A Seismic Test of Large-Scale Liquid-Filled Piping* 
(Related to Liquid Boundary Conditions)

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In order to study piping dynamic response related to internal liquid behaviour and liquid boundary conditions during earthquakes, a large-scale seismic test has been conducted using a 15 m × 15 m shaking table. A test piping system which is 40 m in length and 254 mm in inner diameter was supported by two main and some auxiliary frame structures on the shaking table. A long straight part of the piping system was extended outside of the shaking table and supported by uniaxial smooth-sliding supports. In the vibration test, some conditions of the internal liquid and their effects were investigated. The experimental results showed that the internal liquid behaved dynamically, not as a simple lumped mass, especially under a pressurized condition, and the liquid boundary conditions influenced on the system behaviour during strong excitations.

**Key Words**: Pipeline, Seismic Motion, Vibration Coupled with Fluid Motions, Vibration Test, Negative Pressure

1. Introduction

The internal liquid of a piping system has been treated as a lumped-mass in seismic response analysis. The lumped-mass model of liquid, however, is not always reliable for exact analysis. The liquid in the piping may have some dynamic effects on the piping seismic response due to pressure wave propagation.

This problem has already been investigated in the past years by several theoretical and experimental methods(1)–(12). However, in order to verify the liquid dynamic response, experimental investigations using the large-scale piping model are required. Thus, the authors have conducted a vibration test of liquid-filled piping in which some types of liquid boundary conditions are considered. This paper presents the main results of the experiment. Analytical simulation and further discussions are given in Ref. (13).

2. Piping Model

2.1 Test case and test conditions

To clarify the liquid effect in piping seismic responses, a 40-m-long piping model, which consists of a 25 m long basic piping system on a large-scale shaking table and an extended straight pipe beyond the table, was set up. Four basic test conditions of the internal liquid were used for this structural model:

1. no water, 
2. completely closed and pressurized system, 
3. open static system (free surface tank and closed end), 
4. open flowing system (free surface tank and pump).

Condition 4 above was used to examine the pump boundary effects so the flow rate (about 10 cm/s) was very slow and the effect of stationary flow was assumed to be negligible. In cases 2–4, two models (with orifice and without orifice) were used. Table 1 shows the summary of the test cases and test conditions.

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2.2 Details of test model

2.2.1 Main features Figure 1 shows an outline of the model. The piping has some bends but no branching point except for the connecting hose to the tank or pump. One end is a structural anchor to the reaction frame. At this position, two types of liquid boundary conditions (closed end and tank) are considered. The boundary condition can be changed by valve operation. A small reservoir tank was fixed at the upper part of this reaction frame. One end of the straight extended piping was connected to the piping on the shaking table by a flange, and the other was free. Both ends of the piping system were closed by flange plates, and a short branch pipe and hose (50 mm in diameter) were attached for connection to the tank or pump. Three shut valves, an inlet valve to the tank from the pipe, a return valve to the pump from the tank and a supply valve to the pipe from the pump, were used.

A dummy valve weight and flange connection for orifice insertion were equipped at the center part of the model. The position and weight of the dummy valve and the supports were designed for 5 through 10 Hz of the first natural frequency.

2.2.2 Pipe supports The main part of the model was supported by an anchor and structural restraints. A plate support (9 mm in thickness) was used near the connecting flange of the extended piping, which restricted perpendicular or torsional motion of the pipe. The spring constant of this support was measured to be about 490 kN/cm (50 tonf/cm) for the pipe axial direction. The extended piping beyond the table was supported by a smooth-sliding mechanism. The motion of the extended piping is free in the axial direction and restrained in other directions.

2.2.3 Liquid conditions In a completely closed and pressurized model (D or F-1), the piping was filled with water after valve closure and the air contained in the piping was removed. The internal pressure was about 490 kPa (5 kgf/cm²). A hand pump was used for pressurizing. In the open static model (E-1 or F-2, free surface tank and closed end), a valve located at one end of the model, which supplies water to the bottom inlet of the free surface small tank (1 m³ in capacity), was opened and the system was filled with water. In this case, the return valve to

