

DYNAMIC INDUCED FAILURE IN AIR VALVE DUE TO PRESSURE TRANSIENTS IN BURIED IRRIGATION PIPELINE

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ABSTRACT: The present work investigates the response of an air valve in terms of dynamic pressure due to kinematic support excitation. For the purpose of the analysis a full-scale model was installed in a laboratory setting, employing a shaking table to induce the dynamic input excitation in the form of a sine wave. The considered valve is an air release type, as a representative of those widely used in Japanese irrigation systems. Experiments were performed regarding the initial static pressure and the shaking parameters. The dynamic pressure and the movement of the valve's float was measured to establish the relation between the peak pressure and the mechanical response of the valve. After the analysis of the measured data some results and discussions are presented.

KEY WORDS: air valve, shaking table, dynamic load, internal pressure.

1 INTRODUCTION

Buried pipelines play a vital role in agriculture and rural engineering all over the world. Thousands of miles of buried pipelines have been placed as integrated irrigation systems to accommodate the agricultural production. Irrigation pipe systems have to maintain fluctuations of the internal pressure due to day-by-day operations of pumping systems, opening and closing of valves and other interferences, as well as due to out-of-regular operation conditions. Irrigation systems consist of various pipes, fittings, valves and other equipment depending on the kind of system, type of installation and operational conditions.

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During the 2016 Kumamoto earthquake, numerous failures of air valves on pipes of irrigation systems were recorded in Japan [1]. Earlier, similar failures were registered during the 2011 Tōhoku earthquake, too. Thus, the question was asked about the failure mechanism of the air valves at such pipelines during earthquakes which caused operation interruptions and big losses, respectively.

The first suggestion was that the failures were caused by hydraulic transients. It is well known that earthquake-induced hydraulic transients in water conveying pipes can result in pressure pulses of relatively high magnitude. However, there are almost no available sources on the problem of the failure of air valves on water pressure pipes especially during seismic excitation, due to the following reasons. On the one hand, the hydraulic transients in this case developed during an earthquake and not due to a change of the operational conditions, and this is a specific phenomenon. Furthermore, the operational performance of such an air valve requires specific modeling. The physical problem becomes much more demanding if fluid-structure interaction in the system has to be considered. On the other hand, air and control valves are usually modeled in Lifeline Earthquake Engineering as concentrated masses, and although widely used – Tsfamariam and Goda [2], Taucer and Apostolska [3], this approach does not represent adequately the real structural performance of the particular mechanical device, moreover, with respect to specific operational conditions.

The above-mentioned reasons lead to the necessity of either an extremely complicated modeling approach of the observed phenomena related to the earthquake-induced air valve behavior, or development of a special analysis procedure consisting of implementation of different models and approximations, respectively. Below, a few examples are given as an impression of the literature fields related to the considered case here.

Hydraulic transients in pipeline systems have been an object of scientific interest for more than a century. Numerous models of pipeline systems were developed by many researchers considering various configurations, boundary conditions and equipment components. In general, transient flow represents transition flow state. It is developed when flow conditions change from one steady state to another due to an introduced disturbance of the flow parameters, Chaudhry [4]. The most common types of disturbances are starting or stopping of pump/turbine, opening or closure of valves, changes in transmission conditions. Furthermore, a special case is the so-called “column separation” when the flow pressure drops to the vapor pressure of water, and then cavities are formed in the water column. During the subsequent pressure recovery, the cavities collapse and large pressure shocks can occur, Collins et al. [5], Lee and Leow [6]. In regard of the triggering mechanism, another particular case is the support excitation of the pipe system in the case of an earthquake. There are not many studies dealing with this special case, for example Kolic and Trifunac [7] and Wang [8].

To prevent pressure fluctuations or to decrease pressure amplitudes during transients, especially for avoiding column separation, control devices such air valves are usually installed at the potentially affected points in water supply and irrigation systems. Important related general recommendations to the design and operation of valves on water pipe systems are formulated in [9].

A comprehensive review on the air valve design, including size and positioning along the pipeline, was presented by Ramezani et al. in [10]. It is concluded that although there are some studies on air valves adjusting based on transient conditions, in-depth studies on valve sizing still need to be performed. The authors reported that a limited number of experimental studies on air valves dynamic behavior were published and highlighted the need of experimentally based approach in air valves numerical modeling.

