JAPANESE EXPERTISE ON INFLATABLE GATES: TECHNICAL DEVELOPMENT, STANDARDS AND LONG-TERM EXPERIENCES

by

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1. INTRODUCTION

Japan is considered to be the world's technological leader and a good reference for inflatable gates. Many inflatable gates have been constructed there since the first rubber gate was installed in 1964. Japan has more than 3,900 movable weirs equipped with inflatable gates. In addition, the first steel-rubber (SR) gate was constructed in 2001. In the early days, rubber gates were used only on small rivers mainly for irrigation purposes. In time, the advantages of rubber gates, such as reliability and simplicity of inflation and deflation systems, the ease of maintenance, the short construction period and low cost, have been recognized by both customers and operators. Hence, the Japanese Ministry of Land, Infrastructure and Transport (MLIT) initiated various technical studies on rubber gates and in 1978 the first technical standard for rubber gates (Japan River Association, 1978) was published.

Meanwhile, rubber gates were also installed for other purposes such as hydropower generation, water supply, etc. and the number of installation and the size of the gates increased significantly. The height limit for rubber gates increased to 6.0m through installing and investigating a 5.0 m high experimental rubber gate. Since 1978, the technical standard for rubber gates has been updated twice; firstly in 1983 (JICE, 1983) and subsequently in 2000 (JICE, 2000). In 2007, the first edition of a standard named "Design Guideline for steel-rubber gates" was published (JICE, 2007). In 2015 the latest standard relating to inflatable gates was published which focuses on the rubber components of inflatable gates especially their design, manufacturing, installation and maintenance, including replacement (MLIT, 2015).

2. INSTALLATION RECORD OF INFLATABLE GATES (RUBBER GATES & SR-GATES) IN JAPAN

Approximately 3,900 rubber gates have been installed in Japan from the first installation in 1964 up to 2013, as shown in Fig. 1. Since then, approximately 20 to 40 inflatable gates have been installed every year. The main application is irrigation and 90% of inflatable gates are used for this purpose. Others are used for many different purposes such as intake gates for small hydro power plants, tidal barriers, city water use, sewage water control, recreation, etc. Almost all rubber gates installed for irrigation use are operated in either the fully closed (inflated) or fully open (deflated) conditions. Rubber gates installed for other purposes are used to maintain or control the upstream water level with a fully-automatic operation system.

Rubber gates have been installed in many different places such as in the upper reaches of a river (in mountainous areas), in the middle reaches and in the lower reaches (including the river mouth or estuary). The site conditions at these locations are very different.

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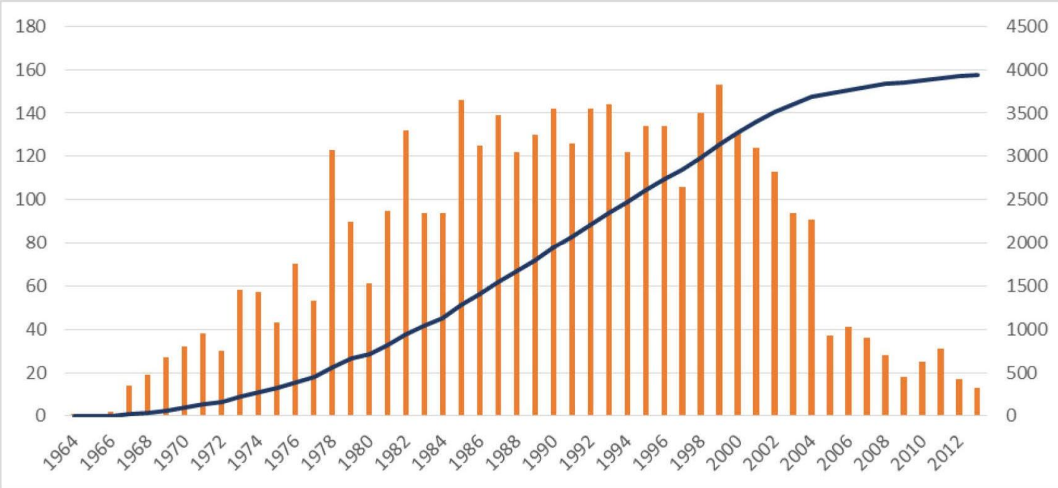

Figure 1: Installation records of inflatable gates in Japan between 1964 and 2013. Information provided by the Japan Association of Dam & Weir Equipment Engineering (JADWEE).

