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Control of Surging in Concrete Pipe Distribution Systems*

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SYNOPSIS

Surging in concrete pipe systems preventing or delaying delivery of irrigation water necessitated field and laboratory studies to determine the cause and provide a means of control. The studies show how surging can be controlled by the creation of a system out of resonance, thus holding surge amplitudes within tolerable limits.

INTRODUCTION

A peculiar trouble sometimes occurs in concrete pipe distribution systems provided with overflow pipe stands. A periodic variation of flow or surge becomes, in some cases, so violent as to prevent delivery of water. First Bureau of Reclamation experience with it was in the pipe system in the Coachella Valley, Calif., where some of the lines surged so persistently that it became necessary to determine the cause and to find a solution. Some of the undesirable effects of surging are shown in Fig. 1 and 2. A pipe stand overflowing temporarily as a result of surge is shown in Fig. 1. Fig. 2 shows a meter stand overflowing because of an increase of supply due to surges in the adjacent pipe stand. Trouble is especially apt to occur where the topography permits the pipe lines to be run down the section lines with pipe stands at regular intervals. Such is the arrangement on the Coachella system, which is one reason surging was so frequent there. The pipe stands serve, of course, to prevent accumulation of static and water-hammer pressures which would occur in a closed conduit. If they were not present, costs would be considerably higher because of the reinforcement needed to protect the lines against the added pressures.

ANALYTICAL STUDIES

In the field, the surges appear as a periodic variation of flow in a pipe line for which a typical profile is shown in Fig. 3. The period of these changes ranges from about 60 to 100 sec. In their most violent form the surges may

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Fig. 1—Pipe stand overflowing due to line surge

cause the pipe stands to be completely emptied when the waters recede, and overflowing when they return. In their mild form little can be observed other than a periodic increase and decrease in the depth of water flowing over the baffles.

The first case investigated was that of a single pipe reach between open pipe stands. The effect of the inertia of the water in the pipe reach, of frictional resistance to flow, and of changes of level y in the downstream half of the pipe stand at the upstream end of the reach were accounted for. It was found that these individual reaches have natural periods of oscillation given approximately by the formula

$$T_n = 2\pi \sqrt{\frac{FL}{Ag}} \qquad (1)$$

Where

F = water surface area in the downstream half of the pipe stand at the upper end of the reach
L = length of the reach
A = cross-sectional area of the pipe
g = acceleration of gravity

The oscillation causes variations of flow and a periodic rise and fall of the water level y in the upstream pipe stand.

If the flow coming into a reach is now separated into two parts consisting of a steady average flow Q_0 and a superimposed sinusoidal variation, $q \sin 2\pi/T_o \times t$, it is found that the sinusoidal variation will set the reach into oscillation at the incoming period. If the period of the incoming flow variation and the natural period of the reach are widely separated, the amplitude of the driven oscillation will be small. As the period of the incoming flow approaches the natural period of the reach, however, resonance occurs and a driven oscillation of large amplitude can be produced. Resonance in vibrating systems is well known, but in the pipe reach it produces a surprising result. Because the baffle in the pipe stand at the lower end of the reach acts as a weir and can therefore accommodate considerable flow variations

Fig. 2—Surges in pipe stand cause meter stand to overflow

with only minor changes of level, the flow variations induced in the reach are readily carried over it. Since resonance generates flow variations in the pipe reach greater than those fed into it, the reach behaves as an amplifier in the sense that the amplitude of the flow variation discharged at its lower end is greater than the amplitude coming into it. The ratio of the outgoing to the incoming amplitudes is controlled by friction, but the friction losses in pipe lines are proportional to the square of the velocity, and at low flows friction is much reduced and amplification factors of six or more can be realized.

