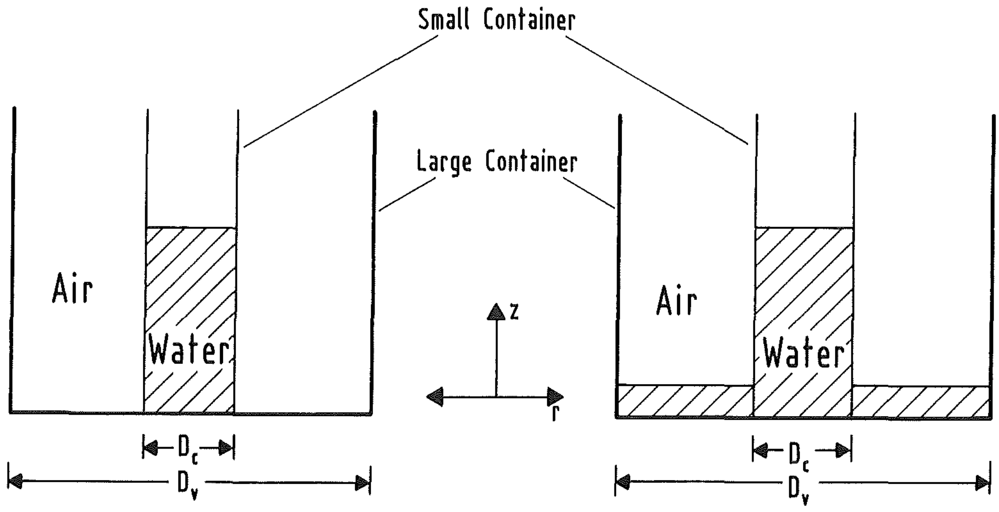


Figure I.2: Schematic dam break and water step experimental set up in the r-z plane

With the experiments performed it was tried to capture the essence of the sloshing process in the accident simulation.
In the accident simulations, the outward sloshing motion of the liquid pool is generally triggered by a pressure buildup in the pool center. The inward slosh is mainly gravity driven. In the experiments, the initial outward slosh is gravity driven, but the essential features of the sloshing process in the accident calculations - pile-up of the liquid fuel at the walls and gravity-driven inward sloshing - are well captured by the experiments.

The phenomenon of resonant sloshing in containers as in ships etc. is not of primary interest in our study. The sloshing processes simulated during core meltdown in the transition phase (in a LMR) mainly consist of only 1 - 2 flow surges due to the direct feedback of the neutronics which leads generally to a break-up of the pool confinement and discharge of the hot fuel into the upper core plenum.

## II. General Description of the Simulation of the Sloshing Process

### Dam break problem

The initial condition choosen for the experiments was a free standing water column that initiated the sloshing process. The sequence of events is displayed in Fig. II.1. The water column collapses and a diverging water wave spreads out. During the collapse the surface remains smooth and a relief wave is travelling into the water column. Due to friction at the bottom of the container the leading edge has not a horizontal tangent (as would be predicted by shallow water theory /13/) but shows a slight water hump. This first part of experiment which initiates the sloshing process can be used to analyze the triggering of base surges /16/. The water wave finally contacts and impacts the outer container wall. By the momentum the water is deflected upwards the outer container wall to a specific height. The crest of the water wave exhibits a slightly irregular, wavy structure but the average height is stable at the specifically chosen initial conditions (Height of water column, diameter of column/vessel). No atomization of the water wave occurs. Behind the primary water wave a second water wave is visible moving on the water boundary layer (see Fig. II.1).
Gravitation reverses the flow and the water collects in an outer ring near the container wall.

The momentum of the water drives the water to the center in a converging motion. Instabilities become visible and along the wave crest several liquid fingers pop up.
Further converging the water sloshes towards the center in a chaotic motion and piles up in a sharp peak. The impact of the converging water wave leads to an atomization of the fluid column and a stream of droplets forms the end of the continuous water peak. The height of the continuous water peak was measured in experiments. A pronounced straight and high peak is synonymous for high symmetry and little damping of the converging wave.
In the following the water peak collapses and another diverging water wave emerges, which contacts the outer wall and sloshes inward again. Due to strong dissipation effects the second sloshing peak is much lower and disturbances in the flow have deteriorated the sloshing symmetry. Therefore the frequency of the sloshing process can hardly be determined in the dam break problem.

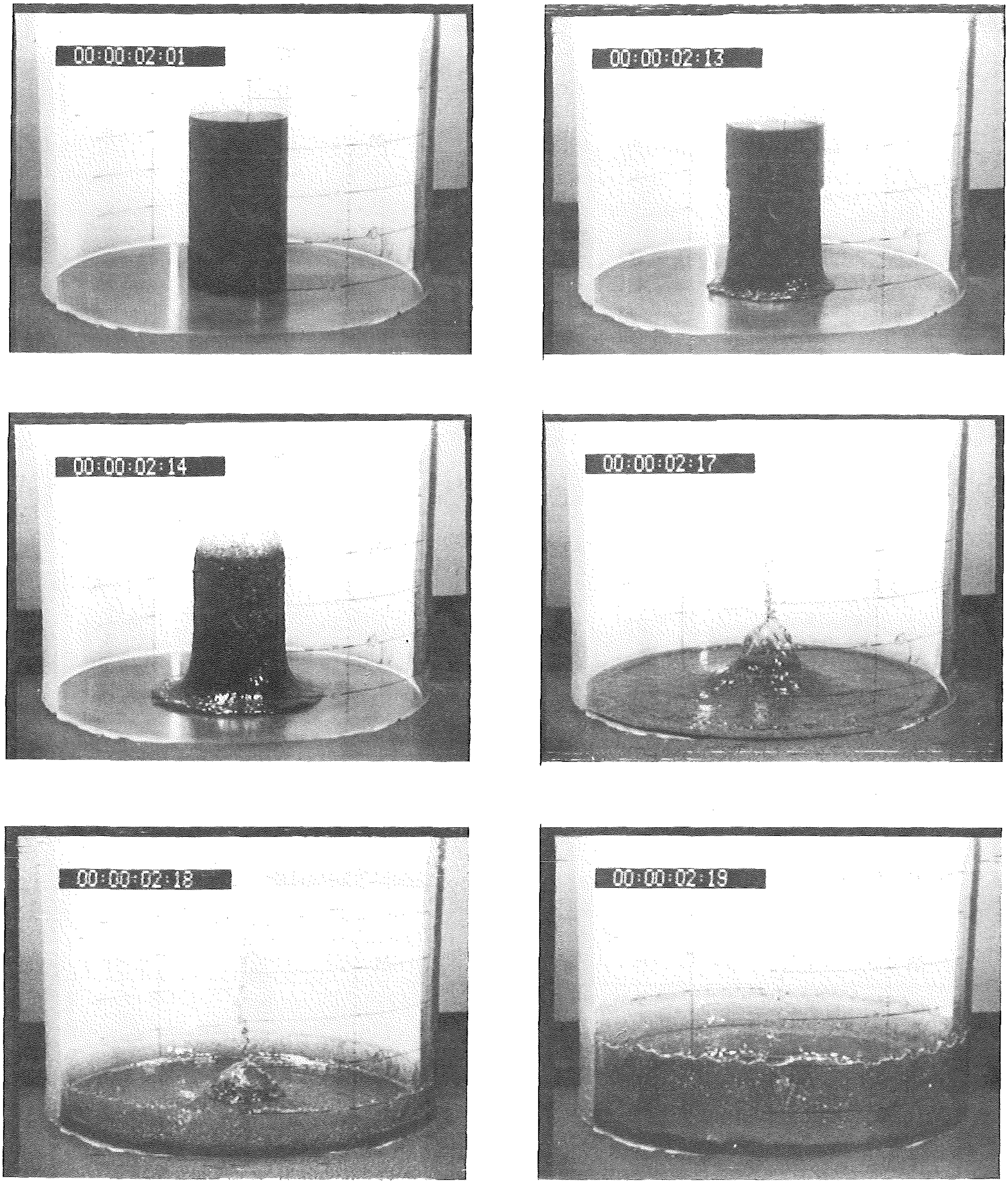


Figure II.1: Sloshing motions seen in a typical dam break problem
(Note: the numbers in the left upper window refer to video frames)
The sequence of figures should be read from left to right

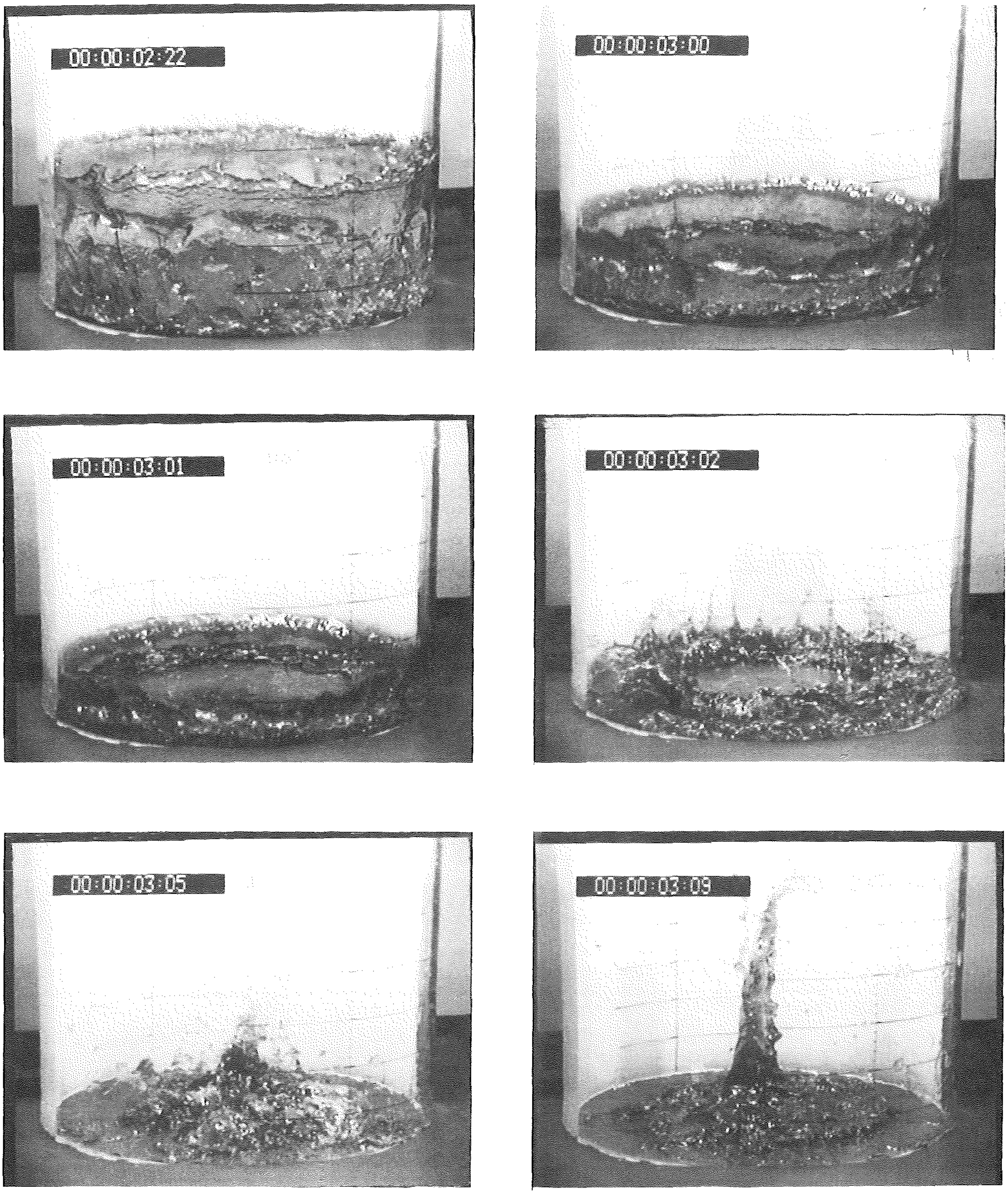


Figure II.1: Sloshing motions seen in a typical dam break problem
(continued) (Note: the numbers in the left upper window refer to video frames)

Water Step problem

The sloshing sequence of the water step problem is displayed in Fig. II.2. The water step problem mainly differs from the dam break problem in that the oszillating system characteristics are much stronger and less damping exists in the system. Many sloshing cycles can be observed and frequencies of sloshing can be determined. Depending on the height of water in the outer container different modes of sloshing can be observed with various shapes of sloshing peaks. Theoretical analyses show that energy is dissipated mainly near the surface of the water (as in the case of the dam break problem) while in the deeper water the dissipation is much less /13, 18/.

As a base case a configuration was chosen where the water masses in the inner and outer cylinder had a ratio of approximately to 1 : 4. The central water column was coloured dark so the different movement patterns could be discriminated. After releasing the water column a water wave made up of the water in the outer container (uncolored) builds-up and travels outward. This is different to the known onedimensional numerical/analytical solution of the shallow water approximation of the problem /13/ (see also Chapt. 5). This phenomenon of a piling up of the diverging wave may also be effective in base surges /16/.

At the same time the water column itself forms a wave which moves outwards in the deep water at the bottom of the pool. The uncolored water wave finally impacts the outer container wall and climbs up, while the colored water is still restricted to an area smaller than the outer container. The colored water sloshes back in the center and forms a water hump without a significant peak. A rolling wave motion can be discriminated and this wave again sloshes outward. The next in-slosh forms the highly centralized sloshing peak known from the dam break problem. This peak collapses and induces further oscillations which show a similar pattern as before with interchanging water humps and water peaks.

In contrast to the dam break problem where only travelling waves (the wave crest travels in and out) are observed, in the water step problem standing wave phenomena (formation of modes) can be observed.
The water step problem shows much less instability than the dam break problem. The surfaces are much more stable and smooth and atomization processes of the flow only occur at the highest central sloshing peak.