In the first stage of rubber gate business in Japan, a rubber gate had been classified in the same category as a steel gate (i.e. flap gate) because the rubber gate was operated by inflation/deflation and this method of operation seemed similar to that of a flap gate. Furthermore, the height of the rubber gate was limited to 3.0 m up to the 1980s which was the same as the height limitation for a flap gate. Later, a trial 5.0 m high rubber gate was developed, manufactured and installed on a river in a mountainous region of Japan and it was operated and inspected for a period of approximately 10 years. Finally, in 1989 a rubber gate with a height of 6.0 m was approved for installation and, since then, more than 30 rubber gates with heights between 4.0 m and 6.0 m have been installed in Japan (Fig. 2).

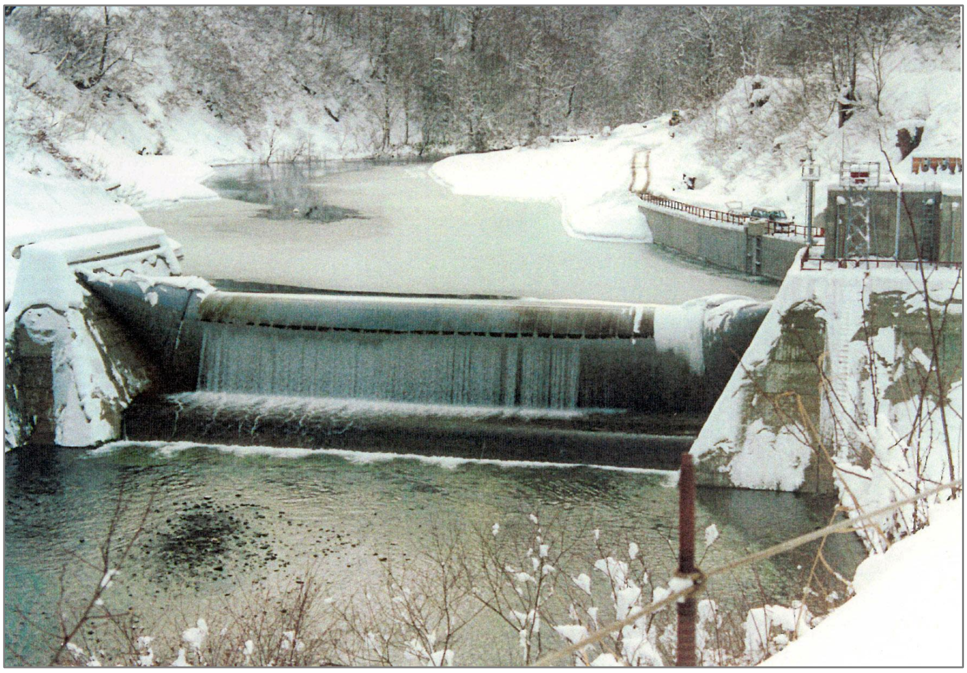

Figure 2: Example of a large rubber gate in Japan; Kurotani Dam was installed in 1994 (air-inflated, height 6.0 m, length 34.5 m, photo courtesy of Marsima Aqua system)

SR gates were also developed in Japan and more than 100 SR gates have been installed since the first installation was completed in 2001. The SR gate shown in Figure 3 is the Nikaryo-Kamikawara SR gate near Tokyo which WG166 visited and inspected in 2014.

Figure 3: Nikaryo-Kamikawara SR gate installed in 2012

3. DEVELOPING TECHNOLOGIES AND IMPLEMENTATION OF STANDARDS FOR INFLATABLE GATES IN JAPAN

During the first stage of rubber gate business in Japan, each rubber gate manufacturer developed its own technology independently such as material composition and specification, design method, operation system, etc. Approximately 10 years after the first installation, the key properties of a rubber gate such as reliable & safe operation due to a simple control system, short construction period, easy maintenance, low construction cost, etc. were recognized by both clients and operators alike.

Eventually, the relevant government ministry came to understand and accept the properties of this “new technology”, and began to study how to develop and standardize this technology in cooperation with the manufacturers. As a result, the ministry compiled a technical standard that covered the whole life-cycle of a rubber gate project, such as planning, design, manufacturing, installation and maintenance. The standard also included a specification for all material used for construction of a rubber gate. After this standard was published, it was applied to all rubber gate projects in Japan. As the technology has progressed and developed, the ministry has revised the standard accordingly.

According to the author the introduction of these standards has had a positive impact on rubber gate business in Japan in that many rubber gates have been designed, installed and operated at various sites for longer than expected periods without any serious failure or faults.

3.1 Main technologies

Several main technologies have been developed in Japan as shown below.