Amplification factors obtained as a result of these studies are shown in Fig. 4. This demonstration of the amplifying possibilities of a pipe reach between pipe stands is one of the important results of the analytical studies. Fig. 4 is actually a simple resonance chart. An exact accounting of forces would require that the changes of water level n behind the baffle, which acts as a weir, should be included. This factor has been omitted because it introduces complications

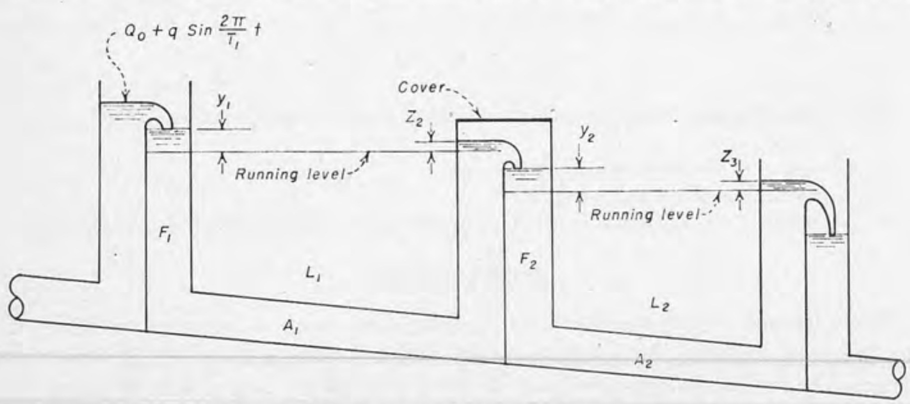

Fig. 3—System with two reaches having the common stand capped

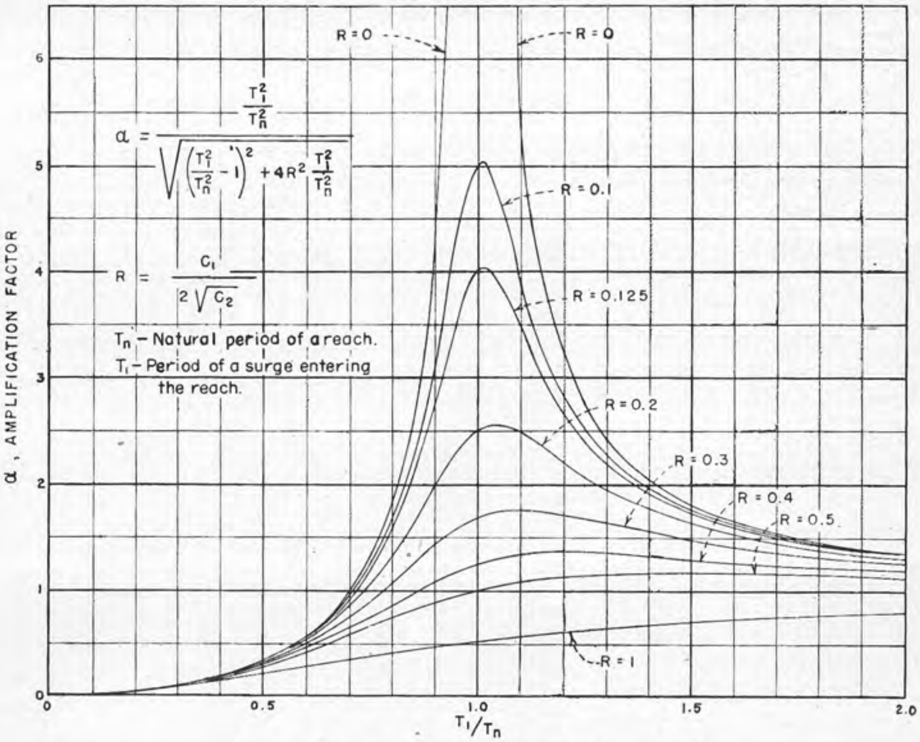

Fig. 4—Amplification factors

without altering materially the magnitudes involved. The effect of accounting for these changes would be to slightly decrease the amplification factors.

The quantities shown in Fig. 4, which have not been previously defined, have the following significance.

