INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH

ASSOCIATION INTERNATIONALE DE RECHERCHES HYDRAULIQUES

TENTH CONGRESS LONDON 1963

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VOLUME 3

Hydro-Elastic Vibrations

Vibrations hydro-élastiques

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Hydro-Elastic Vibrations

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GENERAL LECTURE

"VIBRATIONS AND RESONANCE IN LARGE HYDRO-POWER SYSTEMS"

by

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A.M.I.C.E., M.A.S.M.E.

CHAIRMAN: PROFESSOR A.T. IPPEN.
PRESIDENT OF THE ASSOCIATION

Meeting in the Great Hall

of

The Institution of Civil Engineers

on

Tuesday, 3rd September, 1963 at 12.00. Noon

Professor Ippen said that at their last Congress in Dubrovnik two years previously they had initiated special lectures as highlights of their Congress. It was his pleasure and privilege to preside that day at the first general lecture of the present Congress.

He wished to introduce to those present Dr. Charles Jaeger, who was their first lecturer, and he wished to give them a few details of Dr. Jaeger's exceptional professional career.

Dr Jaeger grew up in Switzerland, and received his technical education at the famous Federal Institute of Technology in Zurich from 1919 to 1923. After a period of seven years in engineering practice, he returned to the Federal Institute to work on many theoretical and experimental studies with Professor Mayer Peter, one of the founder members of their Association. He received there his doctor's degree in 1933 with the topic of his thesis "The general theory of water hammer". In 1943 he established himself as professor with a dissertation on the theorem of minimum energy and momentum. Since 1946 he had taught at the Imperial College of Science and Technology of the University of London, giving lectures on engineering fluid mechanics and on hydro-power. He was simultaneously consulting engineer with the English Electric Company on hydro-power developments.

Dr Jaeger's interests and his contributions covered many fields of civil engineering however. His book on "Engineering Fluid Mechanics" was outstanding and well known to those present, but he had also worked on dam design and dam foundations, on tunnelling and underground works, on rock mechanics, on pump storage and on hydro-power economics. He was an Associate Member of the Institution of Civil Engineers and a Member of the American Society of Mechanical Engineers. He participated in the work of the Committee on Underground Work of the International Commission on Large Dams.

Through his wide professional experience and his deep insight into engineering problems as an outstanding practitioner and basic scientist, Dr Jaeger had become a lucid and accomplished lecturer, and it was with admiration and great pleasure that he presented to those present Dr Charles Jaeger for his first general lecture on "Vibrations and resonance in large hydro-power systems".

Dr Charles Jaeger:

In the Introduction to the 44th Thomas Hawksley Lecture on "Vibrations: A Survey of Industrial Applications" Prof. den Hartog remarks that this field of investigations has grown exponentially. Many modern textbooks have been written on this field. They usually start with a modest, decent, homogeneous second-order differential equation. Then the theory develops. Vibrations in systems of one degree of freedom are just an introduction to vibrations in systems of n degrees of freedom. Linear systems are soon abandoned for non-linear systems, and matrices and series of Fourier are introduced to the great satisfaction of the reader.

Some papers on hydro-elastic vibrations submitted to this Congress also start modestly with a linear second-order differential equation. Others introduce matrices and series. As in any parallel domain dealing with vibrations, the authors are obviously faced with difficult problems.

In contrast to the treatment of "mechanical vibrations", which constitute a well-defined branch of Mechanics, there is still no accepted subject called "Hydro-Elastic Vibrations". This name is not even mentioned, even in the most recent textbooks and handbooks on Fluid Dynamics.

Under such a title we may include phenomena concerned with elastic waves or, more generally, elastic vibrations progressing in water or in a system of two or more media, one of them being water. Most authors deal with vibrations, forced vibrations and self-excited vibrations, and they also cover elastic phenomena where water mass or energy, or both, are being transmitted, and such phenomena where there is no such transport.

On the other hand, the general characteristic of hydro-elastic vibrations is that pressures are variable functions of time and space. This definition eliminates the vibration in air and gases but could be extended to liquids other than water.

The subject under review being a new one, it seems desirable to describe first what sub-chapters are likely to form part of it. Then, by illustration from past experience in the field of hydro-power, the danger of some hydro-elastic vibrations will be discussed.

I

1. A general survey of hydro-elastic vibrations could start with a few remarks establishing parallels with mechanical and electrical vibrations and outlining the mathematical methods to be used.

2. Many problems to be dealt with in this wide chapter are of such complexity that model tests will be required to open the way to better understanding. The question of the validity of a law or of sevel parallel laws of similarity must be discussed.