3.1.1 Design of the working strength of a rubber gate (rubber body)

The working strength of the rubber body in the circumferential direction and the cross section shape is calculated using the gate height, the upstream and downstream water depths and the inner pressure. We developed two methods of calculation. Both are 2D-calculations to define the cross section shape of rubber gate. One is a numerical integration considering the effect of the overflow and the other is an approximate calculation method neglecting the effect of the overflow. The details of both calculation methods and several calculation results are shown in JICE (1983) and JICE (2000).

In addition, according to results of various measurements, the maximum working strength in the longitudinal direction was measured as 2/3 of the calculated working strength in the circumferential direction. That value was measured at both ends of the rubber body near the side walls. The 2/3 value of the calculated working strength in the circumferential direction is now defined as the maximum working strength in the longitudinal direction in the technical standards.

3.1.2 Safety factor of rubber body

The minimum safety factor of the material of the rubber body has been defined as 8 times the calculated working strength since the first rubber gate installation in Japan. It is also specified in the 1st edition of the standard. When we studied the design and performance of a rubber gate during the production of the 2nd edition of the technical standard in 1983, we considered and compared other safety factors that were applied in the manufacture of other rubberized fabric products such as tires, air springs, pneumatic rubber fenders, etc. It was finally decided that we should keep the safety factor of 8 because the rubber gate was expected to have a longer service life such as 30 to 40 years which is much longer than other rubberized fabric products. Since then, we have continued studying the properties of the rubberized fabric and have collected test results regarding the retained breaking strength of the rubber body material that was exposed at the rubber gate sites for a long period. Subsequently, in the 3rd edition of the standard (JICE, 2000), the safety factor of rubber body material is specified as follows:

$$F_S = f_1 \cdot f_2 \tag{1}$$

The safety factor F_S depends on coefficient of creep breaking strength f_1 and the coefficient of retained rubber body breaking strength f_2.The creep breaking strength means that the breaking strength of the material of the rubber body becomes lower after a long period of loading even if the load is small. The creep breaking test result of the rubber body material (rubberized Nylon fabric) is shown in Fig. 4. According to these results, we could estimate f_1 = 2.53 for a 30 year expected service life by using the lower limit value of the variation of the test results.

On the other hand, the test results regarding the retained breaking strength of the rubber body is shown in Fig. 5. We could estimate f_2 = 1.73 for 30 years expected service life. Therefore, the safety factor is estimated as follows.

$$F_S = f_1 \cdot f_2 = 2.53 \cdot 1.73 = 4.38 \tag{2}$$

But the above safety factor is based on the calculated working strength using a two dimensional cross section method of calculation. On an actual rubber gate, stress concentration occurs in the rubber body and this is calculated to be 1.75. Consequently, considering the effect of stress concentration, the safety factor should be almost 8 times the calculated working strength which is the same value we had used for the calculated working strength in the two dimensional cross section analysis.

In case a rubber gate is damaged by rolling rocks or vandalism, etc., stress concentration occurs at both ends of the damaged portion and a rubber gate might be broken or burst if a smaller safety factor is used. Then, according to the author it is desirable that the safety factor should be more than the value of 8 that we have used for many years.