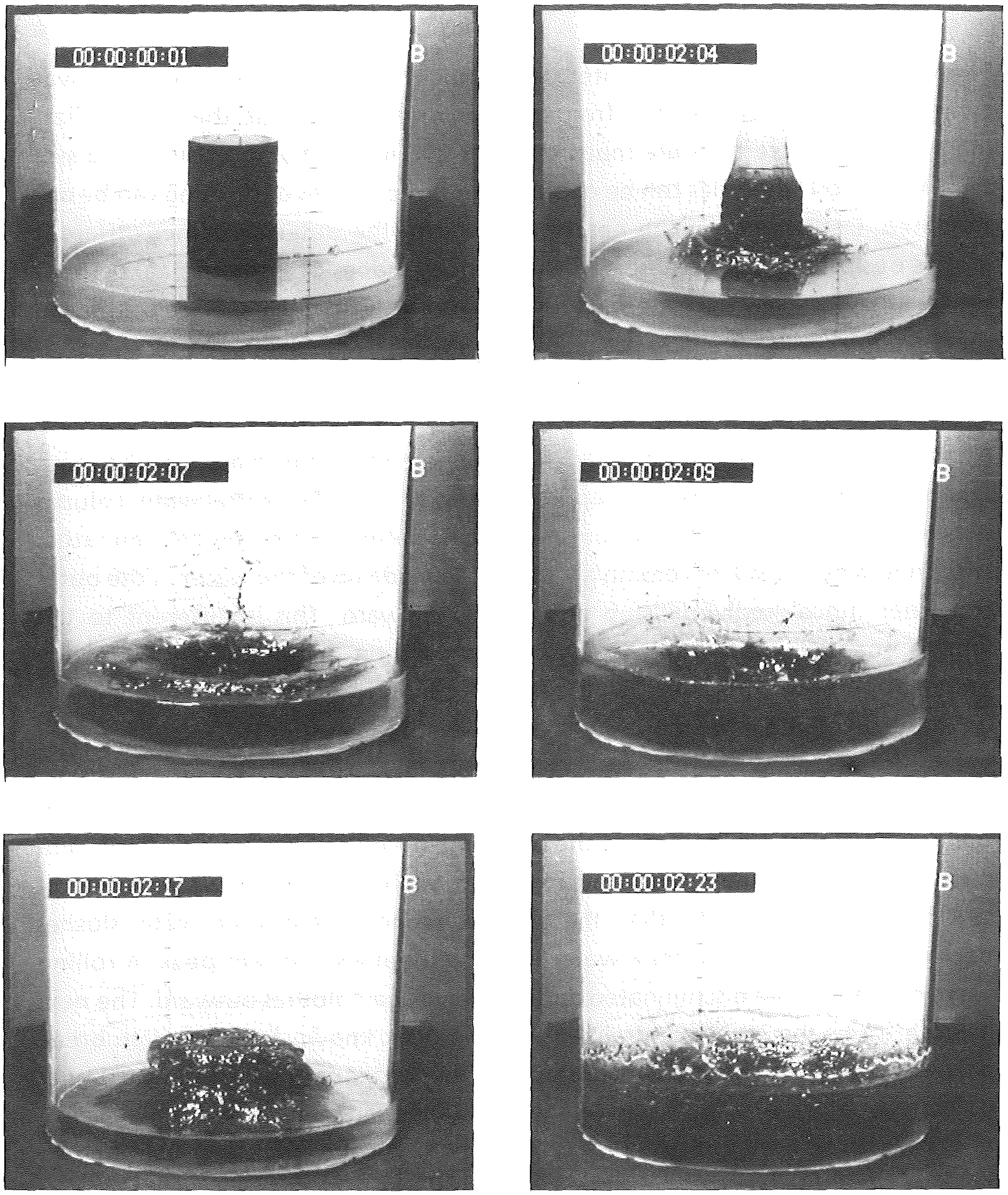


Figure II.2: Sloshing motions seen in a typical water step problem

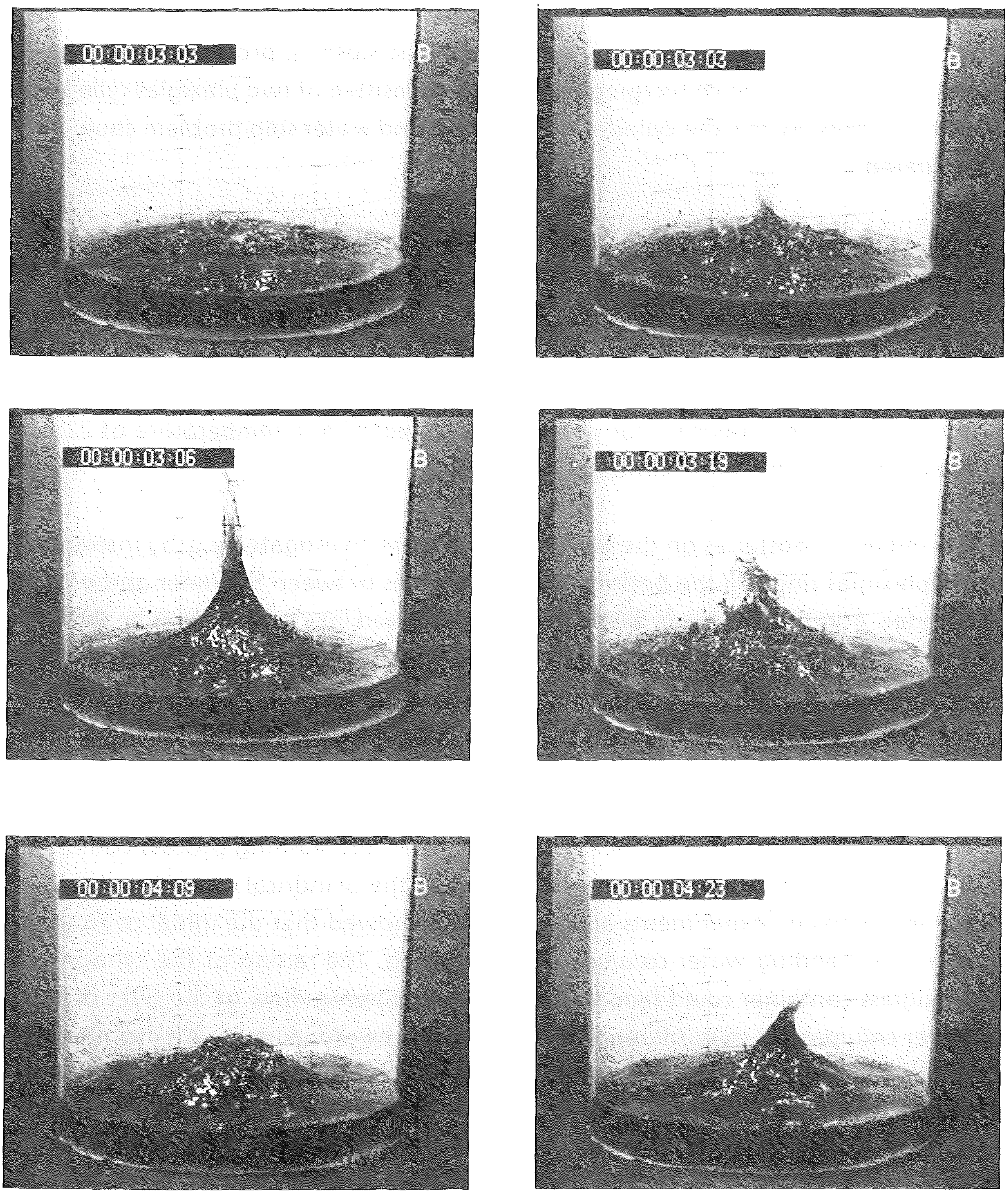


Figure II.2: Sloshing motions seen in a typical water step problem (continued)

## III. Experimental Set-up

The basic experimental set-up to initiate the liquid sloshing process and simulating the diverging and converging water waves consisted of two plexiglas cylindrical containers. By this the cylindrical dam break and water step problem could be simulated.

In the experiments a central water column with different heights (5 - 20 cm) and diameters (11 cm and 19 cm) is released from a plexiglass cylinder which is moved upwards with a speed of ~ 3 m/s. This velocity is sufficient to obtain a free standing water column. The water motion was filmed by a video- and a high speed camera. In this way sloshing heights and velocities of reassembling liquids could be determined. The fluid properties for water were 998 kg/m$^3$ at a temperature of 22$^0$C. The diameter of the outer container was 44 cm.

The impact of obstacles on the sloshing process was investigated e.g. by introducing plexiglas rings on the bottom or rod structures between the inner and outer cylinder. Additionally the influence of particles mixed into the flow was analyzed. These particles were either released with the water columns or distributed in the outer cylinder.
For investigating the influence of asymmetries on the centralized sloshing process the central water column was positioned in an off-centered scheme.

A source of possible disturbance and influence on the sloshing process could be the release of the water column by shooting up the cylindrical container. A comparison between experiments and calculations showed that the initial condition of a free standing water column is well achieved. The raising of the cylindrical plexiglass container could tend to retard the downwards flow of the sides of the water column and thus influence the initial outflow of the liquid. An estimate of the error can be given by comparing the energy introduced to the water column by the moving cylinder (via the friction force according to boundary flow) with the potential energy of the water column. The error amounts to about 3 %. Since there is some uncertainty in the nature of the boundary flow an upper estimate gives about 8 %. As can be seen visually (Fig. II.1), the main bulk of the water column was undisturbed and only a thin layer around the boundary of the column was moved upwards.

The movement of the plexiglas container could be the source of slight initial disturbances (e.g. by a slight tilting of the water column) which finally lead to the strong disturbances observed when the water waves converge again after contacting the outer wall.

It should be mentioned that the outward slosh and the pile-up of the water at the outer wall was very stable for all experiments performed. From this stable configuration however no conclusion could be drawn on the stability of the later converging water wave. In many cases the sloshing peak was strongly distorted sidewise or did not build-up correctly. These experiments were not taken into account. So in the tables displayed in chapter V only the "successful" experiments are listed.

When disturbing structures were introduced into the flow a sloshing peak usually could not develop. The combination of the inherent instability of the converging water wave together with the intentionally introduced disturbances lead to a highly instable situation where a straight and symmetric central sloshing water peak was extremely difficult to achieve. There the maximum height of the water/air mixture is given in the tables.

# IV. Scaling Considerations

As the sloshing experiments are used to obtain a better phenomenological understanding of the sloshing process in a real pool, scaling laws have to be taken into account. Generally the sloshing dynamics also depends on the geometry of the container, on structures within the flow and on the properties of the liquid.
The last issue is of special importance when impact pressures are of interest in an investigation. Compressibility effects however do not play a role in our investigations. For our purpose the effect of geometrical structures in the flow are of prime interest. Scaling considerations related to the situation when disturbances like rods are placed into the flow will be discussed in the specific chapter V.4.

For a system where waves are present or possible the Froude number **Fr** can be used for a basic scaling

$$Fr = \frac{v}{\sqrt{gl}}$$

v ... velocity
g ... gravitational constant
l ... characteristic length.

The **Fr** number compares the ratio of inertial to gravity forces at a free surface liquid. If **Fr** is small gravity keeps the surface effectively planar. With a high **Fr** number gravity plays a minor role and the fluid motion is controlled by dynamic pressures. With the Froude scaling the liquid surface shape during the sloshing period will be simulated geometrically. The velocities v of the model (m) scale to real velocities (f) by a factor $\lambda^{1/2}$ where

$$\lambda = \frac{\text{model characteristic length}}{\text{full scale characteristic length}}$$

$$V_m = V_f \cdot \lambda^{1/2}$$

Correspondingly the time scales as

$$t_m = t_f \cdot \lambda^{1/2}$$

## V. Sloshing Test Series

The sloshing test series performed are displayed in Tab. V.1 and are ordered according to geometry. It starts with the basic sloshing series (labelled SA) of symmetric dam break and water step problems. These experiments define the reference set. The influence of various disturbances on sloshing is performed in the following sequence of experiments labelled SB to SE. The influence of large assymmetries on sloshing is investigated in series SB where the water column is released off-centered.

In the experimental series SC and SD the impact of obstacles in the flow on the sloshing process is studied. In the series SC symmetric rings are placed as obstacles on the bottom of the pool to deflect the flowing water. Rods in symmetric and/or asymmetric fashion are placed in the flow in series SD.

Finally in series SE particles are placed into the flow which could damp the sloshing of liquids.

As mentioned before, high sloshing peaks (as shown in Figs. II.1 and II.2) are synonymous for a high symmetry, little disturbance of the system and non-smearing of the wave packages. The centralized sloshing process however exhibits inherent instabilities when the waves are converging to the center of the pool. These inherent instabilities could be excited by structures within the flow and disturbe the centralized sloshing process.

The basic idea of the experiments SB to SE is to look after effects that will break the symmetry of centralized sloshing, lead to instabilities and smear out of the waves and lead to a damping of sloshing motions.

| Classification of Experiments | Sloshing Test Geometry | Obstacles in the Flow |
|---|---|---|
| SA | Symmetric<br>Dam break<br>Water step | - |
| SB | Asymmetric<br>Dam break<br>Water step | - |
| SC | Symmetric<br>Dam break<br>Water step | Symmetric rings at the pool bottom |
| SD | Symmetric<br>Dam break<br>Water step | Symmetric rod structures<br>Asymmetric rod structures |
| SE | Symmetric<br>Dam break | Particles in the flow |

Table V.1: Sloshing experiments performed

## V.1 Sloshing Test Series SA

This test series represents the basic sloshing experiments where a water column collapses either in a dam break or water step mode.
For the dam break problem three characteristic cases with doubling the water height in the inner cylinder are given for the small cylinder (Ø = 11 cm). Two cases are given with a large cylinder (Ø = 19 cm) to study the impact of larger water masses. With the larger cylinder instability effects increased over the Ø = 11 cm cases. The motion of water becomes more chaotic which can be seen when the liquid compacts at the center of the pool.