<table>
<thead>
<tr>
<th>Test case</th>
<th>Liquid boundary condition</th>
<th>Test case</th>
<th>Liquid boundary condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>No water</td>
<td>F-1</td>
<td>Closed-Orifice-Closed</td>
</tr>
<tr>
<td>D</td>
<td>Closed-Closed</td>
<td>F-2</td>
<td>Tank-Orifice-Closed</td>
</tr>
<tr>
<td>E-1</td>
<td>Tank-Closed</td>
<td>F-3</td>
<td>Tank-Orifice-Pump</td>
</tr>
<tr>
<td>E-2</td>
<td>Tank-Pump</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Note) #1 Orifice position: intermediate point of piping
#2 Internal pressure (max.): 500kPa(D, F-1), 20kPa(E-1, F-2), 150kPa(E-2, F-3)

Fig. 1 An outline of test piping
the pump and the supply valve from the pump were closed. The maximum pressure was about 20 kPa.

In the open flowing system (E-2 or F-3, free surface tank and pump), after setting the same conditions as above, the three shut valves were opened and the pump was operated. In this case the flowing water returned to the pump suction from the tank via a long flexible hose which was not used in the test system. The pump was driven by 3.7 kW electric power and has the performance of flow rate of 0.63 m³/min at 22.5 m head. The maximum pressure during operation was about 150 kPa at the plate support position. In cases F-1, 2 and 3, a limiting orifice plate with half the diameter of the pipe inner section and a thickness of 5 mm was used.

3. Test Procedure and Measurement

As the first step of the experiment, the pressure wave velocity in the liquid was measured by a mechanical shock on the flange plate at the free end. After checking the measured value, various input vibration tests followed. Two types of input waves to the shaking table were used as follows.

1. Random wave having a bandwidth of 5 through 30 Hz
2. Simulated earthquake wave

The located measuring points of pipe acceleration, liquid pressure, pipe displacement and strain are shown in Figs. 2 through 4. A digital recording system was used with 200 Hz sample frequency and 64 channels for the shaking table test, and with 2 kHz and 8 channels for pressure wave velocity measurement. Pressure measurement and data processing were performed on the dynamic response exclusive of static value.

4. Test Results and Discussions

4.1 Pressure wave velocity

Pressure wave velocity was measured using increased sensitivity of the amplifiers. Typical propagation waves and the results under each test condition are shown in Fig. 5 and Table 2. The velocity was estimated from the initial main peak propagation as an averaged value. In most cases, under better conditions of air removal, about 1250 m/s velocity was measured, but a lower value of about 1000 m/s resulted in some cases. In case of the open static systems E-1 and F-2, some scattering was observed in the measured values. The measurement was not performed in the case of the flowing condition because of pump pressure noise.

4.2 Basic comparison of dynamic response under each liquid condition

The responses of random wave excitation were compared to examine the difference for each liquid

Fig. 2 Location of measurement points (acceleration)

Fig. 3 Location of measurement points (pressure)
Table 2  Pressure wave velocity by measurement

<table>
<thead>
<tr>
<th>Case</th>
<th>Model</th>
<th>Velocity(m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>40m C-C</td>
<td>1257 (P1-P12)</td>
</tr>
<tr>
<td>E-1</td>
<td>40m T-G</td>
<td>1218 (P4-P12)</td>
</tr>
<tr>
<td>E-2</td>
<td>40m T-S</td>
<td>-</td>
</tr>
<tr>
<td>F-1</td>
<td>40m C-O-C</td>
<td>1106 (P1-P12)</td>
</tr>
<tr>
<td>F-2</td>
<td>40m T-C-C</td>
<td>1107 (P10-P12)</td>
</tr>
<tr>
<td>F-3</td>
<td>40m T-O-P</td>
<td>-</td>
</tr>
</tbody>
</table>

(Note) Abbreviation of Boundary Point
C: Closed, T: Tank, P: Pump, O: Orifice

Fig. 5  Typical measurement of pressure wave propagation (about 1270 m/s from P-12 to P-1, model D)

condition. Figure 6 shows the main part of the measured waves of shaking table acceleration. Only a slight difference of waveform and of acceleration level among the above test cases can be seen. In the waterless condition, the waveform differs somewhat from those of the water-filled cases.