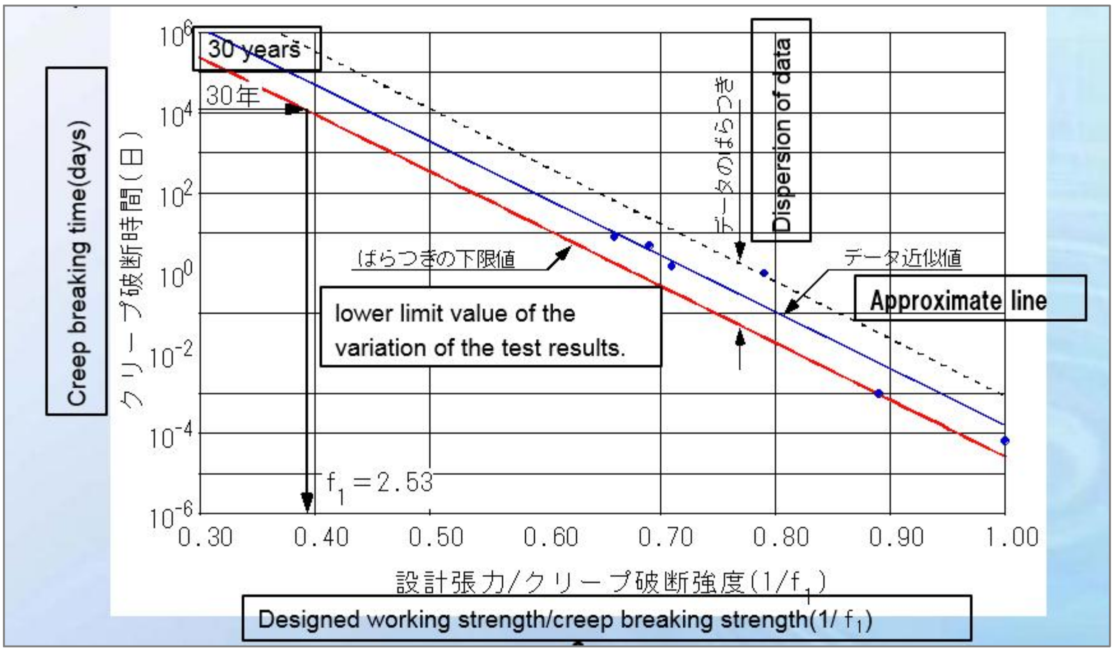

Figure 4: Creep breaking strength of rubber body taken from JICE's presentation to the PIANC working group in 2014

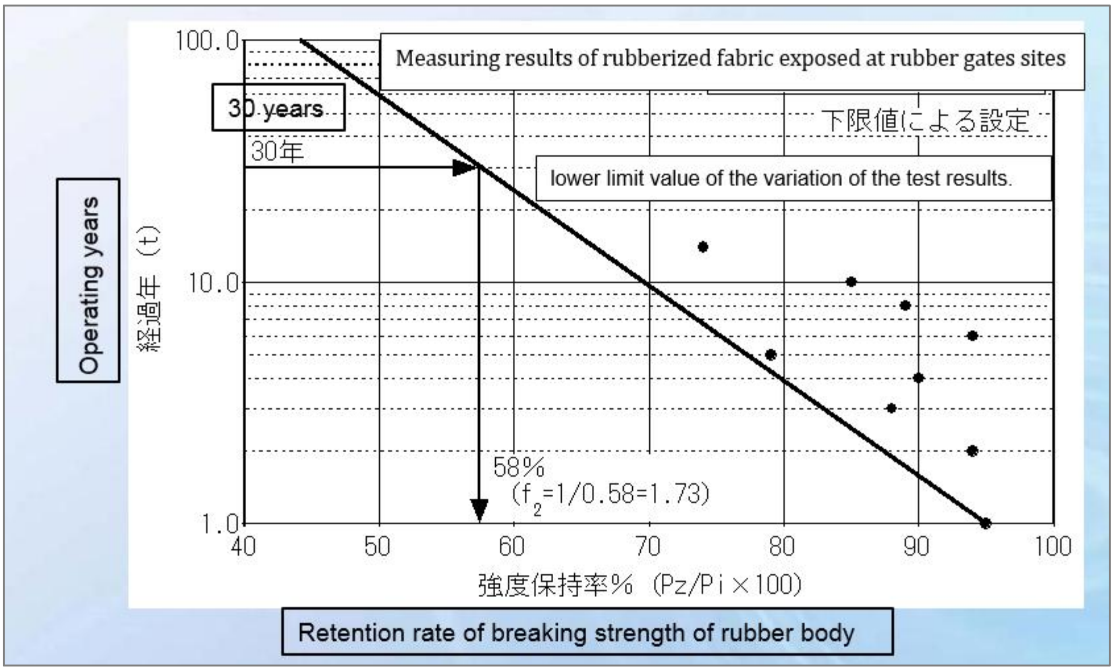

Figure 5: Retained breaking strength of rubber body taken from JICE's presentation to the PIANC working group in 2014)

3.1.3 Specification of the rubber body

A rubber gate is expected to have a service life from 30 to 40 years and the service life depends mainly on the material used in the construction of the rubber body and the manufacturing method. Therefore, we need to pay particular attention to select suitable material; both rubber compound and fabric. The standards show the minimum specification requirement of the rubber body material including both the rubber (inner, outer and intermediate layers) and the rubber body (rubberized fabric) in a table. All rubber gates installed in Japan must meet and have met the specification requirements and almost all rubber gates are operated adequately and effectively still now.

It is assumed that, in the near future, some new rubber gate manufacturers may enter this business and according to the authors opinion it is sufficient for them just to meet the current Japanese technical standard specifications to achieve the required long service life for a rubber gate. At the moment the author always advises all clients and manufacturers that they should execute the long term aging tests in addition to the current specification tests. The long term aging tests are to measure the rubber physical properties (tensile strength and elongation) and adhesive strength of rubber body (rubberized fabric) after the samples have been immersed in hot water at 70°C for approximately one year. This aging condition would be roughly estimated as equivalent to approximately 45 years of actual use in a temperate region.