When hydro-elastic vibrations depend on or are influenced by the frequency of vortices, the similarity law of Strouhal must be used. The Strouhal number S is dimensionless and in first approximation depends on the frequency of the vortices, on a typical dimension of the body obstructing the flow and on the average velocity of flow or a typical dimension of the fluid configuration. This is only one aspect of the problem.

In many cases the flow conditions will depend in addition either on the Froude or on the Reynolds numbers. The elastic deformations of a body depend for true model reproduction on the law of Cauchy.

Finally, the Meier-Windhorst formula for bodies with specific density ρ_2 vibrating in a fluid with density ρ_1 has to be considered in some cases.

This enumeration of conflicting conditions shows that every case has to be carefully examined and dealt with in relation to its particular characteristics. For example, the testing of reversible pump turbine guide vanes against dangerous vibrations requires a precise knowledge of all these laws.

3. It is essential to make a distinction between forced vibrations and self-excited vibrations. A forced vibration is imposed on a system by an external alternating force which has an identity and frequency of its own, independent of the vibrations of the system. Hence the system vibrates with the frequency of the external force. But a self-excited vibration, also called auto-vibration, is a consequence of the vibratory motion itself. Most self-excited systems vibrate at one of their natural frequencies. A classical example is the resonance of a pressure pipeline, or, more generally, of a pressure system.

Research on oscillations starts with single systems. Recently, investigations in two-phase flows, where two elastic fluids are involved, have been given much attention.

4. Then the cause and origin of the vibrations has to be determined.

In some cases, such as vibrations of a gate, the cause of vibration is to be found in the flow itself and in eddies formed by turbulent flow at the point where the jet leaves the edge of a gate. Vortices of a different type may also explain the behaviour of turbine wheels.

In other cases, the origin of hydro-elastic vibrations may be the deflection of an elastic gate or the vibrations of an incorrectly damped valve, or they can be caused by a rotating or a reciprocating machine.

In most of these cases, the origin of the vibrations is given by boundry conditions which are unwanted or even detrimental. The problem will then be to suppress the cause or to dampen the vibrations, or to reduce their detrimental effect. Typical problems of this type are the damping of valve vibrations or the suppression of cavitation or of eddies along the edges of the turbine blades, flutter of rudders, vibrations of hydrofoils, propeller singing, and so on.

Conversely in other cases, the problem consists in deliberately creating artificial vibrations. Into this category falls the rotating cock used by Camichel in 1910-1914 to analyse resonance in pipeline systems. All machinery used to generate elastic waves or to use the waves' energy to convert it into movement belongs to this category. Little has been written about this machinery and how it would be used; some interesting mathematical studies have been published where the words "generator" and "receptor" are used without describing how the author visualises a generator or a receptor.

To the last named category we may place arrangements where hydro-elastic vibrations are generated in the mass of the flow itself by causing vortices to be created and to progress in the hydraulic medium. These vortices can be caused by an obstacle obstructing a passage, or by diverging walls guiding the flow, or by an unsymmetrical or unbalanced body floating in the water.

5. The next point to be considered if the way vibrations and elastic waves are propagated.

A first group of problems comprises waves following the narrow path of a conduit or pipeline. Into this category fall all the classical and special problems of water hammer and the transmission of signals or of energy along a conduit or pipe. Sometimes vibration energy transmission is connected with pumping problems.

In another category belong the more general problems where the flow is not limited by the solid boundaries of a conduit or where these boundaries are disregarded, and where the whole process is either by vibration of internal vortices such as the vortices generated by rotating turbine blades, or the air bubbles entrained in a hydraulic jump.

Finally, there are all the cases where vibration is transmitted by water to a solid structure or by water to another medium - for example, to air.

6. In recent years, research has been going on along all these lines. Papers submitted to this 10th Congress cover practically the whole field described here. Problems

concerning model testing of hydro-elastic vibrations, the laws of similarity to be applied, with special consideration of the Strouhal number, have been discussed by several authors. Vortices, their formation, their use or their suppression, form an important chapter of the problem under review. The generation and transmission of sonic waves has been pursued mainly in Rumania, the U.S.A. and this country as a supplement to Constantinescu's work. Specialised research laboratories concentrate on the vibrations of gates of all types, of valves, on the stability of aerated or non-aerated water jets passing under gates or through valves, or of napes flowing over gates.

All this research comes logically within the definition of hydro-elastic vibrations, where special attention is devoted to rapid changes of pressures and velocities. Depending on the background of each writer, more or less attention will be given to fundamental research or, on the other hand, to industrial applications. Whilst referring to the industrial aspects of research on hydro-elastic vibrations, it is worth underlining how great is the impact of rapidly evolving industries on research.