### Dam break problem

The general pattern of flow for the dam break problem has been described in Chapter II and is displayed in Fig. II.1. Some specific characteristics will be discussed below. The data of the experiments are given in Tab. V.1.1.

One can use the one-dimensional shallow water approximation /13/ to obtain a first rough impression of the structure of the fluid motion. The shallow water theory is a first order approximation of the fluid dynamic equations under the assumption that the water depth of the problem is much smaller than its length scale. This assumption is however not well satisfied for the current problem. Additionally the model does not contain bottom wall friction. Due to the shallow water theory the crest of the wave should have a horizontal tangent to the bottom. As can be observed in Fig. II.1 in the experiments a visible water wave builds up in front. For the dam break problem in theory a rarefaction wave occurs which moves to the right and left with propagation rate 2 $c_o$ and $c_o$, respectively (see Fig. V.1.1). This velocity of the outward spreading wave is proportional to the square root of the gravity and water depth: $c_o = \sqrt{gh_o}$. In the two dimensional case the velocity of the spreading liquid becomes smaller (curved characteristics in the mathematical description of the travelling waves /18/).

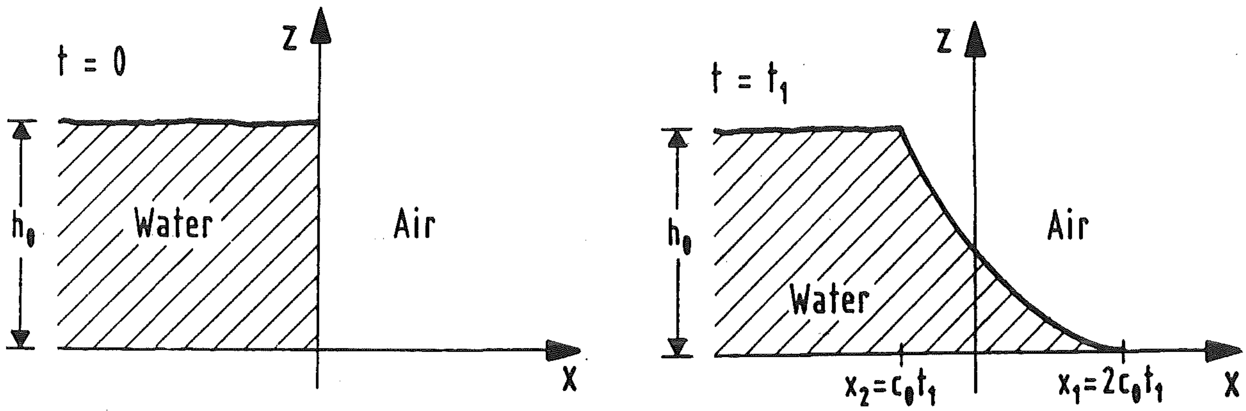


Figure V.1.1: Shallow water solution of a dam break problem in plane geometry

From onedimensional, frictionless theory one would expect a ratio of two for the arrival times at the outer wall for experiments SA-D1-1 and SA-D1-3 (Table V.1.1) when increasing the height by 4, which is clearly not the case. Though the velocity of the waves increases with water height the effect is not so pronounced.

With increased water mass (both in the SA-D1 series and SA-D2) the water level at the outer wall resulting from the out-slosh increases and naturally the height of the central slosh after flow reversal.
The outward slosh is rather stable - including the wave pattern at the outer cylinder wall. The structure of the wave is rather complicated as several water layers interact with each other. The converging waves are highly unstable and are easily disturbed. As can be observed in Fig. II.1 numerous water fingers pile up from the converging wave and at the center a rather chaotic motion finally results in a water peak. After collapse of the peak the water sloshes outward again in another cylce with smaller amplitudes. The sloshing process is finally dampened out. For the dam break problem the motion becomes extremely chaotic therefore no frequency values are given for the sloshing cycle.

SLOSHING TEST CLASSIFICATION : **SA** - Dam break

| Experimental series signature | Diameter of central water cylinder [cm] | Height of water [cm] | | Typ of Obstacle/ Disturbance | Slosh at outer container wall | | | Slosh at pool center | |
|---|---|---|---|---|---|---|---|---|---|
| | | inner cylinder | outer cylinder | | Arrival time at wall [sec] | Time of maximal height [sec] | maximal Height [cm] | Time of maximal height [sec] | Maximal Height [cm] |
| D1-1 | 11 | 5 | - | - | 0.24 ± 0.02 | 0.34 ± 0.02 | 3.0 ± 1.0 | 1.22 ± 0.04 | 3.0 ± 1 |
| D1-2 | 11 | 10 | - | - | 0.21 ± 0.02 | 0.36 ± 0.02 | 9.0 ± 1.0 | 0.84 ± 0.04 | 25.0 ± 5 |
| D1-3 | 11 | 20 | - | - | 0.20 ± 0.02 | 0.42 ± 0.02 | 16.0 ± 1.0 | 0.88 ± 0.04 | 40.0 ± 5 |
| D2-1 | 19 | 10 | - | - | 0.16 ± 0.02 | 0.34 ± 0.02 | 14.0 ± 1.0 | 0.80 ± 0.04 | 40.0 ± 6 |
| D2-2 | 19 | 20 | - | - | 0.15 ± 0.02 | 0.40 ± 0.02 | 22.0 ± 1.0 | 0.82 ± 0.04 | 60.0 ± 10 |

Table V.1.1: Experimental results for the dam break problem
(The signature D1 and D2 refers to the different diameters of the water column)

The determination of the time of the maximal sloshing height and the maximum height itself is a difficult task as with the sloshing peak approaching its maximum the base of the slosh is already collapsing. The peak of water is reduced by this in diameter.
Additionally a long stream of rivulets and droplets brakes away from the top of the sloshing peak and moves up much higher. In Tab. V.1.1 and V.1.2 the heigths indicated refer to the continuous stream of liquid.

In Fig. II.1 the experiment SA-D1-3 is displayed. An experiment with larger water masses SA-D2-2 is displayed in Fig. V.1.2.

For the experimental series SA-D1-3 an evaluation of the liquid masses compacting at the pool center was performed. The liquid mass within the volume defined by the bottom area with 11 cm diameter (corresponding to the initial water column) and the height of the container was determined. At the time of maximal sloshing height approximately 34 % of the liquid is within this volume. The lower third of the central peak contains about 70 % of this mass.

Water step problem

The water step problem was investigated by varying the water depth in the outer cylinder i.e. ratio of the water masses in the inner and outer container (Tab. V.1.2). The water step represents an oscillating system where deep water waves and surface waves interact with each other. Generally from fluiddynamics theory /13/ one can interfere that most of the damping in the oscillating system is related to surface waves. The kinetic energy is mostly stored in these wave packages. In the water step system with deep water areas the damping will be much less than in the dam break problem and several oscillating sloshing cycles can be observed (see Fig. II.2).

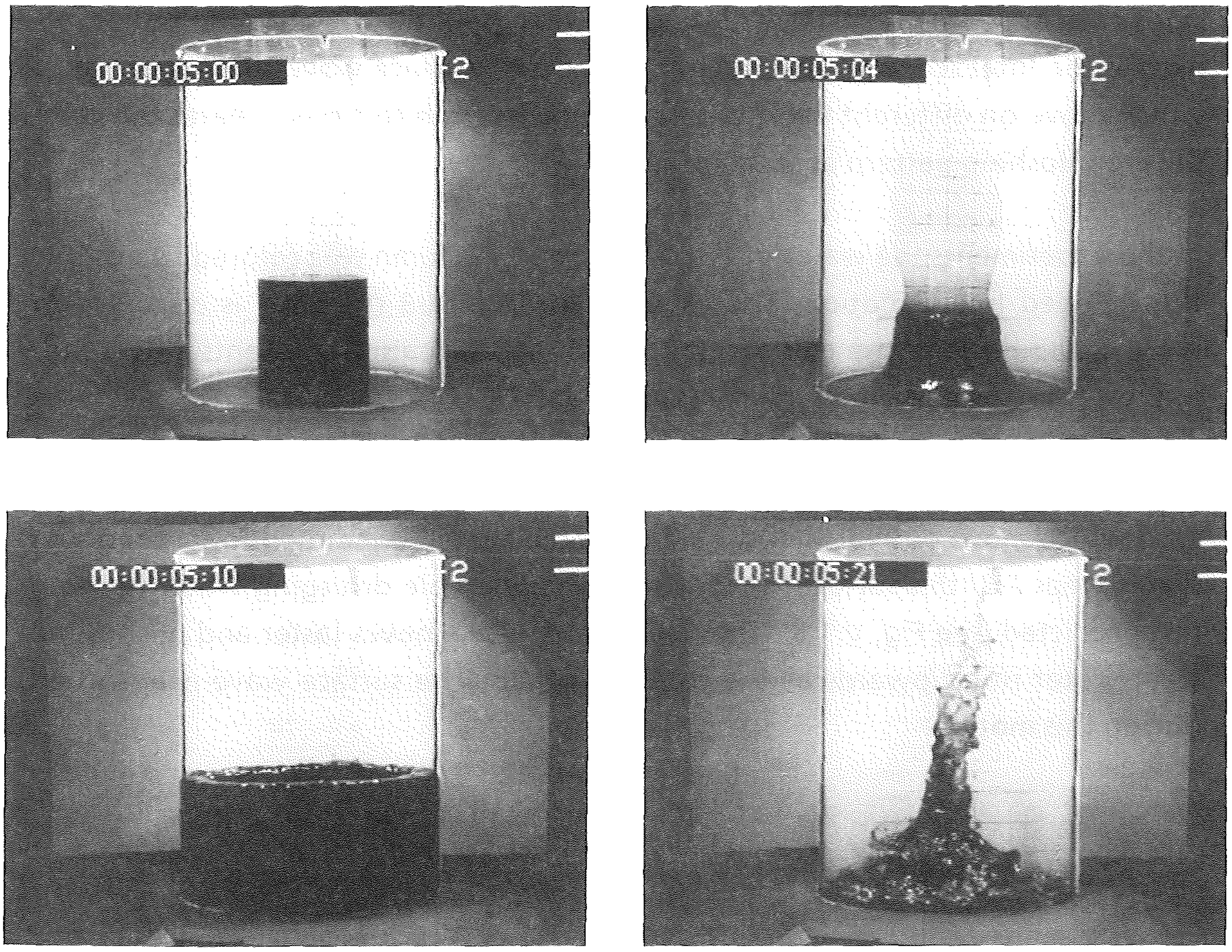


Figure V.1.2: Dam break problem SA-D2-2

The water step problem represents an oscillating system by the interaction of the central water column with the outer water ring. Under specific mass combinations as in experiment SA-D1X-3 ($M_{column} : M_{ring} = 1 : 3.75$) which is used as reference the interaction of deep water waves with surface waves (layers of water which move on different time scales and in different directions) creates the complicated sloshing pattern as seen in Fig. II.2

In the experiments the water of the central water column was colored to observe the detailed liquid motion. The experiment SA-D1X-3 (Fig. II.2) is discussed in more detail because the complicated motion pattern also represents a demanding test for the simulation with computer codes.

After release of the water column a surface wave and a deep water wave are created which move outwards. It should be noted that in onedimensional theory of water steps /13/ this surface wave with a clearly visible diverging water hump is not predicted (see Fig. V.1.3). The deep water wave moves faster and pushes the clear water ring upwards at the container walls. The surface wave is absorbed during this motion.

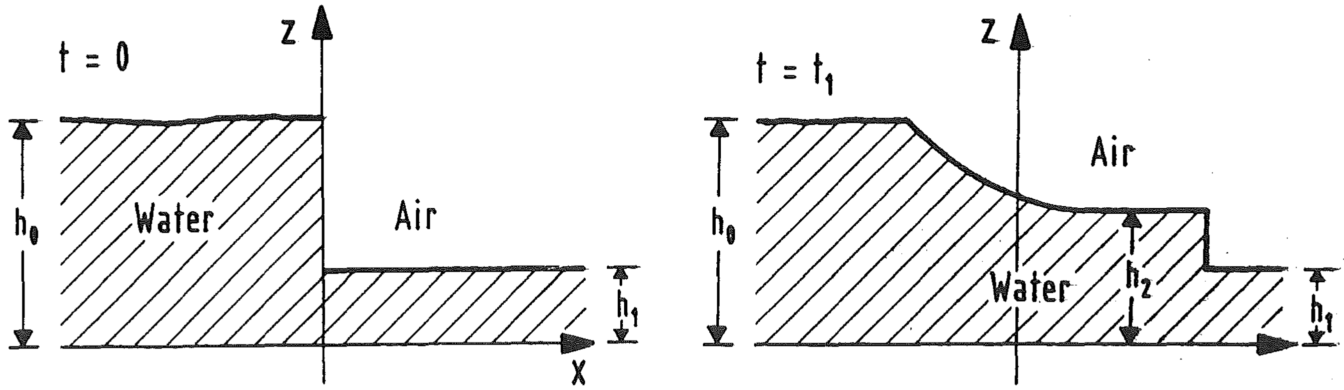


Figure V.1.3: Shallow water solution for a water step problem in plane geometry

It is the clear water of the outer ring that is pushed upwards at the outer container walls. The dark water does not reach the outer container and stays at the pool bottom. In sloshing back the clear water compresses the dark water and pushes it upwards in the pool center. A dark water hump is formed. The dark water hump collapses in a broad roll and triggeres a outward motion in the deep

| SLOSHING TEST CLASSIFICATION : | | | | | **SA** - Water step | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Experimental series signature | Diameter of central water cylinder [cm] | Height of water [cm] | | Typ of Obstacle/ Disturbance | Slosh at outer wall | | Slosh at pool center | | | | |
| | | inner cylinder | outer cylinder | | Time max. height at wall [sec] | max. height at wall [sec] | Time of 1. Peak [sec] | Height of 1. Peak [cm] | Time of second Peak [sec] | Height of second Peak [cm] |
| D1X-1 | 11 | 20 | 1 | - | 0.40 ± 0.02 | 17.0 ± 1 | 0.74 ± 0.04 | 35.0 ± 5 | 1.46 ± 0.04 | 25 ± 3 |
| D1X-2 | 11 | 20 | 3 | - | 0.38 ± 0.02 | 14.0 ± 1 | 0.68 ± 0.04 | 32.0 ± 5 | 1.32 ± 0.04 | 40 ± 5 |
| D1X-3 | 11 | 20 | 5 | - | 0.36 ± 0.02 | 11.0 ± 1 | 0.62 ± 0.04 | 15.0 ± 3 | 1.24 ± 0.04 | 50 ± 5 |
| D1X-4 | 11 | 20 | 10 | - | 0.40 ± 0.02 | 12.0 ± 1 | 0.50 ± 0.04 | 34.0 ± 5 | 1.12 ± 0.04 | 22 ± 4 |
| D2Y-1 | 19 | 20 | 10 | - | 0.36 ± 0.02 | 17.0 ± 1 | 0.58 ± 0.04 | 40.0 ± 5 | 1.16 ± 0.04 | 28 ± 6 |

Table V.1.2: Experimental results for the water step problem
(The additional signature X, Y identifies the experiments with liquid in the outer container)

water but also a surface wave travels outward. The clear water is again pushed upward the outer container walls and again compresses the central dark water which has spreaded out below the surface. The high water peak which has been observed in the dam break problem experiments emerges. The high sloshing peak thus appears in the second sloshing cycle. Both the water hump and the high water peak consist of the dark water.