3.1.4 Hydraulic design of a rubber gate

A rubber gate consists of a rubber body, pipe lines and operation equipment. It is used as a movable weir by inflating the rubber body with air or water. It is a very simple, light and flexible structure and, as a consequence, it can get affected by hydraulic conditions. Therefore, we need to consider such hydraulic effects and understand the properties of the structure such as the V-notch condition, coefficient of discharge, gate vibration due to high overflow and the effect of sedimentation (removing the sediment). These effects are shown clearly in the technical standards (JICE, 1983, 2000).

Gate vibration is one of the most important considerations and the author would like to show the boundary conditions of rubber gate vibration and some countermeasures against vibration that the standard shows in detail. Below are some of the main points.

- The maximum overflow depth should be determined to ensure the safety of the rubber gate and so that it is free from the harmful vibrations.
- The harmful vibration for a rubber gate is one that occurs when the gate is in the inflated condition.
- Generally the maximum overflow depth should be less than 20% of the gate height for an air-inflated gate and less than 50% of the gate height for a water-filled gate.
- If a rubber gate is possibly used in the vibrated conditions, proper countermaesures against vibration should be taken and the effectiveness of the countermeasure should be confirmed.
- In addition to the above, the standard describes the following two countermeasures against vibration and it also shows that both of these countermeasures could be effective in stopping vibration of a rubber gate even in the condition that the overflow depth is approximately 50 % of gate height.

  (1) Widening the spacing between the anchor bolt lines. This will make the cross section shape of the rubber gate close to a semi-circular shape. This could stop a rubber gate from vibrating due to high overflow depths.

  (2) Installing deflectors or similar devices to potentially reduce vibration. The effect of the deflector is shown in detail in the PIANC WG166 working group report. But the effect of increasing the spacing of the anchor bolt lines is not shown in detail in the report. Fig. 6 shows the relation between the cross section shape and vibration boundary.

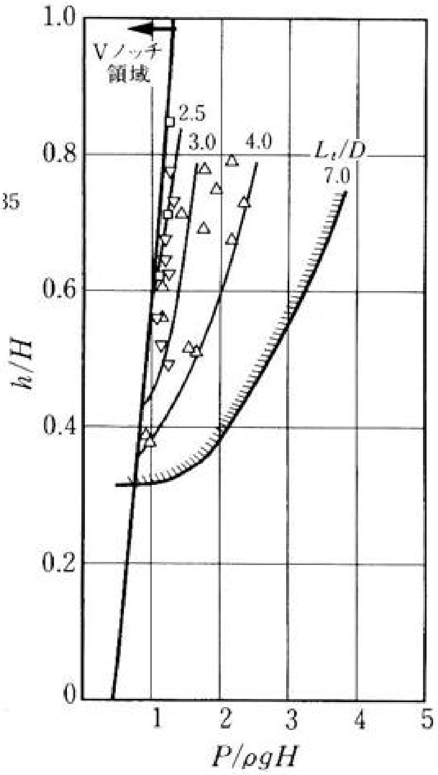

Figure 6: Relation between the cross section shape and vibration boundary, where L = total length of rubber bag including spacing (D) between clamping lines: H = gate height; P = internal pressure; h = overflow depth (JICE, 2000)

3.1.5 Safety equipment (overpressure protection equipment and back-up deflation system)

It is described in the standard that a rubber gate should have safety equipment that prevents damages caused by overpressure and ensures a rubber gate deflates reliably even when the normal deflation system is not functioning. Since publishing the standard, such safety equipment have been installed even for rubber gates that are provided with a fully automatic operating system or even for rubber gates that are required to maintain a constant upstream water level. Rubber gates equipped with overpressure protection equipment will not suffer damage due to overpressure and will not deflate accidently during high flow rate events.

Examples of two different types of mechanical safety equipment are the air blow-off tank and bucket-type deflation system for air-inflation type rubber gates and the siphon pipe and bucket-type deflation system for water-filled type rubber gates. These are shown in Fig. 7.

