EARTHQUAKE-INDUCED PRESSURE SURGES IN
AIR VALVES ON BURIED IRRIGATION PIPELINES

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ABSTRACT: The main purpose of this paper is to present some aspects of a
seismic induced performance of an air valve. The considered valve is an air
release type widely used in irrigation systems. Since the physical modeling
is a powerful tool for dynamic behavior assessment of engineering structures,
a full-scale model of a tank – pipe – air valve system was installed at NIRE’s
Three-dimensional Earthquake Testing laboratory. Shaking table tests with real
acceleration time histories were performed. Static tests to obtain some mechan-
ical properties of the used air valves also were performed. Comparison of the
results obtained by the different approaches is presented in attempt to achieve
in-depth understanding of the complex dynamic interaction within the air valve
structure and its failure mechanism.

KEY WORDS: air valve, seismic excitation, shaking table, internal pressure.

1 INTRODUCTION

Hydraulic transients in water-conveying systems are not generated only by chang-
ing of the actual operation conditions. The trigger of such transient pressures often
happens to be an earthquake excitation.

The research field of fluid-structure interaction (FSI) between a vibrating pipe and
the flowing liquid inside it (water) is quite complicated due to the physical phenom-
ena occurring. The latter ones become even more complex and physically manifol-
d when the pipe is deformable, and moreover, when not a simple pipe but a spatial pipe
system with various additional equipment components is considered, and when the

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fluid flow is non-stationary, i.e. when hydraulic transients are present. Furthermore, the pipe supports may be subjected to a kinematic excitation, e.g. earthquake-induced one. Thus, the seismic vulnerability of air valves on an irrigation pipeline is directly related to that of the whole system itself.

Based on all these aspects, the dynamic structural response of air valves in irrigation pipe systems under seismic excitation cannot be treated separately from the formulation of the above-mentioned problems, every group of which has been subject of special research interest in the last decades. In the following, some representative sources in every one of these groups will be shortly presented for emphasizing the physical complexity of the subject of this paper.

A vast amount of research work has been done in the field of hydraulic transients in penstocks and pipeline systems for various spatial configurations, boundary conditions, equipment components and flow regime scenarios. A comprehensive review of these works would go far beyond the frame and the scope of the current paper. Yet with respect of the air valves in such systems and their modeling approaches, some sources have to be at least mentioned. Malppan and Sumam [1] performed many analyses on complicated systems containing a large number of pipe sections and (air) valves. In other sources [2, 3], special cases of systems with air valves were analyzed, and the need for transients’ control was focused on the development of flow regime identification methods for evaluation of the operational state of air valves, or operational algorithms for particular scenarios were suggested for improving of the hydraulic transients’ control in terms of reducing the developing pressure amplitudes. In most of these works, logically the experimental approach in laboratory conditions was implemented.

A special group of works among the studies on hydraulic transients constitute the research activities dedicated to the FSI during water hammer, i.e. to the mutual influence between the pressure pulsations of the flow domain and the pipe, including by accounting for the so-called “precursor wave” in the pipe. Here, the numerous papers by Tijsseling et al. [4], Daude et al. [5], Bai et al. [6], the PhD-thesis by Svingen [7] and many others have to be mentioned.

Special attention has to be paid to the review paper by Ramezani et al. [8]. In this work, a thorough analysis is presented of the problems related to the dimensioning and location of air valves, to their operation and maintenance as well as to the dynamic behavior of the system caused by the secondary transients during the operation of the valves. However, there is no comment neither on the pressure transients generated by a seismic event, nor on the performance of an air valve under such conditions. Such a discussion cannot be expected, either, since the earthquake-induced pressure transients in a pipe-valve system strongly depend both qualitatively and quantitatively on the configuration and parameters of the considered system.
Regarding the practical aspects of the problems with air valves, Sparks [9] should be mentioned here. In different sections on this web-site, comprehensive discussions are dedicated to a large variety of hydraulic and gas transients related to the operation of valves and the problems caused by such phenomena. The covered spectrum of valves and their operational conditions is extremely broad, and the given explanations emphasize practical aspects of the valve’s operation and cases of failure. In this connection, the special section on reciprocating compressor describes the repetitive impulsive pressure loading on different types of valves caused by such type of compressors.