Some of the studies based on laboratory experiments were currently reported by Bergant et al. [11], Matuda et al. [12]. Bergant et al. [11] performed an experimental study on the dynamic behavior of air valves under controlled, dynamic flow conditions in a test facility. The performed experiments showed interesting results regarding the relation between the speed of closing and the subsequent considerable positive pressure surges as well as a delay in the valve response to a sudden pressure drop. It was noticed that the response of the valve is not instantaneous as traditionally assumed in literature on transient flow in liquid conveying pipelines. The development of negative pressures and possible cavitation is another important problem in this field, Gao et al. [13].

A laboratory model of an air valve attached to a pipe was studied experimentally by Matsuda et al. [12]. During the tests, the initial pressure in the model was varied and vibrations were applied to the model. The results showed that the pressure fluctuations follow the vibration pattern with a magnitude depending on the magnitude of the initial pressure.

Based on the above presented short review and in the lack of experimental studies, this paper is aimed at particular knowledge gapfilling on the dynamic behavior of an air valve under kinematic excitation. The study presented further below was performed by an experiment on a shaking table of a full scale irrigation system part containing air valve of the damaged type during the mentioned earthquakes in Japan. The carried out experimental analysis represents a research phase logically following the information survey on the real performance of such valves [1] and the preliminary tests performed by Matsuda et al. [12].

Furthermore, the motivation for this study also is based by the fact that failures of air valves installed on irrigation pipelines are recognized as a factor influencing the normal operation of water-conveying systems in general.

2 EXPERIMENTAL MODEL AND APPLIED METHODS

2.1 TEST INSTALATION AND INSTRUMENTATION

For investigation of the failure mechanism of an air valve caused as suggested by pressure fluctuations in a pipeline during seismic excitation, a full-scale model was built of part of an irrigation pipe containing such air valve. The experimental installation was constructed in laboratory conditions at the National Research Institute for Rural Engineering (NIRE) in Tsukuba, Japan.

NIRE's Three-dimensional Earthquake Testing laboratory facilitates the study of large-scale models of structures under various dynamic loads. It is equipped with a shaking table 6.00 m x 4.00 m, that allows different types of loading in the form of harmonic load with a wide frequency range as well as of real or artificial kinematic time history records.

The air valve used in the laboratory model was of air release type as representative for those widely used in Japanese irrigation systems. The valve with its main components as a corpus (i.e. body), a guide, a ball, and a float is shown in Fig. 1.

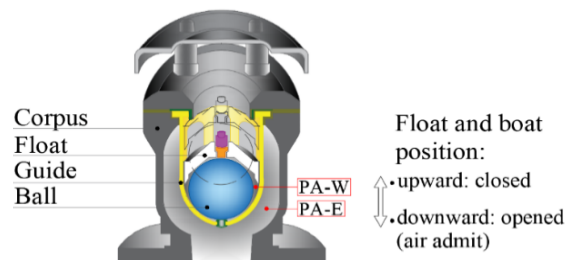


Fig. 1: Air valve.

The experimental installation consists of a water tank creating the simulated operational pressure in the system, main horizontal pipe, secondary vertical pipe and the air valve, Fig. 2.

The water tank was a pressure vessel connected to allow the application of an initial internal hydrostatic pressure within the experimental model of the system. It was made of steel, with a volume of 2.00 m³ and was equipped with a water level observation window. The initial static pressure within the water tank–pipe–air valve system was controlled by a compressor connected to the top of the tank. The water tank was located outside of the shaking table. A special low-friction joint was provided to connect the main PVC pipe to the tank. This joint enabled axial displacements of the pipe with amplitude up to 0.15 m without leakage at any magnitude of the internal pressure. The main PVC pipe had an inner diameter of 203 mm, wall thickness of 6.50 mm and a length of 8.00 m. The main pipe was 2.00 m longer than