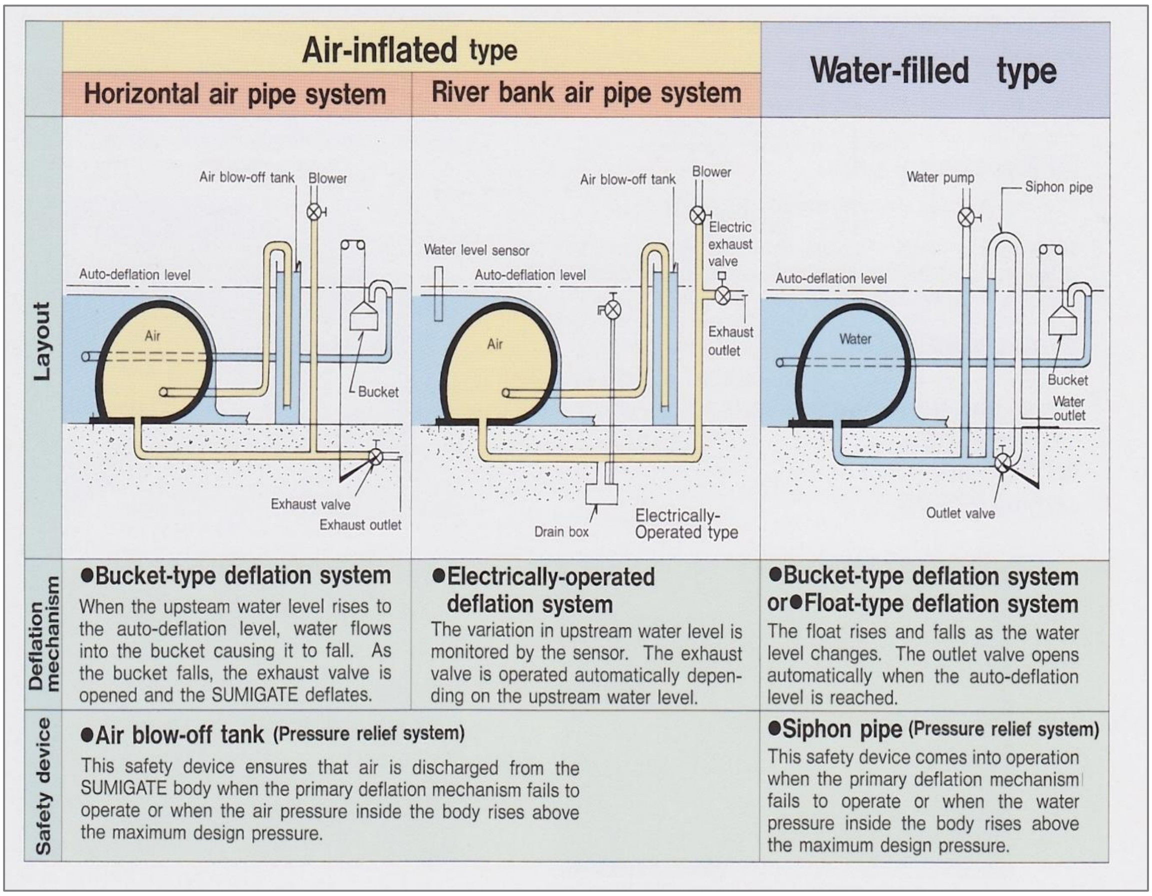

Figure 7: Examples of mechanical safety equipment (taken from Sumitomo Electric's brochure)

3.1.6 Countermeasures against rolling rocks and debris

As mentioned previously, in Japan, many rubber gates have been installed in the upper reaches of rivers for the purposes of small hydro power generation and irrigation. Naturally, at these locations, the gradient of the river bed can be very steep. In these conditions, a number of rubber gates were damaged by rolling rocks and other river-borne debris that passed over the deflated rubber body especially during the rainy season in Japan or when typhoons occurred. Therefore, countermeasures were needed to protect the rubber gates against rolling rocks.

In the standard, it is shown that "a rubber gate should have proper countermeasures against rolling rocks when it can be damaged by them". The standard also shows a cushioning system and thick rubber body as examples of countermeasures. The likelihood of damage caused by rolling rocks can be calculated from the river flow velocity, the size of the rolling rocks and impact energy imparted on the deflated rubber body. Following on from this calculation, the manufacturer will select a suitable type and thickness of cushion material or decide to increase the thickness of the rubber body material. One example of a cushioning system is shown in Fig. 8.