Another physical phenomenon to which a large amount of scientific works was dedicated is the pipe motion induced by pressure pulsations in the flow domain, sometimes leading to structural instability of the supported pipe reach for some flow velocity ranges. Here for example, the applications of the experimental approach [10, 11] should be mentioned as studies presenting important particular aspects of pipe structural response to pressure pulsations.

Another special problem is the reverse one – when the pipe motion affects the pressure field in the flow domain [12]. Such analysis is inevitable when the interaction between pipe structure and water flow is actually considered.

A very few sources deal with the development of flow transients due to seismic excitation of the pipe supports. Leon [13] cited theoretical studies of Nakagawa (1969) which had led to the development of calculation formulas for the hydraulic transients in pipes during earthquakes at some particular boundary conditions.

In this short overview, some review papers of particular importance have to be outlined on contemporary developments in combining FSI, pipe dynamics and flow transients for both simple penstocks and pipe systems, such as [14]. They are especially valuable with the conceptual summary of both description of the related physical phenomena and the modeling and solution approaches to the observed problems resulting from these phenomena as well as with the explanation of the mechanisms of the physical coupling between the pipe motion in the structural system and the hydraulic transients of the water flow inside the pipe. For example, in another source [15] of this group we read: “oscillatory pressures in the liquid exert forces on piping at velocity discontinuities” which represents one of the numerous summarizing conclusions in this highly demanding field.

The above short review formulates the task of this paper as quite specific. A problem in such formulation has not been addressed so far to our knowledge. However, based on the experience from the 2011 Tōhoku earthquake and 2016 Kumamoto earthquake, with numerous failure records of such valves, the problem seems to be of particular importance for the operation of irrigation systems containing such valves in seismic regions.
The failure conditions of an air valve were studied experimentally. In fact, such conditions can occur during earthquake excitation mainly due to pressure pulsations inside the valve and at its connections caused by the earthquake. The experimental approach and set-up, respectively, were chosen and applied to a representative full-scale prototype consisting of a pipe part of the system containing an air valve of a widely used type at typical operating conditions, Fig 1. The valve itself and its structural components can be regarded in this approximation as rigid with respect to the other system components. The experimental laboratory installation was built in the National Research Institute for Rural Engineering (NIRE) in Tsukuba, Japan.

In a first stage of the study, the well-known experimental “frequency sweep” technique was applied to the studied prototype [16]. On the one hand, this helped identification of the eigenmodes / eigenfrequencies of the valve as system part prototype. On the other hand, this approach enabled finding of the pressure pulsation amplitudes corresponding to the stepwise changed and applied periodic excitation signals.

This work presents a second stage of the experimental study of the seismically-induced air valve behavior. At this phase of the research project, acceleration records from 2016 Kumamoto earthquake and 2011 Tōhoku earthquake in Japan were applied as input signals. Both records were chosen since many air valves failed after these earthquakes in the affected areas. Furthermore, although both earthquakes had different frequency content [17, 18], the excitation contained in both cases the range of the fundamental frequency of the model as identified in [16].

2 Outline of Full-Size Shaking Table Model

2.1 Shaking Table and a Set-up of the Air Valve Model

For the purposes of this study, the full-scale model of an air valve installation built at the NIRE’s three-dimensional Earthquake Testing Laboratory [16] was used, Fig. 1a.

The shaking table with dimensions of 6.00 × 4.00 m allows different types of kinematic loading with real or artificial earthquake time history records. The experimental installation consists of a pressure vessel (tank) providing typical operational pressure in the system, main horizontal pipe, secondary vertical pipe and an air valve [16]. The pressure tank allowed setting of an initial static internal pressure of 40 kPa (additional to the atmospheric one) within the experimental model, controlled by a compressor.