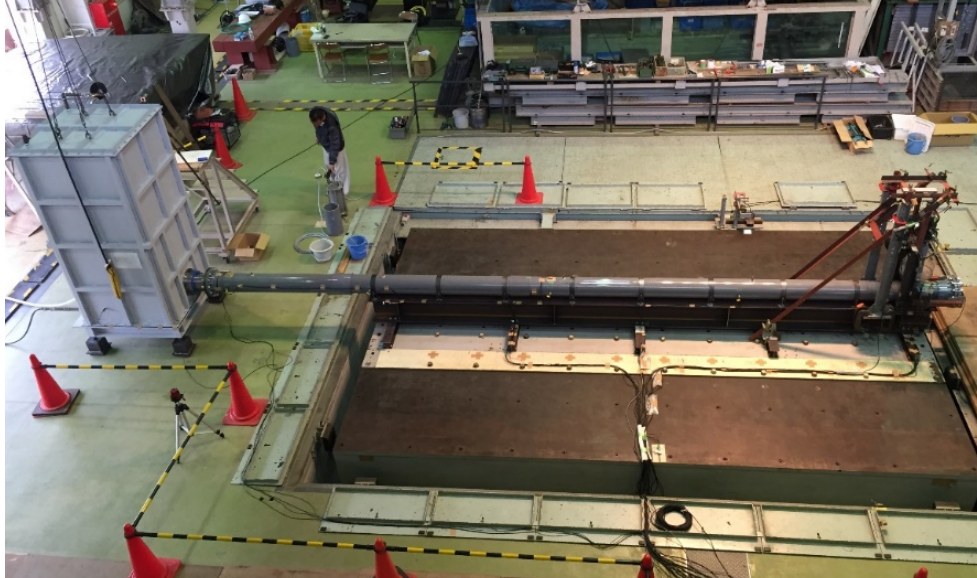


Fig. 2: Full-scale laboratory model of the air valve installation.

the shaking table to ensure the coupling with the tank outside the shaking table. It was supported by a steel beam with a length of 6.00 m which transferred the oscillations from the table. Thus, the kinematic excitation was applied simultaneously to all points of the model's support, which differs from actual earthquake excitation over a long pipeline, but it was a good approximation regarding the air valve, which was the leading object of the experiment.

The air valve was attached to the main pipe through a short pipe (100 mm), as the distance between the main pipe's axis and the mid-section of the valve was about 1.00 m.

A longitudinal section of the experimental installation, including the place of the measurement sensors is shown in Fig. 3.

The instrumentation included different types of sensors for recording all the required data. Since the main factor expected to cause the failure of the air valve was the transient pressure due to the base input motion, pressure sensors were the most essential and most numerous ones in the model set-up. TML pressure transducers with a capacity of 500 kPa and accuracy of 1% were used in the installation. Five pressure transducers (P1:P5) were installed on the main pipe. Two more pressure sensors measured the dynamic pressure magnitude inside (PA-W) and outside (PA-E) the guide of the air valve, Fig. 1. These pressure gauges measured pressure fluctuations with reference to the atmospheric pressure taking into account the initial conditions, so

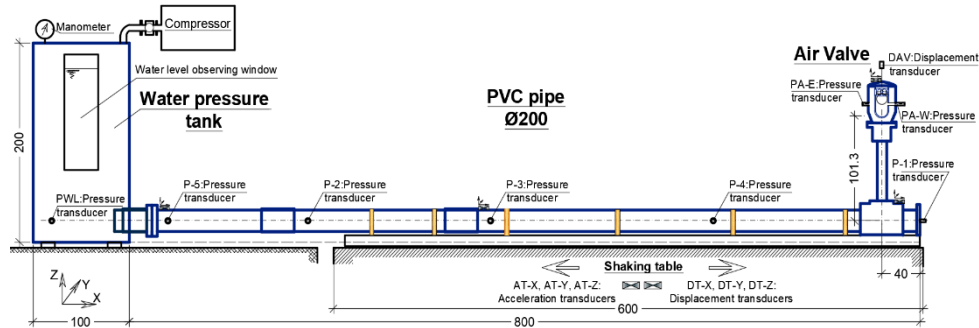


Fig. 3: Longitudinal section of the installation.

both positive and negative data was collected. Here, positive value indicates higher than atmospheric pressure, and negative value indicates pressure lower than the atmospheric one.

Further, to verify the initial static pressure within the installation, an analogous manometer with a range from 0.0 to 3.0 kg/cm² was used. Acceleration and laser displacement transducers were attached to the experimental set-up to collect the data regarding the motion of the shaking table, main pipe and the air valve, respectively. Although the input kinematic excitation was only in axial direction of the model, i.e. X-direction, accelerations and displacements were measured in all three directions: axial, lateral and vertical. The data obtained in lateral and vertical directions was only used to verify the proper operation of the shaking table, without being considered in further analysis. The displacements of the air valve's ball and float due to the dynamic pressure fluctuations also were measured by a wired displacement sensor.

Concerning the signal acquisition, the sampling rate adopted for experiments in the earthquake testing laboratory was 5 ms, thus enabling the record of signals of up to about 100 Hz without aliasing problems according to the Nyquist theorem [14]. The input signals selected for the current experiments were in the form of sine wave and had frequencies up to 10 Hz.

For proper interpretation and understanding of the obtained results, a filtering procedure was necessary and played an important role. A limit of 30 Hz over which the data was filtered, was set to suppress the effects of the noise produced by the shaking equipment.