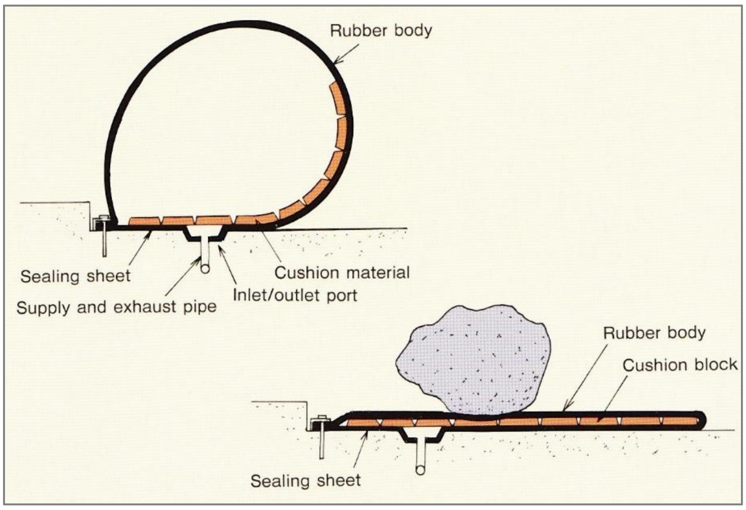

Figure 8: Cushioning system (taken from Sumitomo Electric's brochure)

3.2 Japanese Technical Standards

When the standards are reviewed and revised, the responsible Ministry MLIT organizes a committee that consists of JICE, PWRI (Public Work Research Institute), some professors from universities and representatives of rubber gate manufacturers to study progress in rubber gate technological developments since the standard was last updated. This process can take years and the result is an updated version of the standard. In table 1 all standards, design guidelines and maintenance manuals are shown. It is noticeable that the number of rubber gate installations per year increased rapidly after the 1st edition of the standard was published in 1978. This standard had an important and significant effect on Japanese rubber gate technology and business. Table 1 provides also links to the web sites where the standards can be seen and downloaded. Unfortunately, these are only available in Japanese.

Year	Title of TS	publisher
1978	TS (1st edition) of a rubber gate	Japan River Association
1983	TS (2nd edition) of a rubber gate	JICE (Japan Institute of Country-ology and Engineering)
2000	TS (3rd edition) of a rubber gate http://www.jice.or.jp/tosho/pdf/gomubiki.pdf	JICE
2006	SR gate design guideline (1st edition)	SR gate investigation committee JICE
2006	Maintenance manual of a rubber gate http://www17.ocn.ne.jp/~dam/book/syoseki/gomu.pdf	JADWEE (Japan Association of Dam & Weir Equipment Engineering)
2007	SR gate design guideline (1st enlarged edition) http://www.jice.or.jp/sim/t1/200705210/download/summary.pdf	SR gate investigation committee JICE
2015	TS of a rubber bag applied for a rubber gate & an actuator of SR gate http://www.mlit.go.jp/common/001132480.pdf	MLIT (Ministry of Land, Infrastructure, Transport & Tourism)

Table 1: List of technical standards in Japan (JICE's presentation, translated by WG166)

The PIANC WG166 has unofficially translated some of the standards (PIANC, 2018). The intention is to store these documents and provide access to them on a web site soon for all engineers, clients and operators that have an interest in rubber gates.

3.3 Durability of a rubber gate

The durability of a rubber gate depends to a large extent on the properties and characteristics of the rubber and rubberized fabric that is used in the fabrication of the rubber body which is the main component part of a rubber gate. The fabric used usually has a limited width due to the equipment (textile machine) used in the weaving process. This width is usually from 1.0 m to 1.5 m. A rubber body is therefore manufactured by jointing together the widths of rubberized fabrics.

The adhesion at the joint portion is very important for the durability of a rubber gate. In recent years, the breaking strength of rubber body sample exposed near the rubber gate sites and adhesive strength of a rubber body after long periods of actual operation have been measured. The measurement results of both are shown below. This measurement was executed by the one gate manufacturer and its rubber body was made of rubberized Nylon fabric.

According to these data, the decreasing tendency of the breaking strength and adhesive strength seems almost identical. After 30 years of actual use, the retention rates of both breaking strength and adhesive strength are 57 % and 58% of the original values, respectively (Fig. 9 and Fig. 10). These results indicate that if, in the original breaking test (carried out just after manufacturing) a sample of rubber body material at the joint does not fail at the joint due to peeling (delamination) but fails due to the fabric breaking, we can assume that the rubber body will not fail by peeling (delamination) at the joint after a long period of actual use. It is considered that such a rubber body would be safe and would not burst as a result of low adhesive strength.