The air valve used in the studied laboratory model was of an air release type as representative of those widely used in Japanese irrigation systems, Fig. 1b.
The above short review formulates the task of this paper as quite specific. A problem in such formulation has not been stated as clearly as expected. An air valve installation built at the NIRE’s three-dimensional Earthquake Testing Laboratory [16] was used, Fig. 1(a).

2.2 Measurement System

The response of the model comprising the pressurized tank-pipe-air valve system was mainly studied with respect to the dynamic earthquake-induced pressure transients. For measuring pressure fluctuations, several of pressure sensors were installed at different locations along the main pipe and on the air valve. The sensors on the valve measured the dynamic pressure magnitude inside (PA-W) and outside (PA-E) the guide of the air valve, Fig. 2.

These sensors measure pressure fluctuations with reference to the atmospheric pressure taking into account the initial conditions, so both positive and negative data...
was collected. Here, positive value indicates pressure higher than the atmospheric one, and negative value indicates pressure lower than the atmospheric but higher than the absolute one.

To verify the initial static pressure within the installation, an analogous manometer was used. Acceleration and laser displacement transducers were attached to the experimental set-up to collect the data regarding the dynamic motion of the shaking table, main pipe and the air valve. The displacements of the air valve’s ball and float due to the dynamic pressure fluctuations were also measured by a wired displacement sensor.

2.3 Input Motions

In the frame of this study, laboratory experiments with real earthquake time histories as input shaking signals were performed. Acceleration records from 2016 Kumamoto earthquake, Fig. 3, and 2011 Tōhoku earthquake, Fig. 4, in Japan were applied as input signals. Both records were chosen since their predominant frequency is in the range of the fundamental frequency of the model, and because many air valve failures were observed after these two earthquakes.

Fig. 3: Acceleration time history (gal-min) from Kumamoto earthquake, 2016.

Fig. 4: Acceleration time history (gal-min) from Tōhoku earthquake, 2011.
3 EXPERIMENTS, RESULTS AND DISCUSSION

The data recorded during the experiments allowed comprehensive analysis of the transient pressure and related dynamic behavior of the air valve during earthquake excitation.

Here, the response of the model was mainly studied with respect to the displacement of the valve ball and float along with the dynamic pressure transients within the pressurized tank-pipe-air valve system acting as hydrodynamic loading.

The results showed a direct relationship between the pressure fluctuations and the acceleration, as expected. The magnitude of both positive and negative pressures followed the time history of the particular input acceleration, Fig. 5.

At the previous stage of the analysis of the dynamic-induced air valve behaviour [16], it was concluded that the pressure surges are dependent on the frequency and the acceleration magnitude of the input harmonic excitation. This finding was confirmed in the frame of the current study, too, since the pressure magnitude reached its peaks at times of peak values of the ground acceleration. Time histories of the pressure measured inside (PA-W) and outside (PA-E) the guide of the air valve as well as the related pressure difference are presented in Fig. 6.

The recorded data showed that large positive and negative pressure surges occur in the air valve during the shaking tests, as the pressure has reached peak values of about 400 kPa / -100 kPa (2011 Tōhoku acceleration record) and about 90 kPa / -60 kPa...
Fig. 6: Pressure time histories recorded outside (PA-E) and inside (PA-W) of the valve guide (here, the 2011 Tōhoku earthquake).

(2016 Kumamoto acceleration record). Simultaneously with the peak pressures, a large difference between the pressure values inside and outside the valve guide was registered, which obviously caused unfavorable radial and hoop stresses in the valve guide. In general, the guide leads the valve float in vertical direction to open and close the working orifices, respectively. As clearly observed, the pressure difference outside and inside the guide happened to differ in the registered relatively large magnitude. Furthermore, the change in sign of the pressure difference happened with a high frequency following the input acceleration time history, thus contributing to the highly unfavorable character of the pressure load on the valve guide structure. Hence, the recorded pressure difference in the valve guide were suggested to be one of the main reasons for guide failure. This is an important issue since in general, the valves and their components are designed for single peak pressure values but not for cyclic pressure differences of high frequencies.