2.2 ANALYTICAL MODEL

A closed-form solution was considered to obtain the fundamental frequency of the above presented laboratory model. The fundamental frequency allows for the def-

initiation of other dynamic properties of the model as length of the wave for the first dominant mode of the pipe, etc.

Ogawa [15] proposed general closed-form solution based on the following governing equations of the fluid flow:

$$(1) \quad \frac{\partial}{\partial t} \left(v + \frac{\partial \xi}{\partial t} \right) = -\frac{1}{\rho} \frac{\partial p}{\partial x} - Qv,$$

$$(2) \quad \frac{\partial P}{\partial t} = -\rho a^2 \frac{\partial}{\partial x} \left(v + \frac{\partial \xi}{\partial t} \right),$$

where the propagation velocity of the acoustic wave is $a = \frac{\sqrt{K/\rho}}{\sqrt{1 + KD/Ee}}$, ρ is the density of the water (1000 kg/m³), t is the time (s), x is the axial coordinate of the pipe (m), p is the dynamic pressure (kPa), v is the fluid flow velocity (m/s); $\xi(x,t)$ is the axial displacement of the fluid particle within the pipe (m), a is the acoustic wave celerity (m/s), K is the bulk modulus of water (2.03×10^6 kN/m²), D is the inner pipe diameter (m), e is the thickness of the pipe's wall (m), Q is a resistance coefficient due to the friction between the water and the pipe's wall. The particular value of $Q = 2.8$ 1/s was obtained experimentally in the previous stage of the experiments.

The general solution of the governing Eq. (1) and Eq. (2) is in the form

$$(3) \quad V(x) = V_A e^{-sx} + V_B e^{sx} + \frac{i\omega^2 \xi}{iQ - \omega},$$

$$(4) \quad P(x) = P_A e^{-sx} + P_B e^{sx},$$

where ω is the angular frequency (rad) and i is imaginary unit, along with the integration constants V_A, V_B, P_A, P_B determined by the boundary conditions, and $s = \alpha + i\beta$ is a complex number.

The boundary conditions of the model represent the open end of the pipe at $L = 0$, where the water tank is located, and a closed with a flanged cap end, Fig. 4.

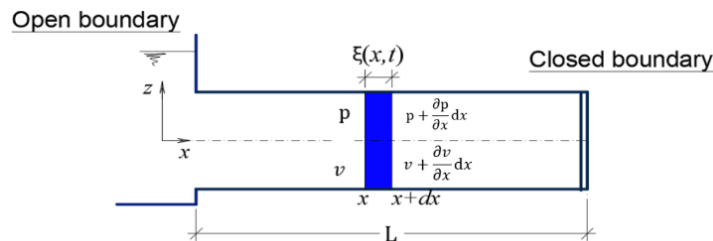


Fig. 4: Boundary conditions of the model.

Considering the particular boundary conditions, the general solution in terms of the transient pressure is given by the following equation:

$$(5) \quad |P_0| = \sqrt{\frac{(-2P_H\omega + R\alpha C_b + R\beta S_a)^2 + (2P_HQ + R\beta C_b - R\alpha S_a)^2}{(QS_b - \omega C_a)^2 + (QC_a + \omega S_b)^2}},$$

where

$$\begin{aligned} C_a &= \cos \beta L (e^{-\alpha L} + e^{\alpha L}), & C_b &= \cos \beta L (e^{-\alpha L} - e^{\alpha L}), \\ S_a &= \sin \beta L (e^{-\alpha L} + e^{\alpha L}), & S_b &= \sin \beta L (e^{-\alpha L} - e^{\alpha L}), \\ \alpha &= \sqrt{\frac{\omega \sqrt{\omega^2 + Q^2} - \omega^2}{2a^2}}, & \beta &= \sqrt{\frac{\omega \sqrt{\omega^2 + Q^2} + \omega^2}{2a^2}}, & R &= \rho a^2 \omega \xi = \frac{\rho a^2 \alpha_g}{\omega}, \end{aligned}$$

here the axial displacement ξ is rewritten with respect to the acceleration of the input signal α_g (m/s²), namely $\xi = \alpha_g/\omega^2$.

Using Eq. (5) with respect to the material properties and geometry of the experimental model, the dynamic pressure developed in the pipe with relation to the natural frequencies was defined. The fundamental frequency of 5 Hz of the built model was obtained analytically during the preliminary experiments, too.

2.3 SHAKING TABLE TEST

An important task was to define the experimental strategy so that maximum information could be obtained by the tests.

- FREQUENCY SWEEP

The frequency sweep technique was applied for identification of the natural frequency of the model in laboratory conditions. Harmonic input signal in the form of a sine wave was applied. The frequency of the input signal varied from 1.0 Hz to 10.0 Hz by an increment step of 0.5 Hz, with a constant amplitude of 1.00 m/s².