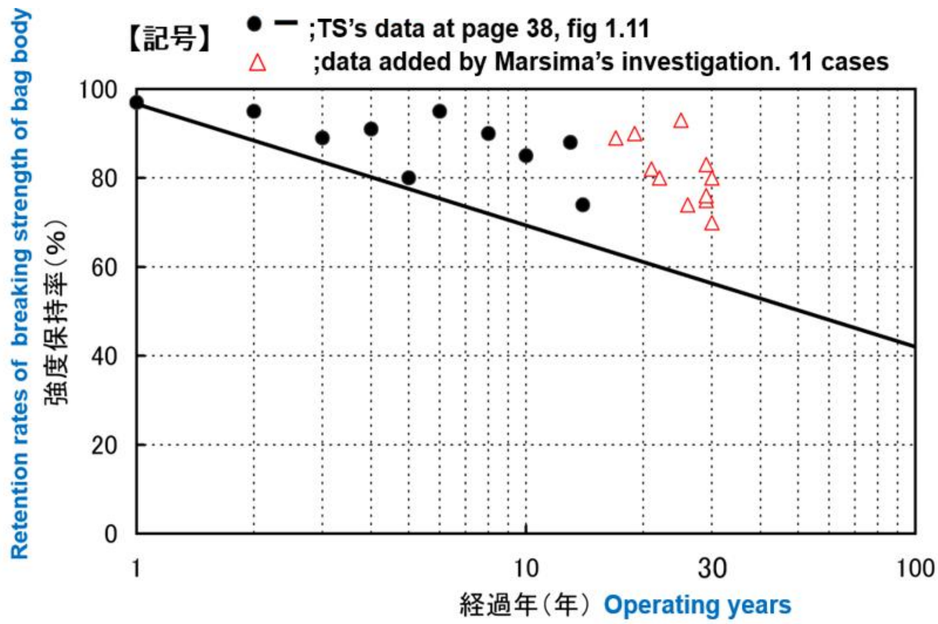

Figure 9: Retention rate of breaking strength of rubber body material (courtesy of Marsima Aqua system)

In the latest standard (JICE, 2015), a requirement has been added that a breaking strength test of the rubber body at joint should be carried out and in the specification it is stipulated that the sample failure in this test must not be at the joint part but in the normal portion of the rubberized fabric on either side of the joint and that failure should be as a result of fabric breaking. The above test procedure and test results seem adequate and effective when the retention rates of both breaking strength and adhesive strength of the rubber body are almost the same.

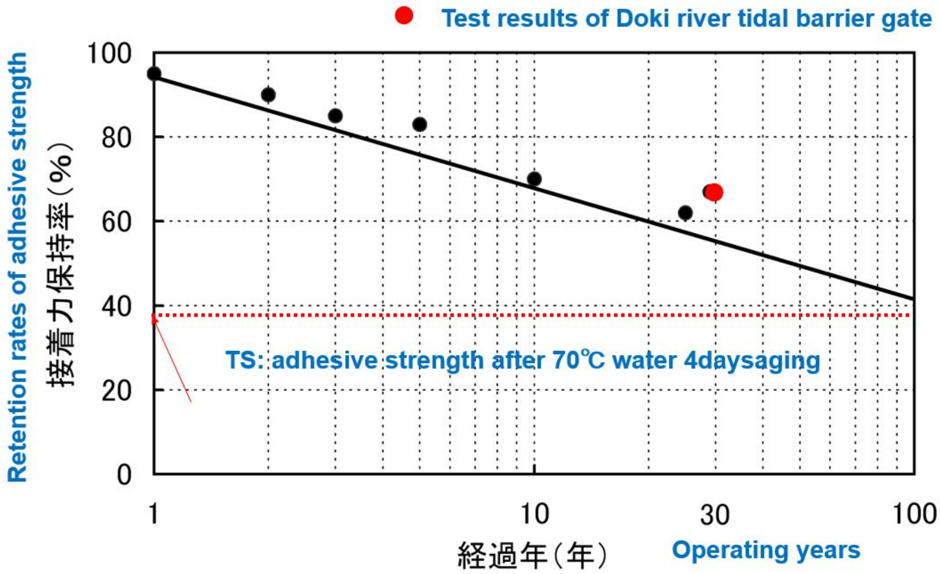

Figure 10: Retention rate of adhesive strength of rubber body material (courtesy of Marsima Aqua system)

As shown in paragraph 3.1.3, the author would like to recommend to all clients and manufacturers that a manufacturer should obtain test results of adhesive strength after the rubber body material aging (long period of soaking) and should manufacture the rubber body with an adequate joint width in accordance with the adhesive strength aging test results and the relevant retention rate. A suitable joint width designed in this way means that the rubber body material should never fail at the joint by peeling or delamination before the rubberized fabric fails.

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