Several damped sloshing cycles appear after these initial cycle where the pattern of motion is conserved with alternating water humps and water peaks. It is interesting to note that the sequence of peaks and humps is reversed after the first cycle. After the first high peak again a second peak follows and after that alternating humps and peaks.

From the visual observation it might be concluded that while the amplitude of the sloshing waves is reduced the frequency is slightly increased, thus the system seems to represent a nonlinear oscillating system /19/. The initial frequency of the sloshes (where peaks and humps are counted) is about 1.56 Hz and the frequency increases to 1.78 Hz after 20 cycles (then videofilms were stopped).

As can be seen from Table V.1.2 the SA-D1X-1 experiment nearly resembles the dam break problems (Table V.1.1) and shows the high water peak at the first sloshing cycle. Experiment SA-D1X-3 with its specific mass ratio clearly shows an exceptional difference with a sequence of low water humps and high sloshing peaks.

Additionally also larger masses (the increase of the central column to a diameter of 19 cm) were investigated. As the experiments with larger liquid masses did not show any significant phenomenological difference, only the experiment with the most balanced mass ratio SA- D2Y-1 (approx. 1 : 2) is displayed in Fig. V.1.4.
In this case too a frequency increase with longer sloshing times can be deduced from originally ~ 1.8 Hz to 2.1 Hz after 10 cycles.

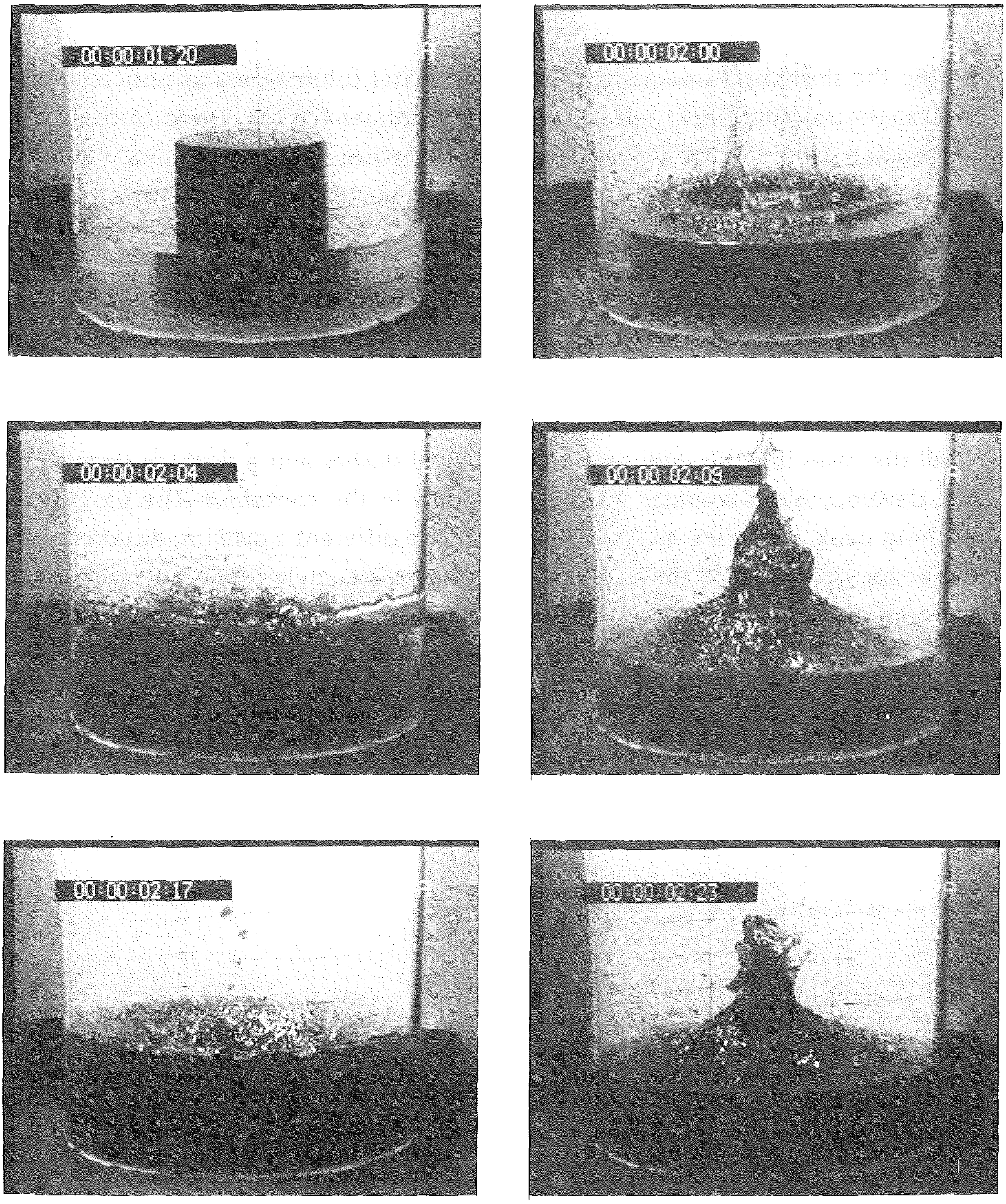


Figure V.1.4: Water step problem SA-D2Y-1

## V.2 Sloshing Test Series SB

During the sloshing experiments with central water columns, it was noticed that even slight irregularities in releasing the water column led to major disturbances of the centralized inward sloshes. Therefore, the effect of an off-centered release of the water column was investigated (Tab. V.2.1). The minimum off-centeredness was one-quarter of the diameter (2.75 cm) of the water column [increasing up to one diameter (11 cm)]. The initial water column is moved towards the left. An example of the resulting liquid motion is given in Fig. V.2.1 with identical conditions as in experiment SA-D1-3 (The water column has the diameter of 11 cm and the height of 20 cm.) but with a three-quarter-diameter off-centeredness of the water column.

In all the cases investigated, centralized inward sloshes and a sloshing peak did not develop, but the water moved chaotically in the container. Therefore no sloshing peak values are given in Tab. V.2.1. The different travelling distances of the water waves do not allow for large local water accumulations but the liquid is smeared out over longer distances. In Tab. V.2.1 the sloshing heights at the cylinder wall and the times of the maximal slosh at the wall is given where it is discriminated between the maximum height on the left and right container wall.

| SLOSHING TEST CLASSIFICATION : | | | | **SB** - Dam break | | | | |
|---|---|---|---|---|---|---|---|---|
| Experimental series signature | Diameter of off-central water cylinder [cm] | Height of water [cm] | | Typ of Obstacle/ Disturbance: Asymmetry of central water cylinder. Off-centeredness [cm] | Slosh at left wall | | Slosh at right wall | |
| | | inner cylinder | outer cylinder | | Time of maximal height at left wall [sec] | maximal Height (left) [cm] | Time of maximal height at right wall [sec] | Maximal Height (right) [cm] |
| D1A-1 | 11 | 20 | - | 5.5 | 0.40 ± 0.02 | 15.0 ± 2 | 0.50 ± 0.02 | 23.0 ± 2 |
| D1A-2 | 11 | 20 | - | 8.25 | 0.36 ± 0.02 | 14.0 ± 2 | 0.48 ± 0.02 | 24.0 ± 2 |
| D2A-3 | 11 | 20 | - | 11.0 | 0.34 ± 0.02 | 16.0 ± 2 | 0.52 ± 0.02 | 25.0 ± 2 |

Table V.2.1: Experimental results for the asymmetric dam break problem
(The additional signature A refers to the assymetry)

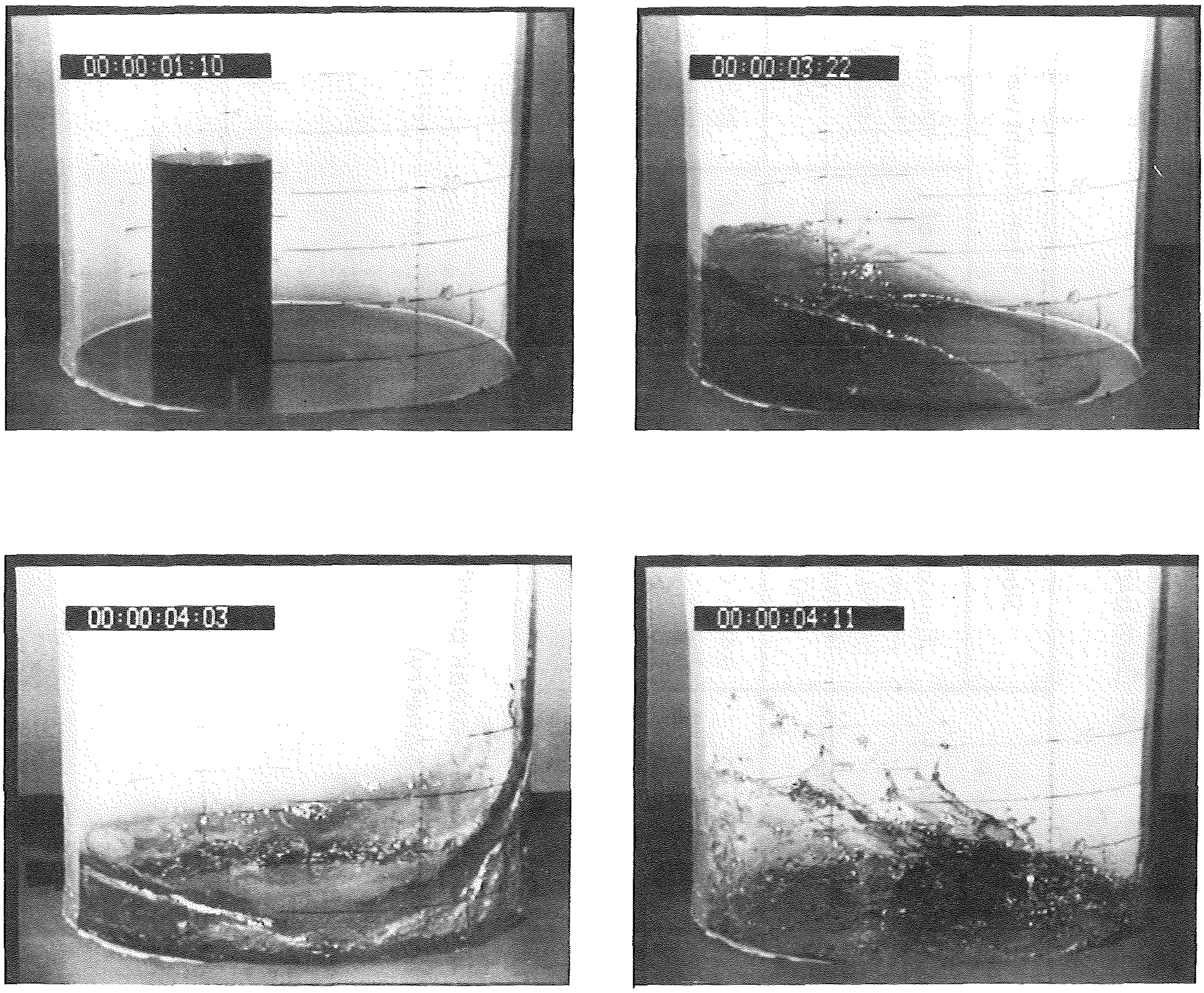


Figure V.2.1: Asymmetric dam break problem SA-D1A-2

## V.3 Sloshing Test Series SC

In these test series obstacles at the pool bottom have been introduced into the flow. Plexiglas rings of the height of 2 cm and 3 cm respectively have been placed around the central water column. The central water column had a height of 20 cms. Both a dam break and a water step problem have been investigated (Tabs. V.3.1 and V.3.2). As symmetric conditions exist, these experiments are suited for investigations of complicated flow patterns with two dimensional codes /18/.