Then, a number of tests were performed as parameter studies with respect to the size of the orifices of the air valve's guide, to the initial static pressure applied in the water tank and to the frequency and acceleration amplitude of the input shaking motion.

- INITIAL PRESSURE

The initial static pressure was set to 0 kPa, 20 kPa and 40 kPa at the free surface of the water in the pressure tank, respectively. Thus, three main cases in relation to the initial static pressure applied in the water tank were formulated. Zero static pressure ($P_{in} = 0$ kPa) in the first case corresponded to the atmospheric pressure. The aim

was to identify, how (if at all) the initial free surface pressure affects the mechanical response of the air valve in the sense of ball movement, opening/closing of the air valve and pressure magnitude.

- FREQUENCY AND ACCELERATION MAGNITUDE OF THE INPUT SIGNAL

The experimental program was divided into a series of tests. Each sub-case included an input signal with a frequency of 1 Hz, 2 Hz, 5 Hz and 10 Hz and for every frequency value, the acceleration amplitude was varied from 1.0 m/s^2 to 9.80 m/s^2 . The particular frequency range and the acceleration magnitude of the input signal were chosen in correspondence with the design standards for irrigation pipelines [16]. One limitation of the laboratory installation was that the differential displacement amplitude of the pipe relative to the tank was limited to 0.15 m. Thus, a frequency lower than 1.0 Hz was possible only with an input acceleration of 0.50 m/s^2 , where the relative displacement in the connection between the tank and the pipe was observed to be about 0.12 m.

- ORIFICES SIZE

The size of the orifices determines the amount of air that is discharged during the air valve's operation and hence influences the hydraulic transients in the pipeline system. Two guides were used in the experiments with different orifice size, as the small size conveys $11 \text{ m}^3/\text{s}$ while the large size conveys $23 \text{ m}^3/\text{s}$. Both were tested because it was expected that the size of the orifices affects significantly the magnitude of the dynamic pressure within the air valve.

3 RESULTS AND DISCUSSION

3.1 ANALYTICAL AND FREQUENCY SWEEP RESULTS

The data recorded during the frequency sweep tests showed a good match with the natural frequency calculated by a closed-form solution of the governing equation of motion, Fig. 5, and allowed us to verify the proposed computational formulas.

The computed dynamic pressure slightly differed from the recorded values, it was larger for the frequencies up to 5.0 Hz and for frequencies higher than 5.0 Hz, the calculated values were lower than the recorded ones, Fig. 5.

The dynamic pressure measured during the frequency sweep test differed in all of the recorded locations, i.e. pressure transducers P1:P5. As expected, the highest dynamic pressure in the main pipe occurred at its closed end (P1), while the lowest values were observed near the tank (P5).

Positive pressure amplitudes measured by the pressure transducer P1 are shown in Fig. 6. The frequencies of the input excitation signal for the test are also denoted on the same figure.

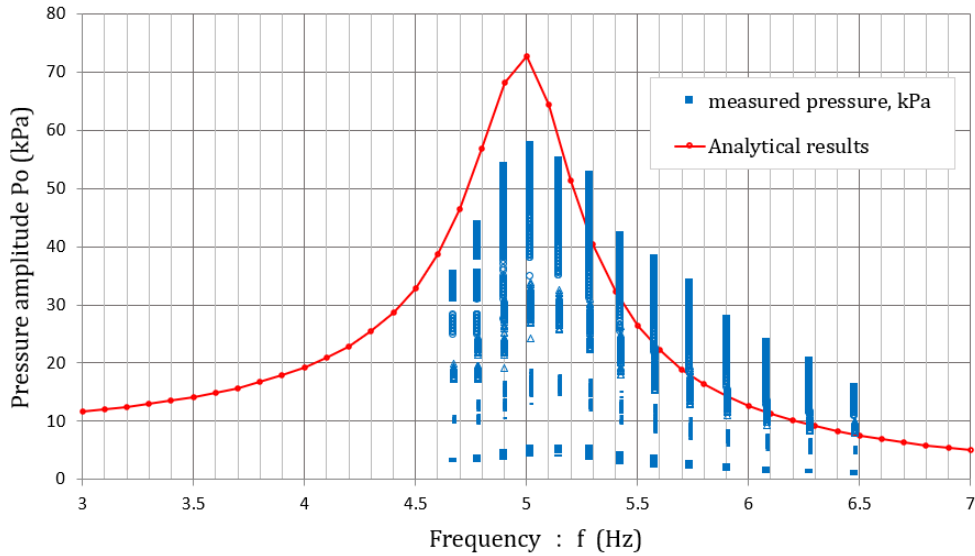


Fig. 5: Laboratory data vs. closed-form solution.