α = ratio of the amplitude of the oscillatory part of the flow leaving a reach to the amplitude entering the reach (dimensionless)

$C_1 = \frac{2\,g\,h_0}{V_0\,L}$

$C_2 = \frac{A_g}{F\,L}$

h_0 = head loss due to friction when the velocity in the pipe is the mean velocity V_0, ft

t = time, sec

T_1 = period of the incoming oscillation, sec

T_n = natural period of the reach, sec

V_0 = mean of the velocities in the pipe taken over a full oscillation period, fps

MODEL STUDIES

Even though these amplification possibilities exist, a pipe line would still run without surging if no source of initiating oscillations were present. An attempt to find the most persistent of these sources by field observation proved fruitless because of the impossibility of seeing into the pipes when water

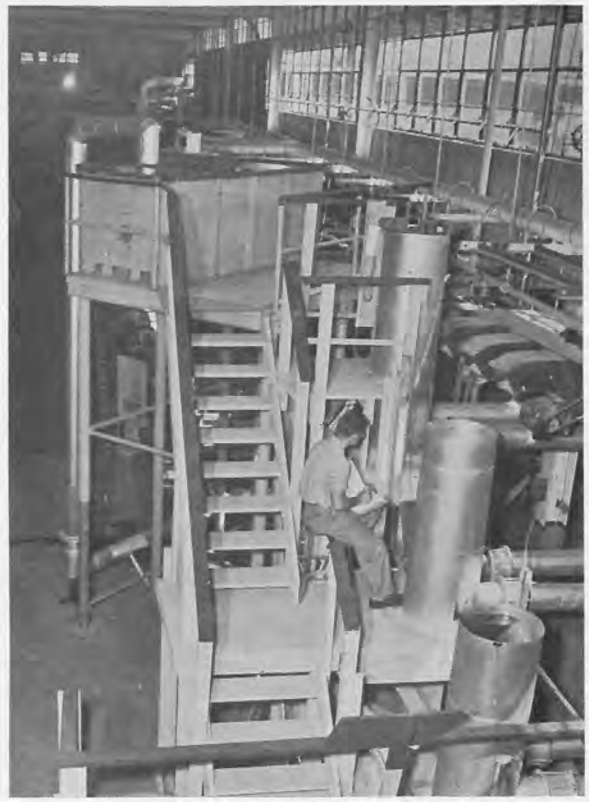

Fig. 5—Laboratory model of distribution system

was running in them. A laboratory model was therefore built and fitted with windows and transparent pipe sections which would permit such observations to be made (Fig. 5). The pipe stands were constructed of 20-in. diameter steel pipe fitted with sheet-metal baffles with adjustable crests. These pipe stands were connected by 125 ft lengths of 8-in. diameter pipe which had 180 deg bends at mid-length so that the pipe stands could be grouped together. Plexiglass windows in the pipe stands permitted an observer to see into the interior below water level. At the upper end of the system a half stand was so attached to a head box that the wall of the head box took the place of the baffle. Water was pumped into this head box and entered the model by flowing into the half stand. A plunger, operated by a variable-speed motor, provided a means of surge initiation. A length of transparent pipe was inserted in the 8-in. diameter line at the half stand as shown in Fig. 6.

When the model was being built it was feared that its small size relative to the field structures would somehow prevent the development of surging. These fears were dispelled, however, when water flowed through it for the first time because it proceeded to build surge immediately. After watching the flow conditions in the transparent pipe, the mechanism of the auto-oscillation which initiated the most persistent of the field surges became clarified. The nappe falling over the baffle carries air with it as it plunges into the pool on the downstream side of the pipe stand. This air appears as bubbles. Some of these float back to the surface but a part are carried into the pipe. These soon rise to the top of the pipe and collect into a long bubble. The end of this long bubble can be seen in Fig. 6. Since the pipe slopes, this long bubble tends to float back up into the pipe stand but is opposed by the impact of the water coming into the pipe from the pipe stand. As the long bubble grows, however, the flotation force grows with it and finally part of