Figure 7 shows the comparison of pressure response waves. There are remarkable differences among the six types of liquid conditions. The response wave shows a symmetric form in the pressurized condition (model D or F-1), but there are some biased shapes in E-1, 2 and F-2, 3 probably caused by negative pressure. The figure also shows the reduction of pressure response in the piping with an orifice. In those cases, no notable difference was observed between the pressure or the pipe axial force in both sides of the orifice. The pressure response P-1 near the tank could rise above a zero value even in the open

Fig. 6  Main part of shaking table acceleration waves for seven test cases (random wave excitation)

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system because of the boundary effect of a closed flange and a small pipe branch to the tank.

Figure 8 gives the comparison of the transfer function of pressure to shaking table acceleration in three conditions without an orifice. The figure shows two clear peaks, 15.2 Hz and 19 Hz, in model D. The latter peak is also seen in model E-2. The former peak exists only in model D. A simple model of the 40-m straight rigid pipe and the pressure wave velocity in Table 2 can give a first natural frequency, 15.7 Hz, of liquid column resonance. In the real model, it is more or less lowered by the coupling effect of the liquid and the piping stiffness. Therefore, the former peak in Fig. 8 shows a liquid dynamic effect.

The same type of response functions of pipe acceleration are compared in Fig. 9. The peak at 15.2 Hz exists only in model D. This peak is considered to be the result of liquid dynamic response. On the other hand, the peak at 19 Hz exists in every case of Fig. 9 and has about the same value. This response is produced by a natural vibration of the large support frame (S2 in Fig. 2). Of course, at this frequency, pressure can rise to an equivalent value of the liquid lumped mass effect. The pressure response at 19 Hz in Fig. 8 can be explained by this effect, although some dispersion is seen in the open-type model.

Figure 9 also indicates the same level of response at 6.2 Hz, irrespective of the liquid condition. This peak indicates that the piping response did not depend on the liquid resonance effect. That is, it resulted from the lumped mass effect of the liquid. Because of

Fig. 7 Comparison of liquid pressure response waves (P-1, random wave excitation)

Fig. 8 Comparison of pressure response functions for three liquid conditions (kPa/Gal)

Fig. 9 Comparison of acceleration response functions for three liquid conditions (Gal/Gal)
Fig. 10 Comparison of pipe acceleration response waves (A10Z, random wave excitation)

low frequency at this peak, pressure response could not occur.

Figure 10 shows that pipe accelerations in the perpendicular horizontal direction have about the similar tendency as in pressure response comparison. This correspondence can be considered as a result of the liquid acting force to the piping, that is, the pressure difference between two elbows (P-8 and P-9) can generate shaking force in the perpendicular direction. That effect is clear in the closed system but is less in the open low pressure system.

It is supposed that in the long straight part, the higher pressure response and the effect on piping response can increase. The test result has confirmed such a prediction of pressure, acceleration and displacement response of the piping. As an example, the relative displacement of the pipe to a plate support (plate deformation), is shown in Fig. 11, the response functions (Fig. 12) of which have an single peak of 15.2 Hz for model D, two peaks of 14.3 Hz and 19 Hz for model F-1, and a slow peak near 19 Hz for other cases.

Summarizing the above results, three types of liquid-filled piping response can be observed.

1. A liquid condition, in which the resonance of liquid column can increase, produces a marked

Fig. 11 Comparison of relative displacement response waves (D-2, random wave excitation)

pressure response and its dynamic shaking force to the piping. The maximum response and its exact frequency will depend on the

Fig. 12 Amplitude responses of relative displacement D-2 for four liquid conditions (mm/Gal)

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dynamic coupling of the liquid and piping structure. This type of response can occur in closed and long piping systems.

2 Besides the liquid resonance accompanying the above coupling, a system has some resonances of the piping or support structure in which the liquid approximately behaves as a lumped mass. In this case, the liquid pressure response cannot grow as high as a resonance. Many small systems will show this type of response.

3 In an open or low pressure system, pressure energy dispersion or restriction due to negative pressure could dominate the system behaviour. Namely, pressure response and its effect, as described above in 1, would decrease somewhat. But, to the contrary, negative pressure can impact local positions of the piping, as described later.

4.3 Distribution of response value and liquid condition

To examine the relationship between the liquid condition and response distribution in a piping system, maximum response values by the same random excitation were summarized for main measurement points. In this comparison, the frequency characteristics of maximum response are not considered. A numerical filtering for 0 through 33 Hz was used in the analysis.