The analysis of the recorded data from the sweep test showed that the fundamental frequency of the model is 5.0 Hz, which is obvious from Fig. 6. Large values of the dynamic pressure at that frequency were observed within the whole pipe due to conditions of resonance.

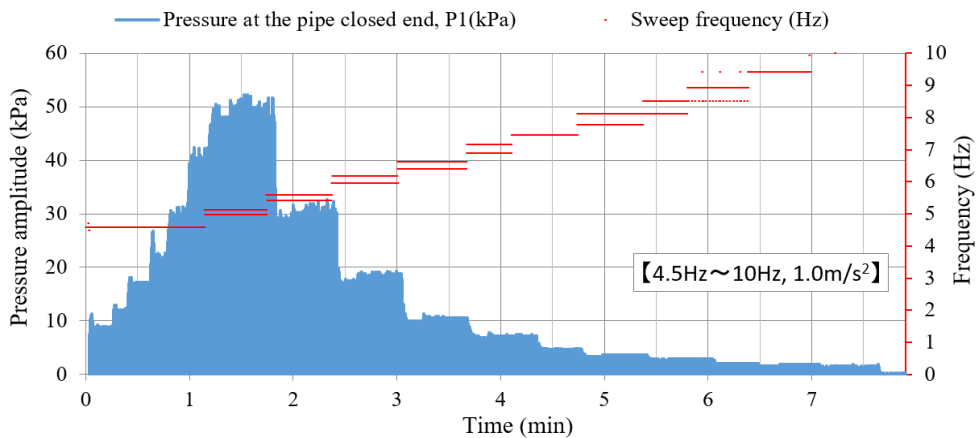


Fig. 6: Time history of the dynamic pressure measured at the closed end of the pipe during the frequency sweep test ($f = 4.5\text{--}10.0\text{ Hz}$, $a_g = 1.00\text{ m/s}^2$).

3.2 INFLUENCE OF THE STATIC PRESSURE, SIGNAL PARAMETERS AND THE ORIFICES SIZE

A number of shaking table tests were performed in order to trace the influence of the frequency and acceleration on the transient pressure developed inside the air valve and the pipe installation under support excitation. The influence of the static pressure set by a compressor at the free surface in the tank as an initial condition also was studied during the tests. Two air valve guides depending on the air discharge capacity were used in the experiments to examine the relation between the size of the orifices and the magnitude of the dynamic pressure developed in the air valve.

It was found that the initial static pressure within the water conveying system has a significant influence on its response under the dynamic excitation. The response of the model representing a pressurized water system was studied mainly with respect to the dynamic pressure surge in accordance with the displacement of the main parts of the air valve, i.e. the ball and the float. The analysis showed that the movement of the air valve's ball, i.e. the part admitting air entrance into the system, was accompanied by a pressure surge, as expected. The relation between the float displacements and the magnitude of the dynamic pressure was identified to be proportional, i.e. the more the float moved downward and a higher amount of air passed into the system, the higher the pressure surge was. The displacements of the float also were dependent on the initial static pressure applied in the system, and the observations showed that the lower the static pressure was, the larger the downward movement of the float became.

Thus, the dynamic pressure measured within the air valve and at the closed end of the main pipe showed a significant dependence on the initial static pressure. This pressure value also was found to be strongly dependent on the combination of the frequency and acceleration of the input shaking excitation.

It was found that in general, regardless of the initial static pressure (0 kPa, 20 kPa or 40 kPa), with the increasing input acceleration, the dynamic pressure amplitudes became larger. This tendency was valid for the pressure fluctuations in the pipe, especially at its closed end (P1) where the maximum values were recorded, as well as in the air valve (PA-E and PA-W). However, the dynamic pressure within the air valve reached a slightly larger magnitude compared to the pressure at the pipe's closed end.

Pressure surges were frequency dependent, too. For the particular model studied, the maximum positive pressure amplitudes were observed at the lower frequencies (up to 5.0 Hz), regardless of the initial static pressure. However, with increasing of the initial pressure, the pressure amplitudes decreased. This tendency was noticeable at the initial pressure of 40 kPa where the amplitude decreased nearly twice compared to the case with an initial pressure of 0 kPa and 20 kPa. This was due to the fact that

higher static pressure inside the installation under normal operation leads to a larger force that keeps the air valve close.