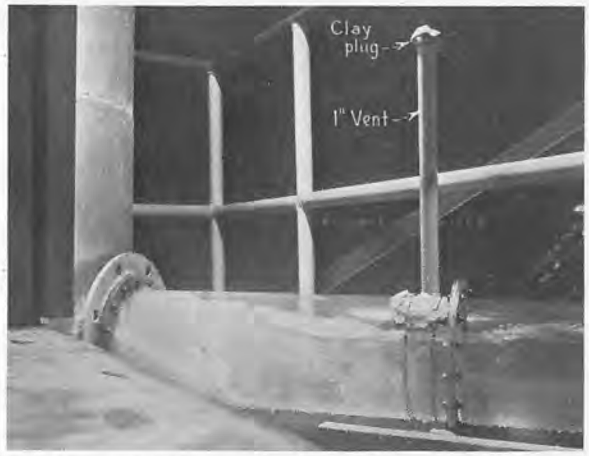

Fig. 6—Air bubble entrapped in transparent pipe section adjoining pipe stand

its volume blows back into the pipe stand. The volume vacated by the air is immediately filled with water whose kinetic energy delivers an impulse to the system and initiates an oscillation of small amplitude. This oscillation has the natural period characteristic of the reach. The velocity changes associated with the oscillation influence the time when the next blow-back will occur. Observation shows that this occurs at a time in the cycle which will permit energy to be fed into the oscillation. The accumulation and release of air thereafter locks into step with the oscillation and feeds enough energy into it to maintain it at a small amplitude.

Although this type of auto-oscillation is of too small amplitude to cause any trouble in the reach in which it originates, it does supply a periodic-change which can be amplified to a surge of unmanageable size in succeeding reaches. Surges can also be initiated by the transient oscillations set up by making or cutting off deliveries and in other ways. At any rate, experience seems to indicate that small amplitude surges are always present. Even the forces produced by winds blowing across the tops of open pipe stands seem to be capable of causing small initiating oscillations which can be amplified progressively in the lower reaches.

Other important information derived from the model include a demonstration of the amplifying potentialities of such systems, a check on the period of oscillation as computed by Eq. (1), the discovery of the effectiveness of covers for control of surging, and a general knowledge of the appurtenances needed to make the covers operate.

CONTROL OF SURGING BY USE OF COVERS

The covers are airtight lids or caps placed on the pipe stand. In the field they are reinforced concrete discs of appropriate size bedded on a rubber gasket and sealed with pitch. Sometimes pitch alone is used for a seal. The pipe lengths used to make the pipe stands are installed with the bell end up and the cover fits into the bell. Model testing indicated, and field experience confirmed, that certain accessory devices were needed to make the covers operate satisfactorily. An air relief valve is needed to relieve excessive pressures likely to occur when water is filling the pipe stand. If this valve is not provided the cover may be blown off. A valve to relieve excessive negative pressures is also needed. Operating stability may be obtained if these valves are omitted but the pressures inside the pipe stand may be so low as to prevent making deliveries of water from adjacent turnouts. The first type of vacuum breaker valve used consisted of a straight piece of pipe passing through a packing gland in the cover. The lower end of this pipe dipped below the surface of the water on the upstream side of the baffle. When excessive negative pressures were present, air would force its way out of the lower end of this pipe and bubble up through the water to relieve the vacuum. To permit a simpler installation, a short nipple and a 90-deg "L" were installed through the pipe stand, connecting to a riser pipe extending to the top of the stand on the outside. Under certain conditions this installation would not relieve the vacuum; therefore, it was necessary to also install a weighted mechanical valve, mounted in a goose neck of small pipe in the cover. The weight is supplied by a length of welding rod which can be cut off to adjust the pressure at which the valve will open. Each valve is tested and adjusted before installation. A water level indicator made of a length of transparent plastic tubing is sometimes added to permit observation of the water level in the pipe stand.

These simple and inexpensive devices have proved effective for control of surging in the Coachella system. They have been installed on many pipe stands in the system with the result that the surging common before their use is now rare. Stable and satisfactory operation is now the rule. Some minor troubles have been experienced, such as occurred when some moss screens became plugged and were removed for cleaning. The sudden increase of flow in this case initiated a surge of sufficient amplitude to lift some of the covers. Strangely enough, the covers often reseat themselves and become airtight again after these incidents. Another incidental advantage which accrues from the use of covers is the elimination of accumulations of trash resulting from unwanted objects being tossed into the open pipe stands.