The peak pressures reached during the shaking table tests were lower than the ultimate structural strength of the guide. The actual strength of several valve guides, collected from the field, was measured in static tests in laboratory conditions. The static equipment consisted of a platform, loading cell and loading hemisphere, Fig. 7. The hemisphere had the same size as a valve ball and were used to apply a uniform load on the bottom part of the valve guide.

The static load was applied with an increment of 500 N until guide break at a load of about 5000 N. The maximum pressure reached during the static test corresponding to the failure load was about 800 kPa, respectively.
As it can be seen from the results for the pressure differences from the performed dynamic tests with real earthquake acceleration records, the obtained earthquake-induced pressures are far from the statically applied failure load. Hence, water hammer related to the high amplitude pressure surges was supposed to be one of the main reasons for failures of mechanical parts of the valve, i.e. float and ball, Fig. 8 and Fig. 9.

Another phenomenon identified as a severe dynamic impact on the air valves is cavitation. The negative water pressure of 100 kPa reached during the Tōhoku seis-

Fig. 7: Static equipment, loading cell and hemisphere, and broken valve guide.

Fig. 8: Damaged guide and ball of air valves, collected on sites after the Kumamoto earthquake, 2016.
mic tests along with the high flow velocities developed within the narrow gaps within the air valve, Fig. 9, constitute conditions for cavitation occurrence. Moreover, a two-phase air-water flow inside the valve was observed during preliminary experiments with transparent air valve models at some time moments of the valve operation during the developing pressure surges.

Vapor cavities due to the dynamic pressure decrease and water acceleration to high velocity were identified within the narrow gaps. During a subsequent rise in the pressure, these cavities collapsed implosively and disappeared. This cavity collapse took place in a very short time and resulted in the emission of shock waves. Noise and strong vibrations of the air valve mechanical components due to the shock waves were observed at the moments of biggest pressure differences, i.e. when suggested cavitation took place. Thus, since the time of cavitation development is relatively very short, the valve failures cannot be related to cavitation erosion but to the additional pressure surges related to this phenomenon, moreover, superimposed with the hydraulic transients resulting from the seismic support excitation. It should be noted that the influence of the cavitation development could be neither separately evaluated nor as component of the earthquake-induced hydraulic transients with the applied measurement technology.

4 CONCLUSIONS
The laboratory prototype of a typical air valve installed on irrigation pipe developed in the previous stage of the project was used in the performed dynamic shaking table tests.

Laboratory experiments with a static loading of the air valve guide up to the failure of latter’s structure also were performed to study the deformation and cracking, and failure mode, respectively, of the valve guide and for estimation of the internal static pressure corresponding to failure.
Based on the carried out static tests and shaking table ones with the real acceleration records, the following main conclusions can be drawn.

During the seismic shaking tests, large positive and negative pressure surges were recorded in the air valve. As a time history flow, the magnitude of these surges followed the magnitude of the input support acceleration, and the maximal pressures were recorded at the moments of peak acceleration, respectively. It may be assumed that these resulting pressure transients directly affected the structural response of the air valve since the developed dynamic pressure amplitudes were considerably smaller than the statically applied failure loads. Moreover, the hydraulic design of the valves usually does not account for such pressure surges, or at least not for their dynamic character.

Conditions leading to cavitation and related noise and vibration of the valve were observed during the tests. These cavitation-related operational conditions in short time intervals should be regarded as superimposed to the earthquake-induced pressure surges in the valve. However, the high frequency of the pressure surges cannot argue any development of cavitation erosion.

As a task for future research, the problem can be formulated for structural analysis of a computational model of representative valves subjected to the identified here dynamic load in terms of hydraulic pressure surges applied at appropriately introduced boundary conditions. Thereby, real material properties of the valve should be used in this model. Thus, the high-frequent stress-strain response of the valve structure can be analyzed and evaluated.

Further study on the short-term development of cavitation inside the valve and the related dynamic impact on its structure also can be recommended. Such studies can be combined with qualitative experimental analysis of these two-phase flow phenomena by means of transparent models.

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