Unlike the positive pressure amplitudes, the negative ones did not decrease with increasing of the frequency and the acceleration of the input signals. On the contrary, they increased with the increasing of the frequencies, as they reached their peak values around 5.0 Hz and remained in the same range up to 10.0 Hz. Negative pressures reached their peak at the initial pressure of 40 kPa.

The aim of this experiment was to identify the possible failure mechanism of the guide within the air valve due to a pressure surge induced by shaking excitation. It was expected that there would be a significant difference in the magnitude of the dynamic pressure outside the guide, i.e. between the valve body and the guide as well as inside the guide. The preliminary assumptions were that it was precisely the presence of such a pressure difference under dynamic loading that would cause the failure of the air valve.

The obtained results for both air valve guide types ($11 \text{ m}^3/\text{s}$ and $23 \text{ m}^3/\text{s}$) showed that the pressure magnitude inside (PA-W) and outside (PA-E) the guide was in the same range. However, for the initial pressure of 0 kPa, the pressure inside (PA-W) reached slightly larger magnitude compared to the pressure outside the guide (PA-E).

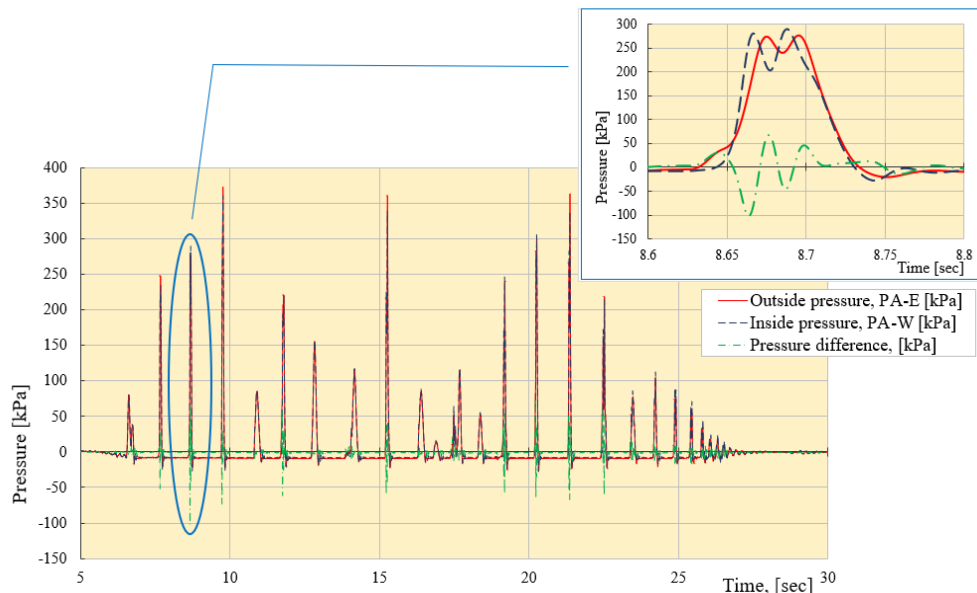


Fig. 7: Air valve $23 \text{ m}^3/\text{s}$; pressure time histories measured inside and outside the valve guide at initial pressure of 0 kPa, frequency of 2 Hz, acceleration of 6 m/s^2 .

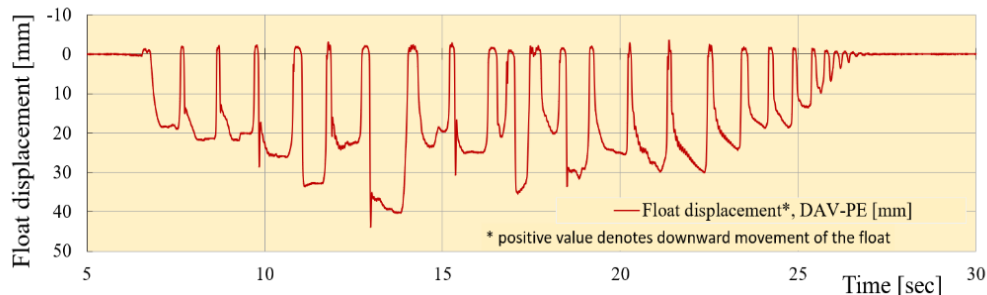


Fig. 8: Air valve $23\text{m}^3/\text{s}$; float movement record at initial pressure of 0 kPa, input frequency of 2 Hz and an acceleration of 6 m/s^2 .