ANALOG OPERATION

After the stabilizing effect of covers had been demonstrated in the model, the device was tried in the field. These field trials showed that a much larger number of covers was needed to produce stabilization than was thought to be necessary from the model indications. It was apparent, therefore, that some further study would be necessary to clarify the action of the covers. An analytical study was first attempted on a system with two pipe reaches having the common pipe stand covered, as shown in Fig. 3. This analysis was carried to the point where it became possible to compute the natural periods. It was found that there were two. It also became evident that the work required to analyze systems with several covers would be enormous. An electric analog device was then worked out to shorten this phase of the investigation. In this analog an electric current represented a flow of water in the hydraulic system. A voltage change represented a rise or fall of a

TABLE 1—CHECK OF NATURAL PERIODS FOR THE MODEL BY COMPUTATION AND ANALOG OPERATION

Open stands	Capped stands	Natural period, sec		
		Computed	Analog	Laboratory model
1	0	21.9	21.6	21.5
1	1	30.1 7.3	31.5 7.5	35.0 7.0
1	2	36.5 9.0 5.2	40.3 10.0 —	42.0 9.2 —

water level, an inductance represented the inertia factor and an electrical resistance represented the hydraulic friction loss.

These analog devices were inexpensive and worked well. By connecting the output of one of these devices to an oscillograph or an oscilloscope, the behavior of the hydraulic system could be easily studied. It was found that a system comprising n pipe reaches with $n - 1$ covered pipe stands between, and parts of the two open pipe stands at the upstream and downstream ends, had n characteristic modes of vibration and that each had its own natural period. Such a system will therefore resonate if an oscillation having a period near to any one of the natural periods is imposed upon it. Only the mode having the longest period, however, will ordinarily resonate strongly enough to be of importance. It appears also that a system created by capping pipe stands will resonate less freely than the individual pipe reaches which existed before the pipe stands were capped. Another discovery, which permits an important simplification of what would otherwise be a complicated situation, is that in the mode with the longest period all the pipe reaches have velocities which swing in unison. It is therefore permissible, as an approximation, to treat the whole system as an individual pipe reach for which Eq. (1) takes the form

$$T = 2\pi\sqrt{\frac{F}{g}\sum\frac{L}{A}} \quad (2)$$

where the summation sign indicates that the quotients of L and A for each of the pipe reaches in the system are to be added together.

From these analog studies also comes an explanation of how the covers produce stabilization. The action is threefold. Briefly, they (1) change the natural periods so that the systems can be thrown out of synchronism, (2) they reduce the number of systems capable of resonance, and (3) they replace the original reaches with systems which resonate less freely. A check of natural periods for the model as obtained from analog operation and by analytical means is shown in Table 1. The substantial agreement between the quantities derived by these different methods is apparent.

FIELD TESTS AND OBSERVATIONS

Two field tests were conducted on laterals modified for this purpose. In the first of these tests, the water surface in the pipe stands was modified to throw the successive reaches out of synchronism. In the first pipe stand an extra baffle was installed to cut down the area of the free water surface and thereby to reduce the value of F in Eq. (1). The next pipe stand downstream was left unmodified and the succeeding pipe stands were also left unchanged, but additional free water-surface area was provided by installing additional pipe stands and connecting them to the pipe. The whole arrangement was planned to make the periods increase in the downstream direction. There were nine pipe reaches in this lateral and the modifications were such as to make the ratio of the natural periods of succeeding reaches 1.4. This modification was unsuccessful, probably because the periods did not increase fast enough and because periods may have been imposed on the upstream end of the lateral which were longer than, or nearly equal to, the natural periods of some of the lower reaches. Reference to Fig. 3 will show that resonance factors greater than unity are always obtained in such cases. While the principle of making the periods increase downstream is doubtless correct, this test showed that the addition of enough area to control surging in this way would be economically burdensome.