A series of pictures are given for the dam break problem both for the 2 cm (SC-D1H-1) in Fig. V.3.1 and the 3 cm (SC-D1H-2) obstacle in Fig. V.3.2. In case SC-D1H-1 after release of the water column the water is deflected upwards by the perturbing ring structure. A bowl-shape liquid structure develops and finally contacts the wall. Some water flows further upward the wall up to ~ 18 cm. The water drains back and sloshes back towards the center. The converging sloshing wave consists of a wave from the water within the inner plexiglas ring and from the water coming down from the outer container walls which must again move inwards over the obstacle. (The main contribution to the slosh however comes from within the perturbing ring.). In all the experiments performed no effective centralized slosh developed but only a highly turbulent central flow region resulted.
With the higher obstacle (SC-D1H-2) the diverging water wave is deflected somewhat higher and does not contact the outer wall but the bowl-shape structure collapses into a chaotic motion (only during this collapse at a late stage the water wave also hits the outer container walls). Again a centralized sloshing peak does not develop.

Similar as for the dam break-problem also for the water step problem (SC-D1HX-1, SC-D1HX-2) the sloshing motion is heavily dampened by the obstacle in the flow. Compared to the unperturbed problem the maximum sloshing heights are reduced by a factor of more than 2 or 3 (Tab. V.3.2 and Fig. V.3.3).

These experiments show that ring structures at the bottom of the pool very effectively damp out sloshing motions and effectively disturbe any centralized sloshing processes (see also /18/).

| SLOSHING TEST CLASSIFICATION : | | | | | **SC** - Dam break | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Experimental series signature | Diameter of central water cylinder [cm] | Height of water [cm] | | Typ of Obstacle/ Disturbance: Ring structure around central water cylinder | Slosh at outer wall | | | | | | Slosh at pool center | |
| | | inner cylinder | outer cylinder | Heights of Cylinders [cm] | Arrival time at wall [sec] | Contact point at wall [cm] | Time of maximal upward deflection [sec] | Maximal upward deflection [cm] | Maximal height at wall [cm] | Time of maximal height [sec] | Time of maximal height [sec] | Maximal Height [cm] |
| D1H-1 | 11 | 20 | - | 2 | 0.32 ± 0.02 | 14.0 ± 1 | 0.32 ± 0.02 | 14.0 ± 1 | 18 ± 1 | 0.40 ± 0.02 | 0.60 ± 0.06 | 5 ± 3 |
| D1H-2 | 11 | 20 | - | 3 | - | - | 0.36 ± 0.02 | 15.0 ± 1 | - | - | 0.64 ± 0.06 | 5 ± 3 |

Table V.3.1: Experimental results of the dam break problem with obstacles at the pool bottom (The additional signature H refers to the ring structure at the bottom)

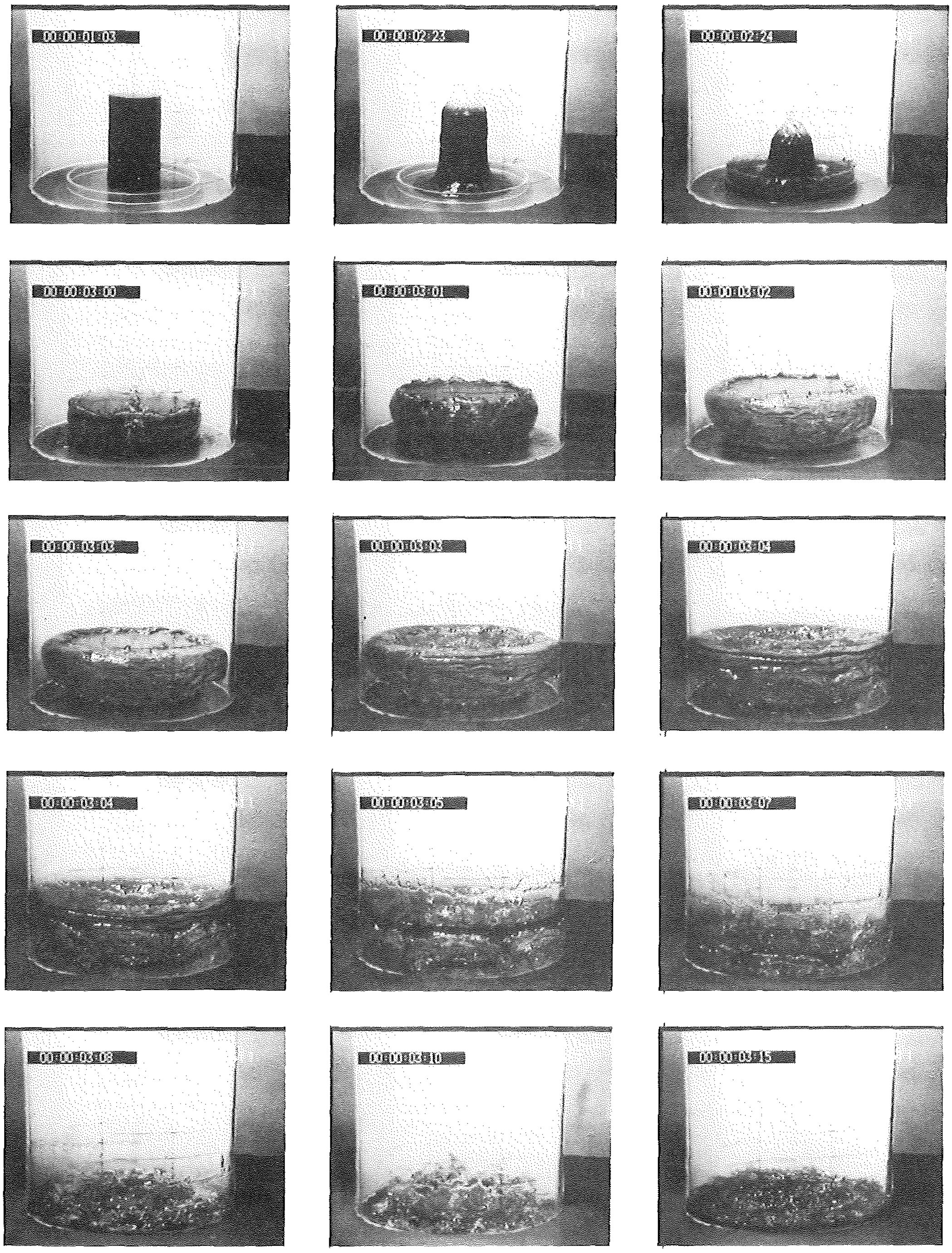

Figure V.3.1 Dam break problem SC-D1H-1 with a 2 cm obstacle at the pool bottom

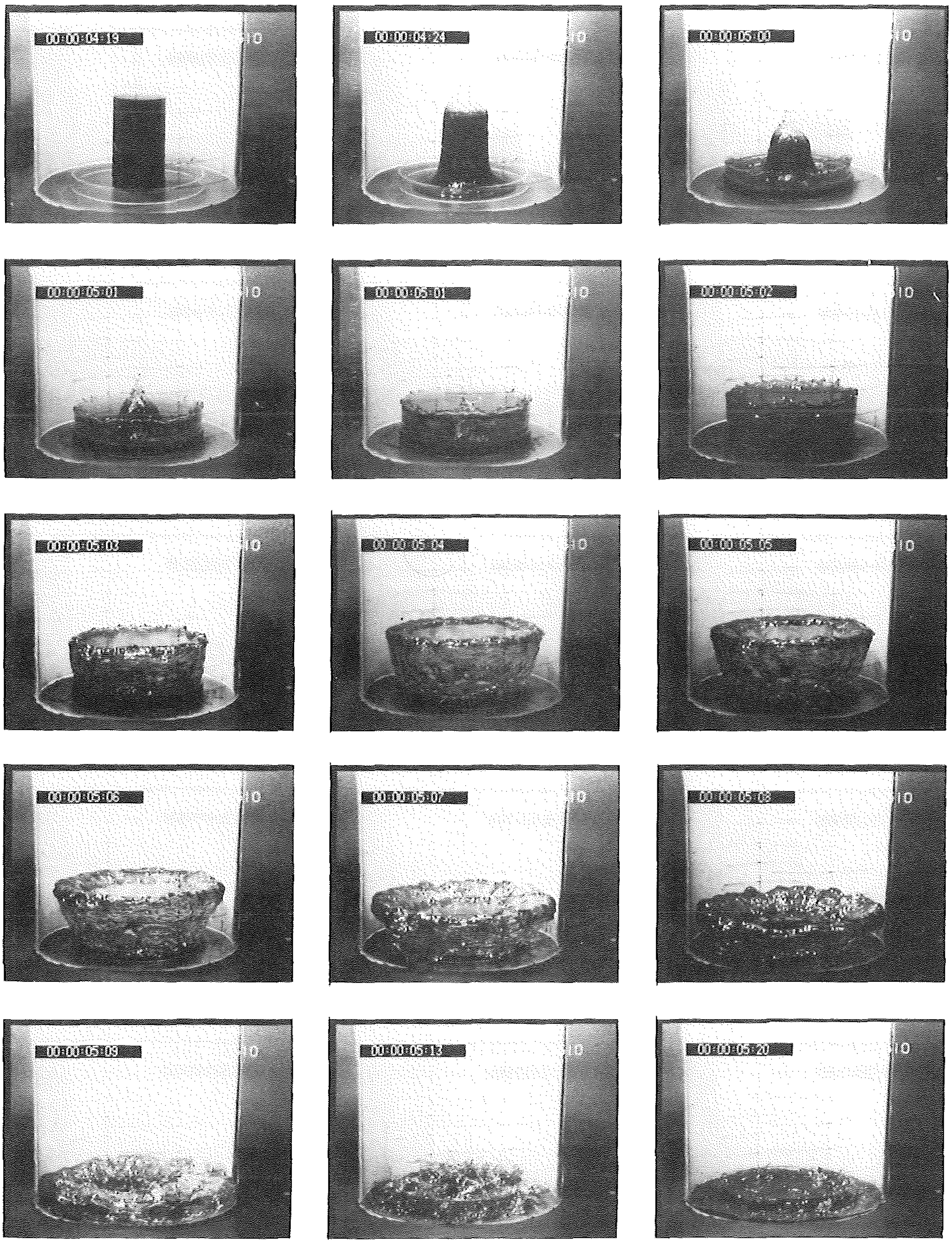


Figure V.3.2 Dam break problem SC-D1H-2 with a 3 cm obstacle at the pool bottom

| SLOSHING TEST CLASSIFICATION : | | | | | **SC** - Water step | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Experimental series signature | Diameter of central water cylinder [cm] | Height of water [cm] | | Typ of Obstacle/ Disturbance: Ring structure around central water cylinder | Slosh at outer wall | | | | Slosh at pool center | |
| | | inner cylinder | outer cylinder | Heights of Cylinders [cm] | Time of maximum at wall [sec] | Max. height at wall [cm] | Time of central hump [sec] | Height of central hump [cm] | Time of maximal Peak [sec] | Height of maximum Peak [cm] |
| D1HX-1 | 11 | 20 | 5 | 2 | 0.40 ± 0.02 | 13.0 ± 1 | 0.68 ± 0.02 | 18.0 ± 2 | 1.28 ± 0.04 | 15.0 ± 4 |
| D1HX-2 | 11 | 20 | 5 | 3 | 0.36 ± 0.02 | 12.0 ± 1 | 0.64 ± 0.02 | 10.0 ± 2 | 1.24 ± 0.04 | 20.0 ± 4 |

Table V.3.2: Experimental results of the water step problem with obstacles at the pool bottom

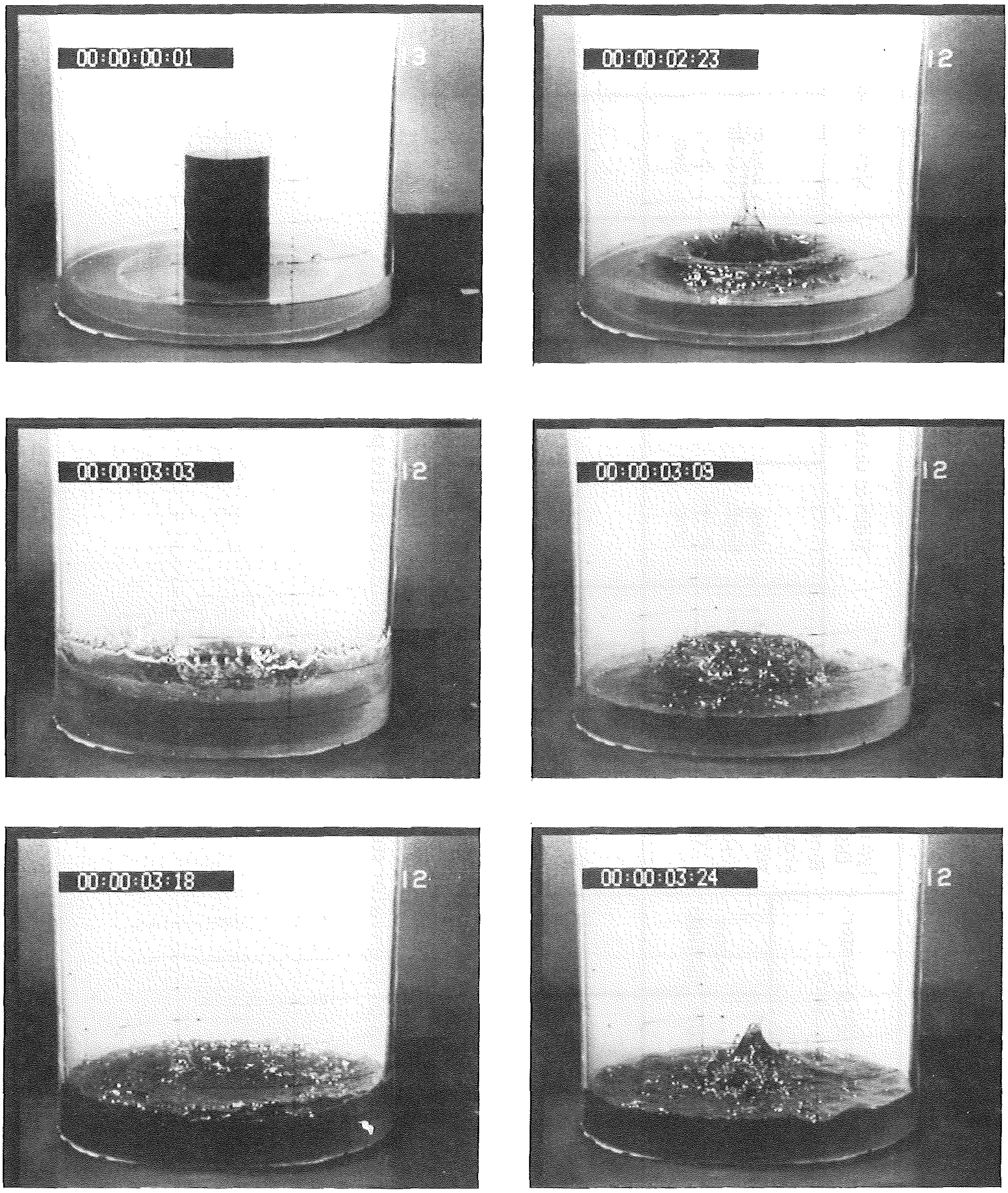


Figure V.3.3: Water step problem SC-D1HX-1 with a 2 cm obstacle at the pool bottom

## V.4 Sloshing Test Series SD

The influence of rods in the flow on the sloshing process has been studied in the sloshing test series SD. The effect of obstacles in the flow in breaking up coherent wave motion is also well know from marine engineering. The background for our interest in the area of accident analyses was to study the impact of still existing control rod or blanket structures in the pool on the sloshing process.