7. Since rockets and satellites have been developed, a new science, the Aero-Space Science, has emerged - with new problems, new methods. Vibrations in liquids contained in tanks, the breathing vibrations of thin pressurized cylinders containing compressible liquids or liquids with a free surface, are the objects of vast new chapters of the theory of vibrations.

8. In recent years the progress of gas bubbles in a liquid, a problem of vital importance to atomic engineering, has been the focus of a great deal of research. Similarly, studies have been published on the entrainment of air in the hydraulic jump. This may lead to the study of unsteady pulsations of two-phase flow adding another chapter to our problem.

9. Finally, dynamic water pressures caused by earthquakes, a problem of importance to dam designers, should also be mentioned.

10. Most scientists interested in this research expect a positive result from their efforts. The creation or the transmission of a signal, or the generation and transmission of an energy, is the final aim of their research.

Are their efforts free from danger ? Let us imagine the case of a sonic signal which has to be transmitted along a pipe. Suppose that the excited fluid causes resonance to start and to grow in the pipe: what happens then ? And what happens when successful laboratory tests are to be extrapolated to full scale designs ?

Are some particular hydro-elastic vibrations dangerous ? Which ones ? How great is the danger ?

It is well beyond our capacity to write such a chapter. Let us be content with the description of a few typical cases. Den Hartog has adopted this method in his brilliant paper on vibrations. Inspired by this example, let us modestly follow a similar path in our own domain, which is concerned with the design of large hydro-power systems.

II

Many engineers have been trained in the belief that hydro-elastic vibrations are dangerous and may cause disaster. This may be termed the negative approach to the problem. A discussion of some cases of failure caused by such vibrations is a useful guide for further research; it will show that there are limits to what can be expected from the positive use of hydro-elastic vibrations.

Dangerous hydro-elastic vibrations have been caused by turbulent flow or cavitation, by mechanical devices and machinery, and by auto-oscillation of hydraulic systems, or by a combination of such causes.

1. <u>Vibrations caused by highly turbulent flow</u>

The classical example of dangerous vibrations caused directly or indirectly by highly turbulent flow concerns vibrations of gates of different shapes. Many gates exposed to flow of water have been set to vibrate; some have been damaged, some others have been utterly destroyed.

Research on vibrations of gates caused by turbulent flow of water started in Germany after the destruction of a roller gate at Poppenweiler in 1912. Model tests showed the cause and the mechanism of the failure, and since then simple design rules derived from tests have been applied for roller gates to avoid dangerous conditions.

Each type of gate has its own problems. Vibrations may be caused by negative pressures and suction, by incipient cavitation, when a high speed water jet passes under a partially opened gate, or by a phenomenon of acoustic vibrations of a volume of air trapped under a jet spilling over a gate.

Systematic research work on gates in general has been published by Dr Petrikat in Germany, and others in other countries. An interesting thesis due to Naudascher supplements this research and given information on vibrations of a sluice gate which is submitted simultaneously to overflow and underflow. The work of Pariset at the Laboratoire Dauphinois d'Hydraulique should also be mentioned here. Pariset investigating the behaviour of a jet flowing over the top edge of a sluice gate shows that the vibrations depend on the volume of air trapped under the overflowing nape of water. The vibrations of the water nape are transmitted to the steel gate by the air. Pariset does not attempt to write dynamic equations for such a complicated treble system consisting of water, air and steel structure. A very intuitive method of reasoning helps him in the interpretation of the main test results.

Such intuitive methods, linked to model tests, may show the way in the many cases where a direct mathematical approach to the problem is difficult. The discussions on this 10th Congress on gate and valve vibrations show how seriously the problem is being tackled. Definite progress has been achieved on theory and on model research.

Another example of dangerous vibrations caused by excessive turbulence of water inside a steel-lined gallery is worth describing.

<u>Fig. 1</u>. A rockfill dam was under construction. Provision for discharging water during the construction was through a 22 ft or 6.70 m diameter steel-lined straight scour gallery, built in blocks of concrete, at the bottom of the rockfill dam at level 580 ft. Fig. 1 shows a plan view and a cross-section of the dam. At a certain stage it was decided to plug this gallery as water had to fill progressively the large storage reservoir during the construction of the dam.

It was thought that the power intake with sill at level 630 ft should be used for controlling the water level in the storage reservoir, before the incoming flood period, in order to avoid overtopping of the rockfill dam. The spillway on the right abutment of the dam was still under construction.

This power intake feeds water through an inclined shaft with two bends before joining the bottom scour gallery just downstream of the plug. The lower end of the inclined shaft and the scour gallery were steel lined. Such a design was at that time recommended as being safe and conservative.