The second test was performed by Concrete Conduit Co. which modified a lateral at its own expense by replacing the straight baffles with a circular riser pipe. This riser pipe was concentric with the pipe stand. With this arrangement the water entered the pipe stand by way of the riser and overflowed at the riser top to form an umbrella-shaped nappe. This concentric arrangement is very effective in preventing air entrainment, as was demonstrated in the model where its action could be observed through the windows. It is, in fact, the only device so far discovered which is effective in stopping air entrainment. In addition to preventing air entrainment, it was hoped that the greater free surface area obtained with this arrangement would reduce surging. This field test was also unsuccessful. The reason for failure of this test seems to be that the possibility of amplification is retained and some initiating oscillation is always present in the field. In the model, stable running could be obtained with the circular risers when the inflow was steady but the introduction of a small forced oscillation of the proper period, by using the plunger motor in the head box, demonstrated the presence of amplification in a most striking manner.

AIR ENTRAINMENT STUDIES

An investigation of air entrainment was made by testing a full-scale representation of a field structure having a straight baffle arranged in a laboratory testing flume with glass walls (Fig. 7). Many devices were tried with this representation to eliminate air entrainment, but no significant improvement was obtained from any of them. The tendency for air entrainment is remarkably persistent and does not cease, even with deep water cushions, until the baffle is nearly submerged.

USE OF GATES FOR SURGE CONTROL

Surging is possible in pipe lines when there is more fall in the line than is consumed by friction losses. This will be the case when the amount of water

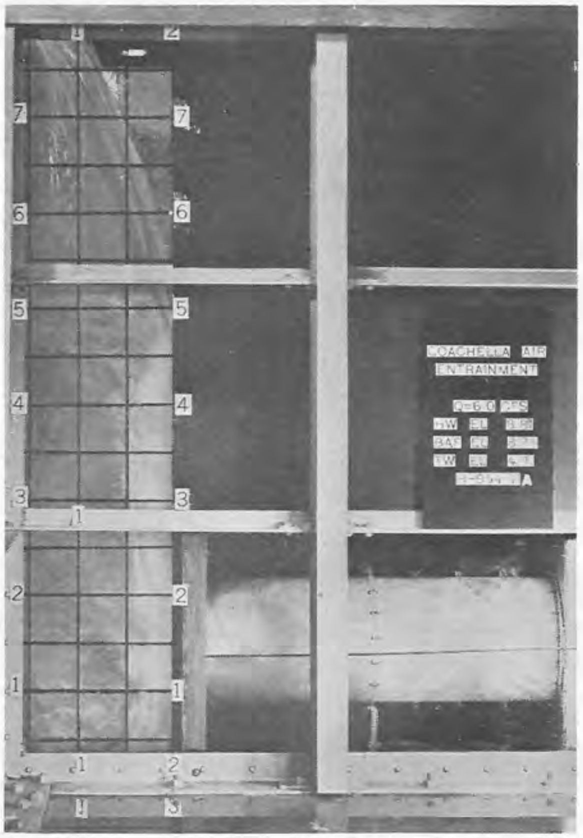

Fig. 7—Apparatus for studying air entrainment in pipe system

running in the line is less than its maximum capacity. One simple way to use up the excess energy is to install gates controlling an opening through the baffle or the entrance to the outgoing line. The physical basis for such an installation is sound and field experience shows it to be effective but much time is required to adjust the gates. When only a few deliveries are being made, this method of control may be tolerable, but when the line has to be operated near its maximum capacity the task of keeping the gates properly adjusted becomes burdensome. The use of gates in considerable numbers for surge control is, therefore, apt to make the distribution system excessively expensive to operate.

VENTS FOR SURGE CONTROL

Since air entrainment and release at the pipe stands was found to be one of the most persistent causes of surge initiation, the use of air vents to draw off the air accumulation in the pipes seemed to offer promising possibilities as a means of destroying these surges at their source. When the idea was tried on the model a definite improvement was noted but field trials were not so successful.