Various patterns of rods positioned around the central water column have been investigated with a maximum of 12 rods in the flow. The diameter of the rods was scaled down geometrically to obtain a blockage ratio

$$B_m = \text{Rod diameter x number of rods / Free flow circumference}$$

for the flow streaming through a bank of rods characteristic for medium size reactor cores.

For relating the effect of rods in the investigated water pool with the impact of rods in an accident simulation one has to consider the drag force for proper scaling. The obstacles slow down the sloshing liquid by drag force, which is proportional to the drag coefficient (specific for the shape and surface of the obstacles) and to the ratio of the obstacle to the free-flow area (blockage ratio). The diameter of the model pins was chosen as 2 cm to obtain a similar blockage ratio in the model and the real size pool. The drag coefficient is a function of the Reynolds number. Both in the model and the real pool, highly turbulent flow conditions prevail with $Re \sim 10^4$ in the model and $Re \sim 10^5$ in the real pool. Taking into account all parameters that have an effect on the drag, such as the number of rows of rods and their relative spacing, the shape and roughness of the rods and the turbulent intensity, the maximum by which the drag coefficient can be smaller in the real pool than in the model pool can be estimated to be a factor of 2.

Several different symmetric and asymmetric distribution schemes and arrangements have been investigated for their effect on the sloshing behaviour. The essence of the impact of the rods on sloshing can be shown in the experiments displayed in Tabs. V.4.1 and V.4.2 and Figs. V.4.1 to V.4.5.

These experiments were also performed to provide data for benchmarking three dimensional fluiddynamic codes. Tests with more complicated rod configurations have not been taken into account in the tables as they do not give any further insight into the sloshing behaviour but would only complicate any set-up for a comparative code calculation.

As can be seen from Tab. V.4.1 and Figs. V.4.1 to V.4.4 for the dam break problem, an inner ring of rods (SD-D1R-1) placed in the vicinity of the initial water cylinder virtually destroys the inward slosh. Due to the rods the outward flow and the structure of the wave crest at the outer container wall is more wavy than without rods. But still the outward slosh is rather stable and reaches ~ 90 % of the height of the undisturbed slosh at the container walls. The inward slosh again hits the central rod structure and the inherent instability of the converging waves is amplified and the centralized slosh is damped out totally (Fig. V.4.1). Even with only 6 rods placed asymmetrically around the central water column the damping effect is quite pronounced (Fig. V.4.3).

If the rods are placed furtherout near the container walls, the influence is smaller because the liquid can flow undisturbed towards the center after it has hit the outer obstacles and the wall. However, the mass of the centralized slosh is reduced by the stronger smearing out of the converging wave (Fig. V.4.2).
Again, using only 6 asymmetric rods has already a significant effect on the sloshing effect by smearing the waves in a way that no efficient centralized sloshing can manifest itself (Fig. V.4.4).

For the water step problem the effect of reducing the sloshing heights is not so pronounced as the whole system is more an oscillating one (see chapter V.1) and less dissipation exists in the system. Nevertheless the sloshing process is retarded and the sloshing peaks are drastically reduced (Table V.4.2 and Fig. V.4.5).

SLOSHING TEST CLASSIFICATION : **SD** - Dam break

| Experimental series signature | Diameter of central water cylinder [cm] | Height of water [cm] | | Typ of Obstacle/Disturbance: Rod structures around central cylinder | | | Slosh at outer wall | | | Slosh at pool center | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | inner cylinder | outer cylinder | Symmetry | Number of rods | Distance from center | Arrival time at wall [sec] | Time of maximal height [sec] | maximal Height [cm] | Time of maximal height [sec] | Maximal Height [cm] |
| D1R-1 | 11 | 20 | - | full | 12 | 9.9 | 0.22 ± 0.02 | 0.44 ± 0.02 | 15 ± 1 | 0.90 ± 0.04 | 3 ± 2 |
| D1R-2 | 11 | 20 | - | full | 12 | 17.6 | 0.20 ± 0.02 | 0.42 ± 0.02 | 15 ± 1 | 0.88 ± 0.04 | 15 ± 3 |
| D1R-3 | 11 | 20 | - | half | 6 | 9.9 | 0.20 ± 0.02 | 0.42 ± 0.02 | 16 ± 1 | 0.88 ± 0.04 | 10 ± 3 |
| D1R-4 | 11 | 20 | - | half | 6 | 17.6 | 0.20 ± 0.02 | 0.40 ± 0.02 | 15 ± 1 | 0.88 ± 0.04 | 20 ± 5 |

Table V.4.1: Experimental results for a dam break problem with rods in the flow area (The additional signature R refers to the rods placed in the flow)

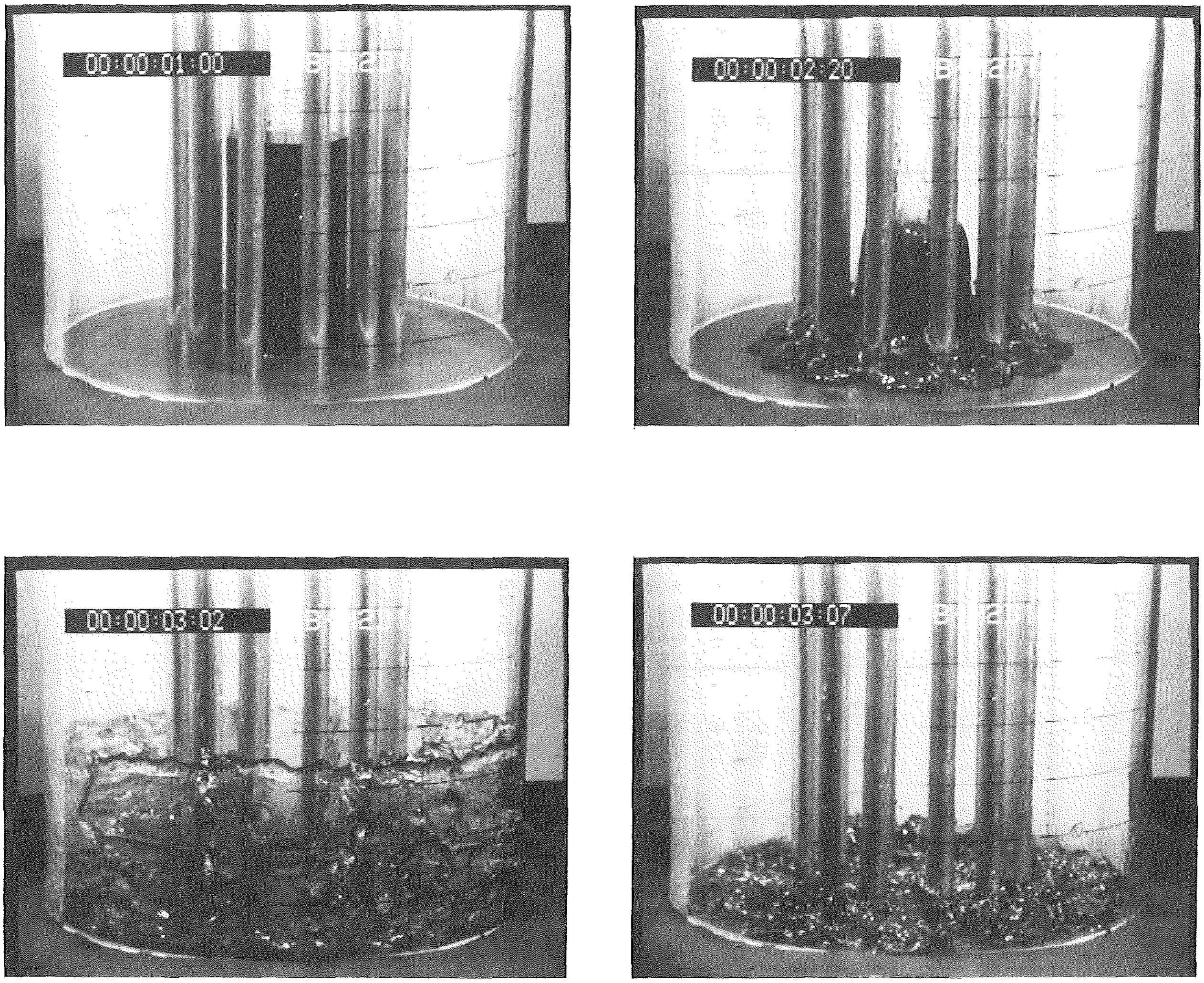


Figure V.4.1: Dam break problem SD-D1R-1 with a central full bank rods in the flow

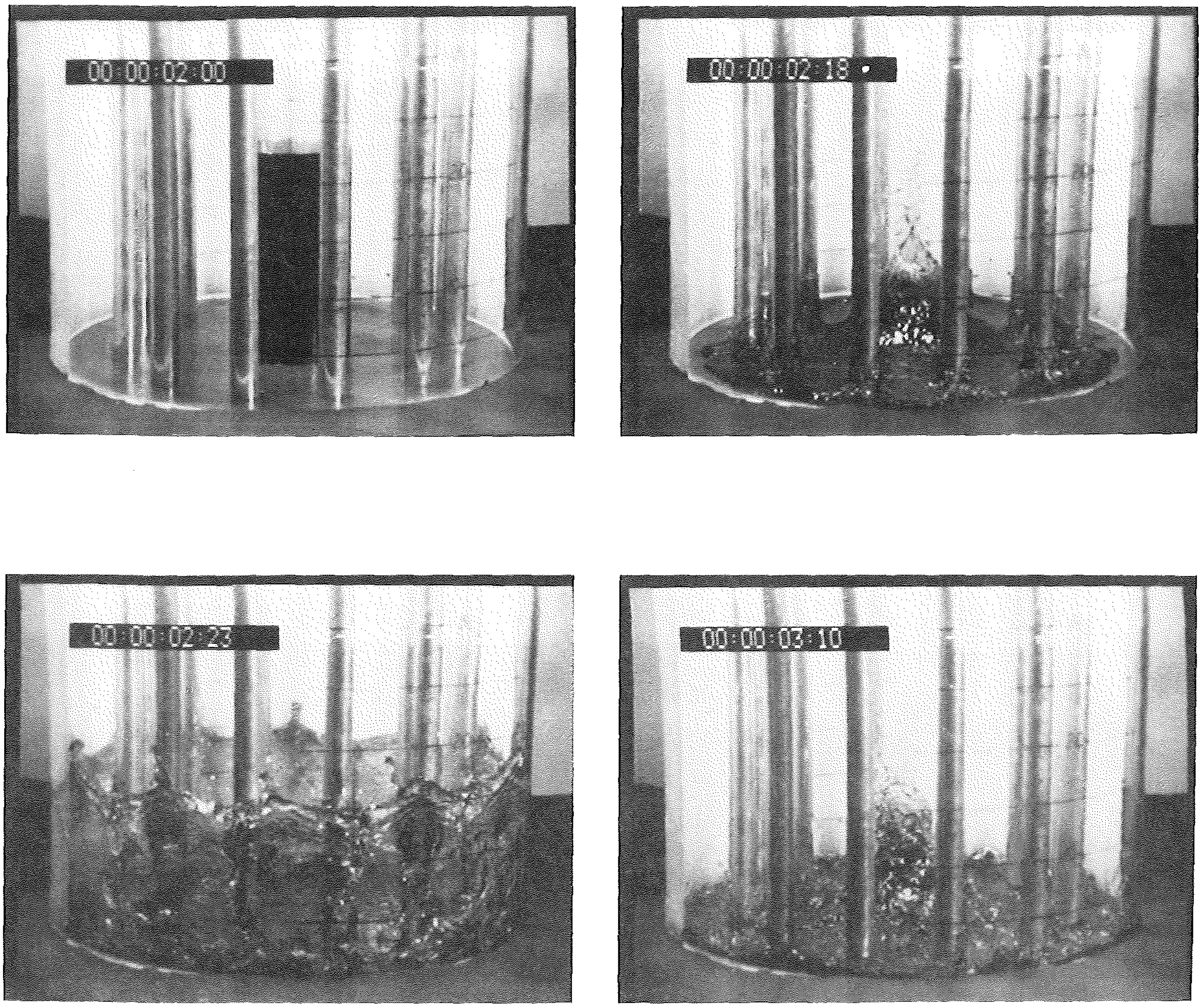


Figure V.4.2: Dam break problem SD-D1R-2 with a peripheral full bank of rods in the flow