With an increase of the initial pressure (20 kPa, 40 kPa), the outside pressure (PA-E) became higher than the pressure measured inside the guide (PA-W). The response pressure inside (PA-W) and outside (PA-E) as well as the pressure difference are presented in Fig. 7 for the case of larger air discharge capacity ($23\text{ m}^3/\text{s}$), input frequency of 2 Hz and acceleration of 6 m/s^2 . This particular case was chosen as representative, with one of the highest reached pressure values and a large difference between the inside and outside pressure. Although the pressure outside and inside the guide happened to differ in such magnitude for a short time only, its continued repetition due to the nature of the input excitation was suggested to be one of the main reasons for guide failure.

The valve's float and ball movement, recorded by the wired displacement sensor (DAV-PE) in the above case is plotted in Fig. 8. Positive ordinates denote downward movement, namely opening of the valve and letting air to pass inside. The float and ball move downward while the orifices are fully opened, and the ball strikes the bottom of the guide. This movement was strongly conditioned by the initial pressure in the tank-pipe-valve system as well as by the frequency of the input shaking excitation, and the valve was not necessarily fully opened in every case.

The time in which the valve remained open was longest in the case with 0 kPa initial pressure and became shorter with increasing of the initial pressure to 20 kPa and 40 kPa. It was found that at the initial pressure of 0 kPa, whereby the head difference between the water surface in the tank and the air valve's float was small (about 70 cm), the air valve opened and closed with a frequency of 2 Hz, regardless of the shaking frequency. With increasing of the initial pressure, the head difference increased, as well as the flow velocity, and the air valve performance followed the frequency of the input shaking.

Regarding the magnitude of the negative pressure within the valve, the obtained

results showed that with increasing of the initial pressure, the negative dynamic pressure also increased and reached the highest magnitude when the initial pressure was set to 40 kPa. Another specific feature of the negative dynamic pressure developed inside the valve was that with increasing of the initial pressure in the installation, the difference between outside and inside pressure became significant.

In a subsequent rise of the pressure, the admitted air was allowed to escape through the guide orifices in a controlled manner, and the valve closed. The discharge of the air was a rapid process followed by rapid elevation of the float, respectively of the water surface inside the valve body. As soon as the float closed, the orifices and the water flow struck the valve, and pressure surges occurred due to water hammer. The magnitude of the positive dynamic pressure was larger than the negative one observed in the case of initial pressure 0 kPa, but with increasing of the initial pressure, the positive pressure decreased while the negative increased, and both were in the same range when initial pressure was set to 40 kPa.

Comparing the results obtained for both guide types with small (11 m³/s) and large (23 m³/s) orifice size, no significant differences were identified between the dynamic pressure generated inside (PA-W) and outside (PA-E) the guide under equal test conditions. There was a tendency that the negative dynamic pressure measured outside the guide with the small orifices (11 m³/s) reached larger magnitude. Peak negative values were reached when the displacement of the float along with the ball were largest in downward direction, i.e. the guide orifices were fully opened.

Larger displacements up to 45 mm were observed in the case of a guide with larger orifices (23 m³/s), compared to displacements of up to 32 mm in the case with smaller orifices (11 m³/s). This was mainly due to the fact that the valve was fully open when the orifices were clear, and the float reached a position below their lower edge. So, the maximum displacements of the float were predetermined by the structural dimensions of the guide and its orifices.

4 SUMMARY AND CONCLUDING REMARKS

The aim of the performed full-scale shaking table tests was to clarify the failure mechanism of the air valve's components under dynamic excitation and to identify the main factors affecting the mechanical response of the valve. The obtained results from the carried-out experiments led to the following main conclusions.

It was confirmed that regardless of the air discharge capacity, large positive and negative pressure surges occur inside the air valve during the shaking tests. Both types of air valves tested enabled rapid ejection of air within a short period of time, which resulted in hydraulic transients in the considered system.

A highly transient pressure difference was indicated between the inside and outside part of the valve's guide. This pressure difference exactly followed the excitation

time history, and directly affected the response of the air valve. With increasing input acceleration, the dynamic pressure amplitudes became larger.

It was also noticed that along with the pressure surges, the water flow reached relatively high velocity, especially in the narrow space between the guide and the valve body. This high velocity together with the developed negative pressure might lead to occurrence of cavitation and subsequent erosion of the valve's mechanical parts. However, the conditions leading to cavitation and subsequent cavitation erosion need to be further studied as well as the particular operation of the air valve under possible two-phase transient flow regime. Further studies should investigate the occurrence of cavitation and its possible contribution to the failure mechanisms of the air valves.

Laboratory experiments with real earthquake time history records as an input shaking signal should be performed as a next step. Real acceleration records from Kumamoto earthquake (2016) and Tōhoku earthquake (2011) in Japan should be applied as input excitation signals.

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