Figure 13 shows the pressure response distribution for three cases without an orifice. This roughly indicates a first mode of liquid resonance, clearest in model D, and a node with minimum response is near P-10. In Fig. 13, P-9 of model D could not be measured because of damage, but other tests for the same liquid condition have shown the minimum value at P-10. The position of P-10 is not the midpoint of the pipeline but is 15.7 m from the free end. Straight piping of the same length would have a resonance node at the midpoint (namely, 0.9 m from P-8 to P-9 in this case). Then, the distribution mode in Fig. 13 may be explained as the result of pressure wave reflection at the elbow and/or coupling with structural stiffness.

Acceleration responses are similarly summarized in Fig. 14 including the case of no water. Some measurement points show responses which depend on the liquid condition and other constant responses which do not. It is seen that the liquid boundary condition gives the larger effect to the responses in the shaking direction (horizontal X) than to those in other directions.

The acceleration A13-15X of the long part indicates a lower response for model D than the other models, contrary to the results of relative displacement, D-2, as shown in Fig. 11. This is because the high-frequency component (19 Hz) is larger for models E-1 and E-2 than for model D in absolute acceleration response A13-15X.

The typical effect of the orifice are compared as shown in Fig. 15 and Fig. 16. The pressure response is considerably decreased by the insertion of the orifice. In acceleration, a constant pattern cannot be seen, but a clear difference exists in vertical response A8Y.

4.4 Response by high-level simulated earthquake wave excitation

The piping model in each liquid condition was excited by a high-level simulated earthquake wave...
and the results were compared. The maximum table acceleration was about 2.1 G for each condition, and the difference observed among waveforms was sufficiently small, similar to the random wave excitation. The results show the liquid effect almost in the same manner as for random excitation.

As a typical result, Fig. 17 shows the comparison of pipe strain responses in five liquid conditions. The bending or elbow hoop strain near the long straight pipe should be noted. This comparison is simply summarized as follows:

- Cases of high response: D, E-2;
- Cases of low response: F-3, F-2, E-1.

Namely, the response level depends on internal pressure and the orifice.

The above results relate to the vibration mode including the perpendicular direction displacement of elbow 54LA. It is a low frequency (6.3 Hz) main mode. Although the liquid behaves like as a lumped mass at this low frequency, the difference in the maximum value is very clear, as shown in the elbow strain of Fig. 18. The maximum elbow strain of model D consists of a single peak. Acceleration at A10Z also shows a similar single peak. Exclusive of this peak, about the same response can be seen in models D and E-2. Hence, the high response at this single peak is supposed to be due to the effect of the liquid shaking force formerly described and/or to hammering by negative pressure.

4.5 Negative pressure and its effect on piping response

High-level sinusoidal excitations have generally caused high amplitude pressure, and reached negative pressure at the closed end of the pipe. Even in an open system, pressure response, such as impact probably due to negative pressure, was observed. High-level simulated earthquake excitations have also produced impact response of pressure or acceleration. For this type of response, hammering noise of the liquid and abnormal response of the pressure gauge were observed.

Figure 19 shows a typical behaviour of pressure gauges which were attached to the closing flange plate of the extended straight pipe. The pressure gauge P-14 at the upper position showed the abnormal response due to slight damage to the diaphragm (9800 kPa in capacity), and on the contrary, P-12 at the pipe axial level exhibited a normal response. Both gauges in Fig. 19 showed a restriction of negative pressure, but hammering by the cavity is supposed to have occurred strongly at the upper part of the pipe section.

This type of behaviour was also observed at the elbows (P-9 etc.). Negative pressure response and liquid hammering have the potentials to locally damage pipe fittings or instrumentation, but they also behave as a damping factor of the system by the restriction of pressure response.

5. Conclusion

Vibration tests of a large piping model in various

![Fig. 16 Acceleration response of piping with and without orifice (random wave excitation)](image1)

![Fig. 17 Comparison of pipe strain response by simulated earthquake wave excitation](image2)

![Fig. 18 Response waves of elbow strain for three liquid conditions (simulated earthquake wave excitation)](image3)
liquid condition have shown the liquid dynamic effect. Seismic responses of a large piping system depend not only on structural conditions but also on liquid boundary conditions. Negative pressure in the liquid due to seismic excitation may cause local impact on the piping system.

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