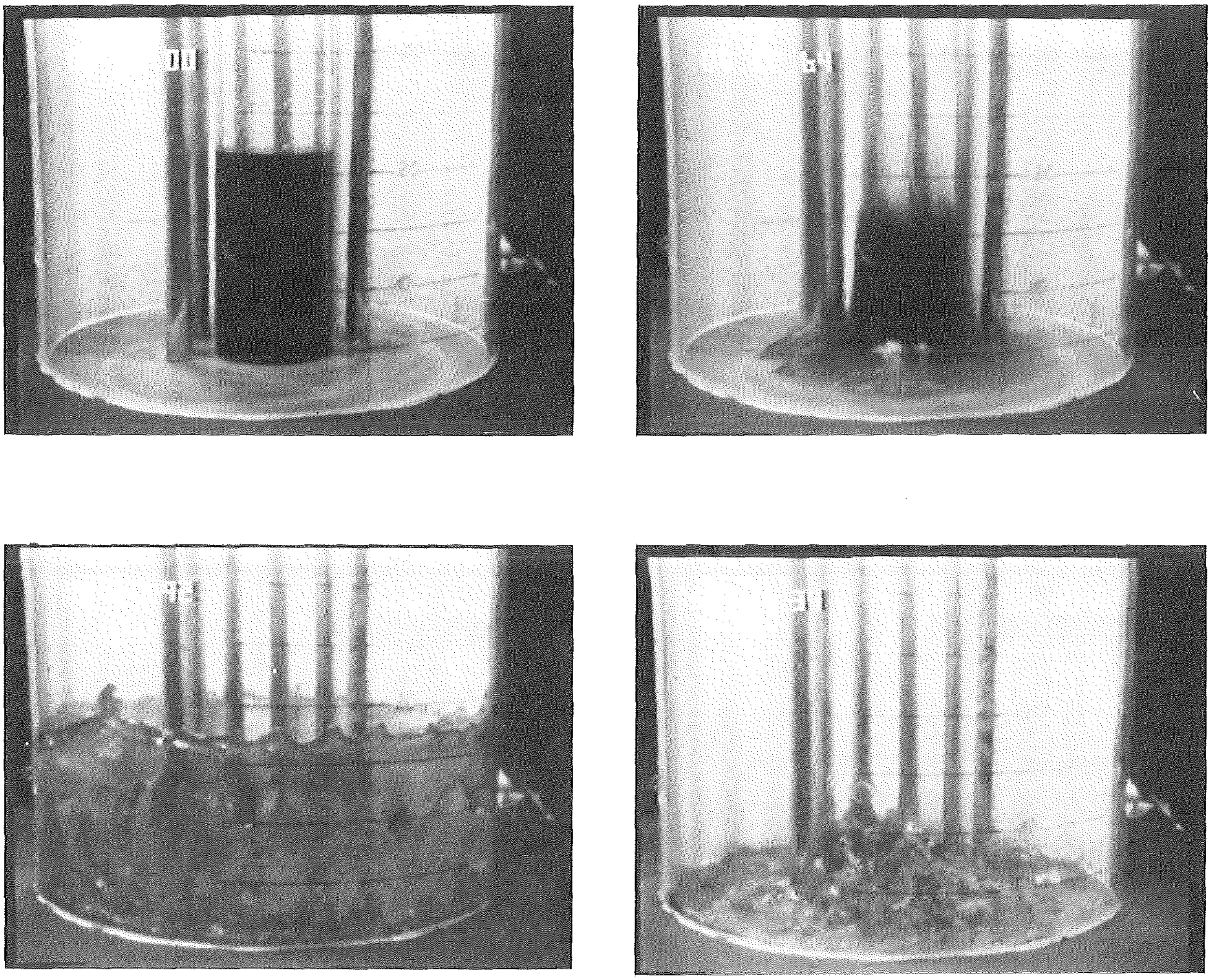

Figure V.4.3: Dam break problem SD-D1R-3 with a central half bank of rods in the flow

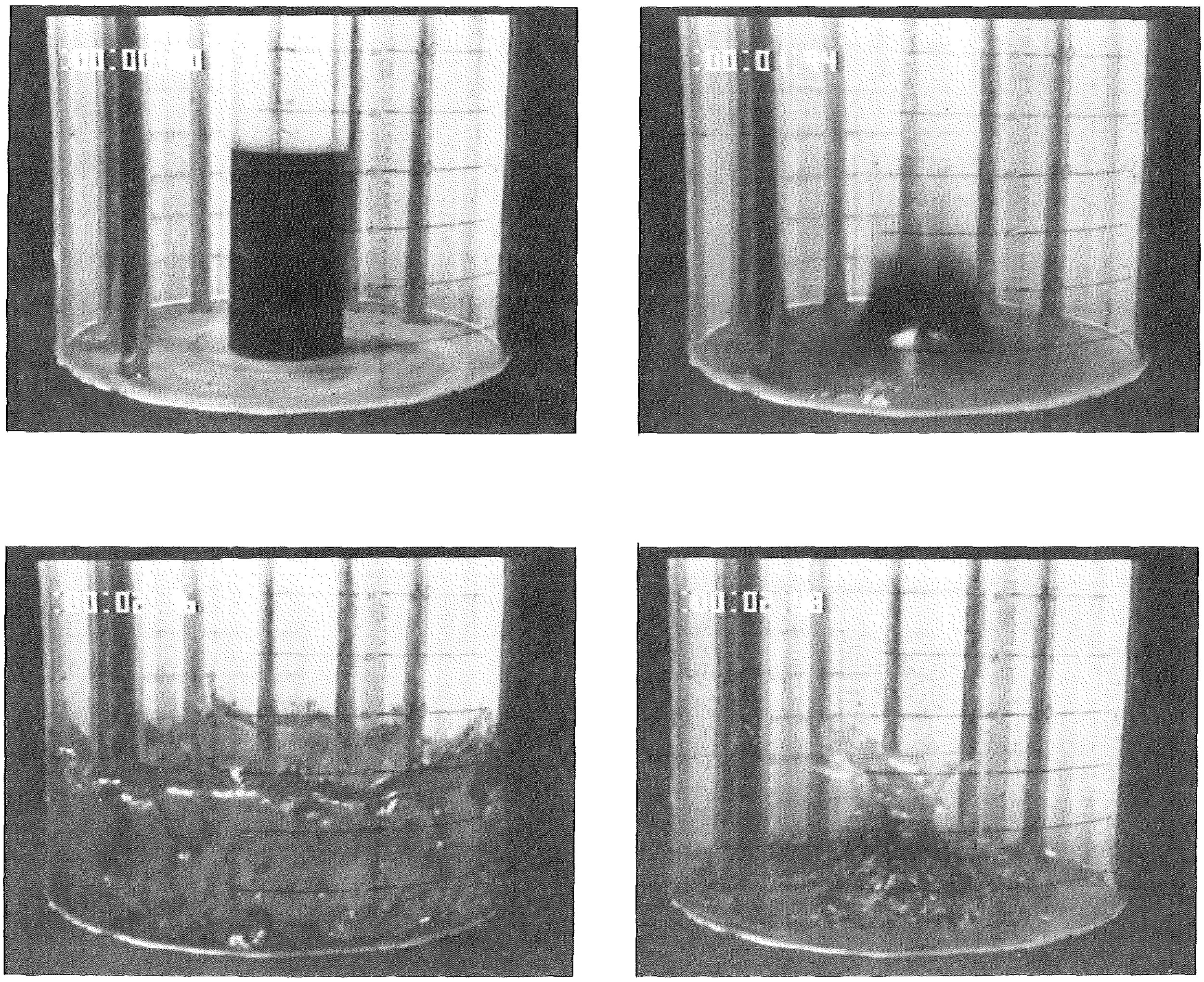

Figure V.4.4: Dam break problem SD-D1R-4 with a peripheral half bank of rods in the flow

SLOSHING TEST CLASSIFICATION : **SD** - Water step

| Experimental series signature | Diameter of central water cylinder [cm] | Height of water [cm] | | Typ of Obstacle/Disturbance: Rod structures around central cylinder | | | Slosh at outer wall | | Sloshes at pool center | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | inner cylinder | outer cylinder | Symmetry | Number of rods | Distance from center | Time max. height at wall [sec] | max. height at wall [cm] | Time of 1. Peak [sec] | Height of 1. Peak [cm] | Time of second Peak [sec] | Height of second Peak [cm] |
| D1RX-1 | 11 | 20 | 5 | full | 12 | 9.9 | 0.36 ± 0.02 | 11 ± 1 | 0.62 ± 0.02 | 23 ± 3 | 1.24 ± 0.04 | 30 ± 4 |
| D1RX-2 | 11 | 20 | 5 | full | 12 | 17.6 | 0.42 ± 0.02 | 11 ± 1 | 0.66 ± 0.02 | 16 ± 3 | 1.32 ± 0.04 | 35 ± 5 |

Table V.4.2: Experimental results for a water step problem with rods in the flow area

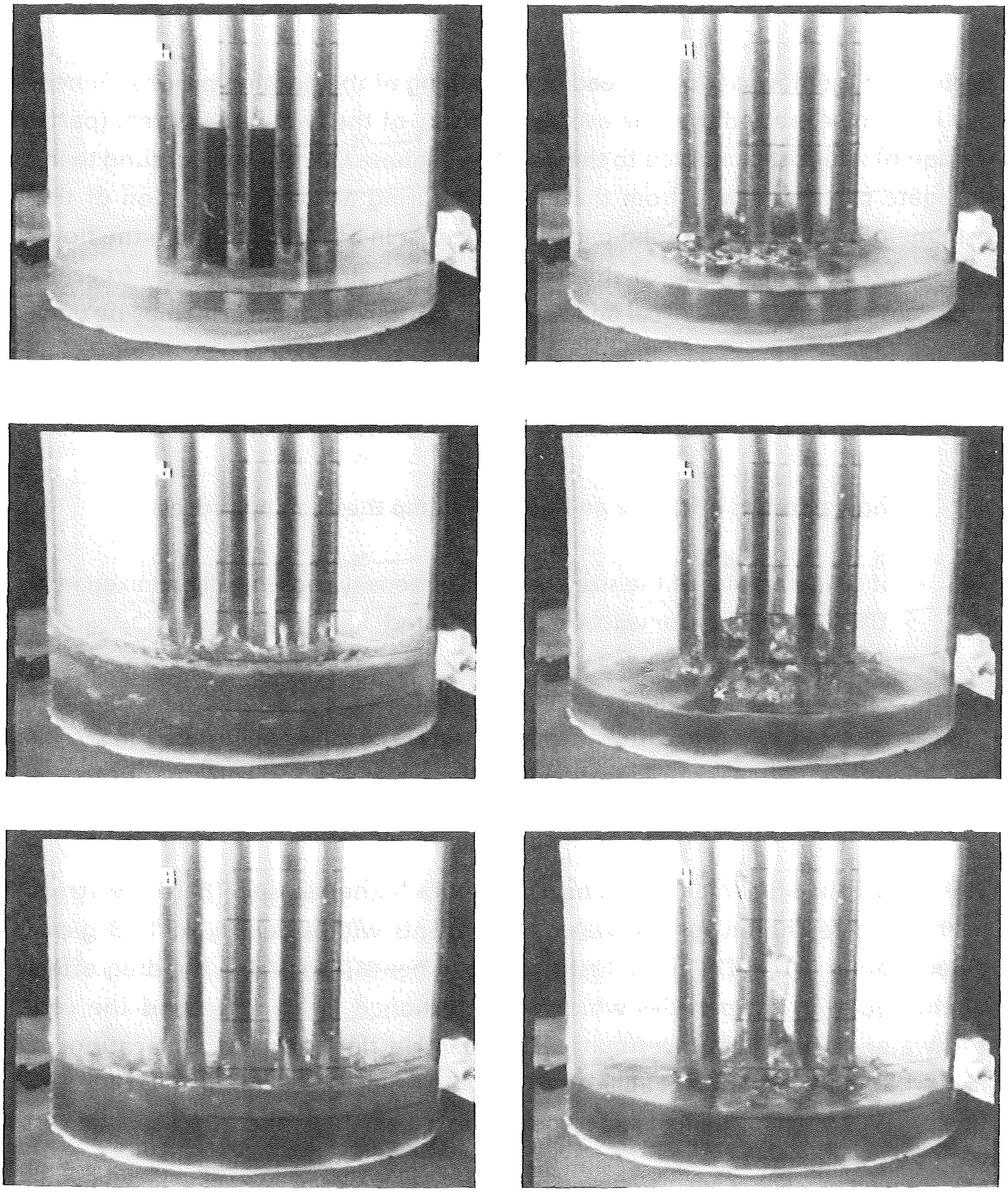

Figure V.4.5: Water step problem SD-D1RX-1 with a central full bank of rods in the flow

## V.5 Sloshing Test Series SE

Particles in the flow could also lead to a damping of the sloshing process. Generally it can be expected that the average viscosity of the two phase system (particle/liquid) is higher compared to the pure liquid phase /20/. The background to investigate particles comes from the fact that during accident simulation of the core meltdown phase /21/ solid particles may exist in a large amount in the flow. Due to break-up processes of still existing rest-pin structures, by local freezing processes and due to fuel/steel and fuel/sodium interaction particles may be generated.

The intention of the experimental series SE was to investigate in a first step

- how particles influence and possibly damp the sloshing process
- if solid particles of the size and specific density chosen will be mixed into the sloshing flow or will be early separated

For the experiments a special size and particle density was chosen. The shape of the particles was cylindric with a diameter of 2.5 mm and a height of 3 mm. This would approximately represent a scaled down pellet size and corresponds to the scaling also used in experiment SD.