The reason for the failure of this device in the field may be found in the amplifying characteristics of the open pipe stands. The vent does tend to destroy the effectiveness of surge initiation by accumulation and release of air and even though air will often accumulate downstream of the vent and maintain an auto-oscillation by blowing back into the vent, the amplitude of the surge maintained in this way is much less than would be observed if the vent were absent. While these improvements may be realized, they are of no avail in a long line where strong amplifying possibilities are naturally present.

Consider, for example, the case of a pipe line 5 miles long with a pipe stand at ¼-mile intervals which, at a certain flow, has an amplifying factor of four in each reach. Then for a surge initiated in the first reach the over-all amplifying factor for the whole line would be $4^{19} = (27.5)\,(10)^{10}$. With such tremendous amplifying possibilities as this it does not matter whether the installation of a vent cuts the auto-oscillation surge amplitude in the first reach from 0.1 ft to 0.01 ft because the line will remain inoperable. So long as these amplifying possibilities remain it would not help greatly if vents completely destroyed auto-oscillation in every reach in the system, because there are other causes of surge initiation. An attempt to deliver water at a turnout on such a line would be immediately followed by violent disturbances. Even a gust of wind blowing across the top of one of the pipe stands would cause pressure changes sufficient to create a small oscillation in the adjacent reach which could be picked up and amplified in the reaches downstream. Disturbances originating in this way are eventually damped out by friction, and if no other disturbances occur the line will quiet down, but this possibility does not help if the pipe stands overflow in the meantime. The ability of such a line to respond to transient disturbances was demonstrated many times with the model. By holding a hand for a few seconds on the overflow crest at the head of the first reach and then removing it, surges sufficiently violent to cause the third pipe stand to overflow were often produced. Such demonstrations, backed by field experience, lead to the conclusion that it is futile to try to control surging with vents on a line where strong amplifying tendencies are present.

SUMMARY

The principal results of operating experience and laboratory investigations of the operating characteristics of concrete pipe distribution systems with pipe stands are:

1. Surging is likely to occur in pipe distribution systems with open pipe stands. Appearance of this trouble is favored if the construction of the line is such as to make the natural periods of the pipe reaches nearly alike.

2. For surging to develop there must be a source of initiating oscillation and an amplifying tendency.

3. Sources of an initiating oscillation seem always to be present in field installations. The most persistent is a self-induced oscillation driven by entrapment and release of air. Among other factors are disturbances due to making and cutting off deliveries and wind pressures.

4. The amplifying tendency is due to the phenomenon of resonance and the discharge characteristics of the overflow baffles. Trouble is most likely to occur in lines laid on a flat enough gradient to have a water cushion at the upstream end of each reach when the line is just filled. The amplification is dependent on the friction losses, and for this reason surging is most apt to occur with flows which are small compared to the maximum capacity of the line.

5. Surging can be controlled by the use of covers fitted with vents to relieve positive pressures and vacuum control devices to limit negative pressures. For best results, the covers should be applied to create systems which are out of resonance, with the

periods increasing downstream. The periods given by Eq. (2), if used with the curves of Fig. 4, will provide a simple means of evaluating the tendency of a line to build surge. Field observation indicates that lines with over-all resonance factors of 20 or less will generally prove satisfactory.

6. Covers do not completely eliminate surges but effectively and economically hold the surge amplitudes to tolerable magnitudes.

7. Since making and stopping deliveries will always induce transient oscillations, it is useful to provide ample freeboard between the cover and the top of the baffle.

8. Vents are ineffective as a means of surge control.

ACKNOWLEDGMENTS

Some important early analytical work was done by Kenneth L. Fienup. Investigations of the natural periods of pipe systems with covers were made by G. G. Balmer who also assisted with the design of the electric analogs. C. R. Daum supervised the building and operation of the analogs and also contributed to their design.

The Concrete Conduit Co., Colton, Calif., modified at their own expense one of the laterals in the Coachella system in an effort to find a solution of the surging problem. Their work contributed important information on the nature of the surging phenomenon.