The particles in a fuel-melt would have an $\sim$ 10 % higher density. Therefore acrylic particles were chosen for the water experiments with a density of 1.13 g/cm$^3$ (Specification: P 210 D). In the first two experiments (Tab. V.5.1) the drag effect of the liquid on the particles which were positioned in a ring around the central water column was investigated. The particle ring starts at a location of R = 14.5 cm for experiment SE-D1P-1 (Fig. V.5.1) and at 13.5 cm for SE-D1P-2. The bottom was filled in the first experiment with a 1 cm high and in the second test with a 2 cm high bed.

As can be seen from both experiments the liquid piles up when it hits the particle area and pushes them upwards the container walls while mixing with the flow. The pure water slightly passes the particles at the wall but generally the particles remain mixed into the flow which can clearly be seen in the centralized slosh. Due to the particles in the flow no symmetric straight sloshing peak can be built up but a cloud of liquid/gas/particles emerges. The coherence of motion is destroyed and the mixed liquid/particle flow is damped.

In the experiments SE-D1PI-1 and SE-D1PI-2 (Tab. V.5.1 and Fig. V.5.2) particles are released with the central water column. In the first experiment only 1/4 of the height is loaded with particles with a packing fraction of $\sim 0.6$. A sloshing process still develops under these conditions, however again the process is damped and no central sloshing peak emerges. A complete damping exists when the whole column is made up of a particle/liquid mixture. The flow stops after hitting the outer container wall.

As can be seen from these experiments a high particulate load in the flow leads to strong damping of the sloshing. Particles of the specific size and density chosen will largely remain mixed into the flow.

| SLOSHING TEST CLASSIFICATION : **SE** - Dam break | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Experimental series signature | Diameter of central water cylinder [cm] | Height of water [cm] | | Typ of Obstacle/Disturbance: Particles | | Slosh at outer wall | | | Slosh at pool center | |
| | | inner cylinder | outer cylinder | Particle height in central cylinder [cm] | Particle height in outer cylinder [cm] | Arrival time at wall [sec] | Time of maximal height [sec] | maximal Height Liquid/ Particles [cm] | Time of maximal height [sec] | Maximal Height [cm] |
| D1P-1 | 11 | 20 | - | - | 1 | 0.28 ± 0.02 | 0.40 ± 0.02 | 10/8 ± 1 | 0.80 ± 0.04 | 25 ± 5 |
| D1P-2 | 11 | 20 | - | - | 2 | 0.28 ± 0.02 | 0.32 ± 0.02 | 10/9 ± 1 | 0.78 ± 0.04 | 30 ± 8 |
| D1PI-1 | 11 | 23 | - | 7 | - | 0.24 ± 0.02 | 0.40 ± 0.02 | 15 ± 1 | 0.84 ± 0.04 | 30 ± 8 |
| D1PI-2 | 11 | 22 | - | 22 | - | 0.28 ± 0.02 | 0.44 ± 0.02 | 2 ± 1 | - | - |

Table V.5.1: Experimental results for a dam break problem with particles in the flow (The additional signature P refers to particles in the flow)

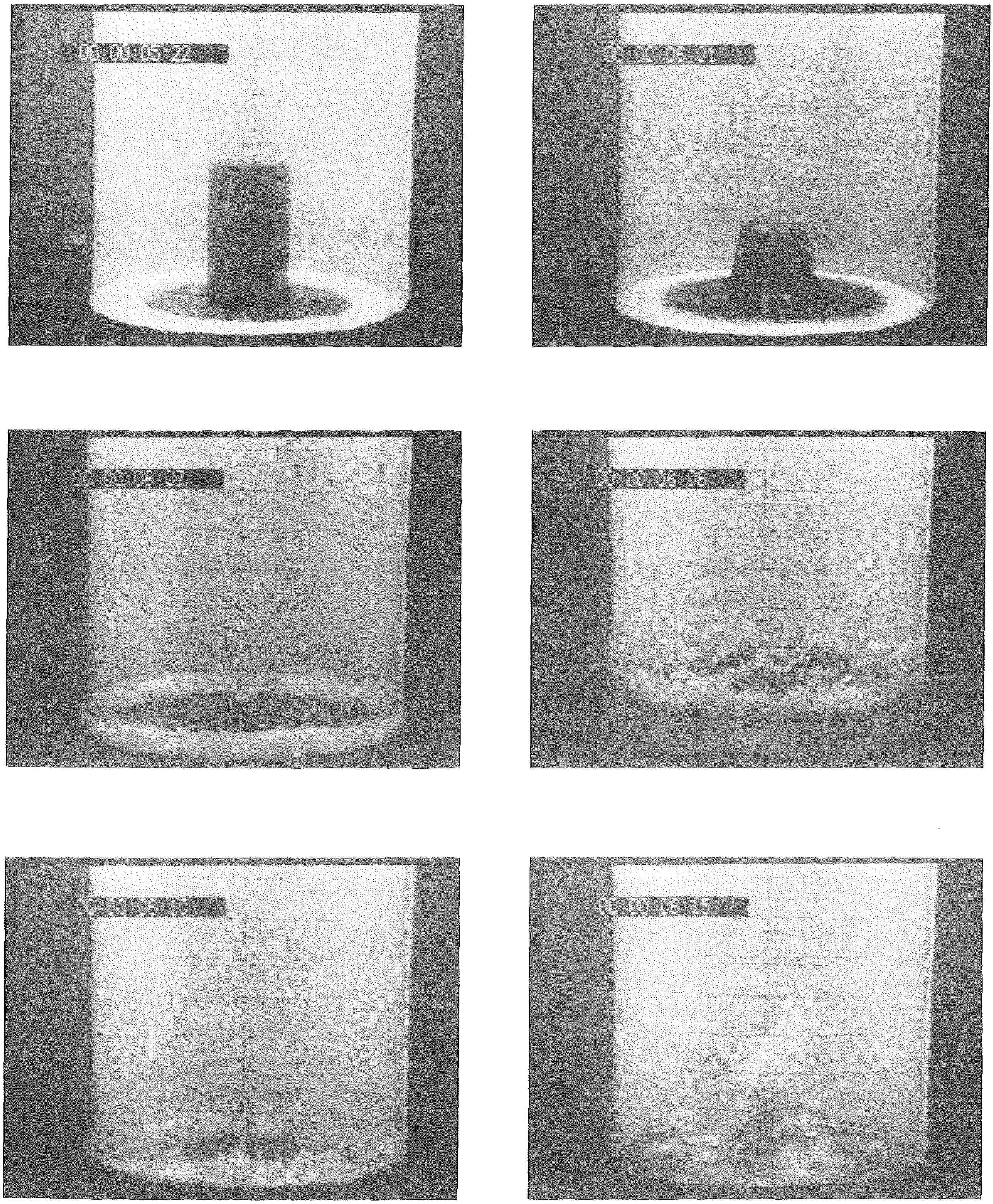


Figure V.5.1: Dam break problem SE-D1P-1 with particles in the flow

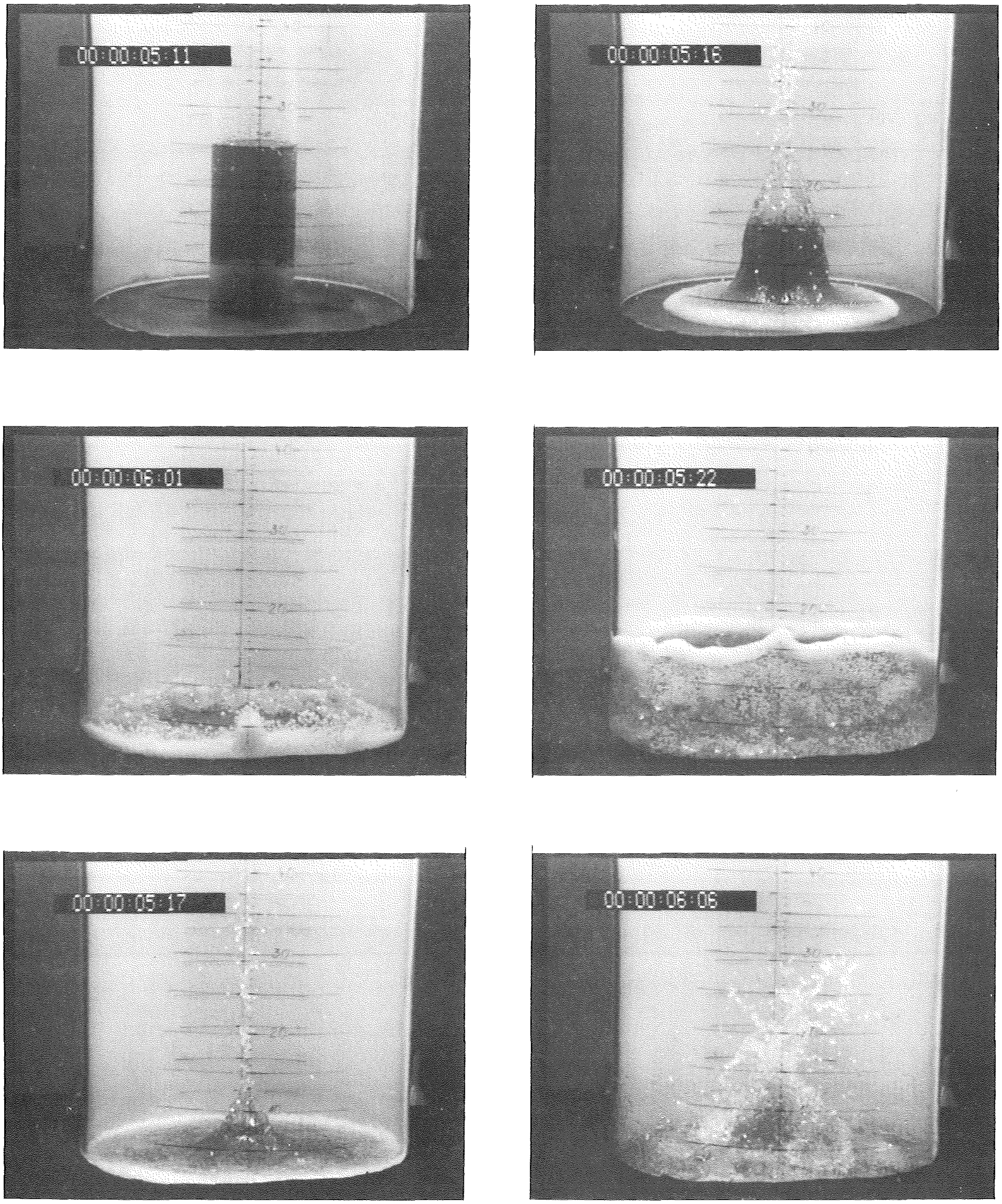


Figure V.5.2: Dam break problem SE-D1-PI-1 with particles in the flow

## VI. Final Remarks

Liquid sloshing is a phenomenon encountered whenever a liquid in a container has an unrestrained surface and can be excited. The impact of sloshing waves on structures has to be investigated in many engineering disciplines.

Liquid sloshing phenomena can be triggered e.g. by seismic effects in stationary containers or can be initiated by movements of the container itself. Examples for the first are large oil tanks and for the latter liquid propellant rockets. Characteristically the sloshing in these systems is a wave motion from side to side within the container.

A specific type of sloshing can result during the core meltdown of a liquid metal reactor (LMR). After formation of a large molten fuel pool a pressure pulse in the pool leads to an outward slosh of the fuel to the core periphery followed by a gravity driven flow reversal and a compaction of the fuel in the center of the core. This type of "centralized sloshing" can lead to energetic nuclear power excursions. Fuel sloshing processes can also be found in LWR meltdown scenarios.

Because of the importance of the sloshing in accident analyses the sloshing process should be understood and the simulation codes used must be able to describe this process adequately. An extensive literature research showed that no experimental information was available on the specific type of "centralized sloshing". Therefore it was decided to set up own simple experiments both to increase the phenomenological understanding and provide experimental data for benchmark exercises with fluiddynamics (accident simulation) codes.

To simulate the centralized sloshing phenomenon the sloshing problem was casted in a simple geometry and two typical configurations have been set up called a "(cylindrical) dam break problem" and a "cylindrical water step problem" for sloshing simulation.
For both configurations, a cylindrical container is divided into two concentric parts by a cylindrical diaphragm. In the first case only the inner cylinder contains water of a certain depth, the outer cylinder contains air. In the water step problem both - the inner and outer cylinder - contain water. The depth of the water in the inner cylinder was higher than in the outer one.

A series of basic sloshing experiments labelled SA (dam break and water step) were performed. Highly symmetric conditions were assumed for these reference set and no disturbances were planted into the flow. It appeared that the centralized sloshing process exhibits inherent instabilities of the converging wave packages which can easily disturb an effective liquid compaction.

The influence of various intentionally introduced disturbance on sloshing was investigated in the following sequence of experiments with the signature SB, SD, SC and SE.

The influence of large asymmetries on sloshing was investigated in series SB where the water column is released off-centered. In the experimental series SC and SD the impact of obstacles in the flow on the sloshing process was studied. In the series SC symmetric rings were placed as obstacles on the bottom of the pool to deflect the liquid stream. Rods in symmetric and/or asymmetric fashion were placed in the flow in series SD. Finally in series SE particles are placed into the flow which could damp the sloshing of liquids.

It can be concluded from the experiments performed that the natural instability of the centralized sloshing will be excited by structures within the flow. An otherwise effective sloshing process can thereby be damped and disturbed. For accident simulation this means that the chance for rapid fuel compaction and accumulation of high reactivity ramp rates can be diminished.

The experiments also served for benchmark purposes for fluiddynamics codes or for the fluiddynamics part in accident simulation codes. The necessary data (sloshing heights and times) are given and the flow structure can also be compared to the figures given in this report.

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