At the end of June, 1957, the water in the reservoir reached level 668 ft, 38 ft or 11.60 m above the intake sill. The two intake gates were opened and water discharged through the power tunnel. The flow under a head of 86 ft or 26 m was a free surface discharge reaching a high velocity. On 21st June, 80 hours after the opening of the gates, a heavy shock occurred inside the gallery, accompanied by a loud noise. A giant spout of water was observed at the scour gallery outlet. These were signs that a major accident had happened.

<u>Fig. 2</u>. Immediately the gates were lowered. When engineers tried to enter the downstream end of the gallery they found the passage blocked by an impressive mass of

folded steel sheets, as the slide shows. Fig. 2 gives an impression of the disaster. A window had to be cut through this mass of steel. Inspection showed that the steel liner inside the gallery had been ruptured.

It was suspected that the highly turbulent flow which had passed through the tunnel could have been the primary cause of the accident.

Fig. 3. Model tests proved that this assumption was correct. Hydrodynamic pressures were measured on the model (Fig. 3) and showed the pressure fluctuations to be at their maximum in the region where the rupture of the steel liner had occurred immediately downstream of the second pipe bend. The line of rupture was a perfect circle in a plane perpendicular to the horizontal scour gallery axis, about a foot upstream of a circular joint in the concrete. Fatigue of the steel plate, caused by vibrations, was suspected, and attempts to explain these vibrations were volunteered.

The report of the metallurgists silenced these theories. Fatigue was the cause of the first rupture, said the metallurgists, but the first fissure was in a direction parallel to the tunnel axis, and not perpendicular to it. The circular line of rupture was by tensile failure. At the same time it was disclosed that at the very spot where rupture had occurred the original concrete lining was locally of poor quality. A large hole had been detected just underneath the ruptured steel plate - at the bottom of it - and had been repaired before inspection by the experts. The steel plate was not properly backed but was bridging a hole 4 ft long at the very point where turbulence pressure variations were at a maximum. Twice the steel plate had bulged at this point and had been repaired. This explained to some extent the accident as being due to fatigue of the steel by vibrations. Three hundred thousand stress reversals had occurred in 80 hours. However, some of the findings of the metallurgists still remained unexplained.

In the meantime, the gallery had been cleared, its downstream end being shaped as a cone in order to force the discharge through the tunnel to occur as a pressure flow. Gates were re-opened.

To clear up many points of vital interest, Prof. Hunter Rouse suggested model tests reproducing the conditions of rupture. Such a model was built and tested. A thin lining represented the steel liner to scale and a small cut parallel to the conduit represented the first fatigue crack in the liner as detected by the metallurgists. The tests showed how water at full speed came through this fissure, and how full Pitot pressure built up behind the liner. This buckled inwards, bulging inwardly like a bag. High tensile stresses developed in a direction parallel to the tunnel axis, and rupture occurred on the model as it had occurred on the prototype, along a circular line, due to excessive tensile stress.

Fig. 4. Fig.4 shows the model from the downstream end, after the liner had buckled. It compares well with Fig.3.

Fig. 5. Fig.5 shows the same model from another angle.

Fig. 6. Fig.6 shows characteristically, the rupture along a circular line and the steel liner bulging in like a bag.

It is believed that nothing would have happened if there had been no hole in the concrete lining. The hole was located just at the worst possible place,where pressure fluctuations were highest.

This example is self-explanatory. Under certain circumstances, high turbulence can be dangerous. It is worth while to compare this accident with the well-known accident at the Gerlos steel-lined shaft in Austria, where conditions were different. Designers of steel-lined shafts are warned by both examples that some rules of safety have to be carefully observed.

2. Vibrations caused by hydraulic machinery

Hydraulic machinery can cause dangerous hydro-elastic vibrations. Reciprocating pumps have caused damage to several pressure penstocks. Schnyder has, years ago, reported and analysed such cases. Vibrations can occur in centrifugal pumps too.

Francis runners may cause severe water hammer conditions when the speed of the rotating turbine, the number of stay vanes and the number of turbine blades start conditions of resonance in the pipeline. This case has been analysed by Prof. den Hartog. Turbine blade vibrations, probably caused by vortices, have been thoroughly investigated and described by Parmakian and Jacobsen and many others.

Cavitation in the turbine draft tube may also cause unfavourable conditions in the penstock upstream of the runner. Hydraulic laboratories are fighting all the time against these and similar recurrent troubles.

It may be worth while to say something about a less well known vibration which occurs when large Francis turbine wheels run at partial load. Dériaz has described and discussed this phenomenon in a paper submitted to a Symposium on Hydraulic Machinery, held in Nice by our Association at the invitation of the Société Hydrotechnique de France.

Pulses of output and instability of draft tube conditions occur some times at about 60 per cent. of the gate opening of Francis turbines. Alleviation of the conditions may sometimes be achieved by air admission into the draft tube, but this measure is not always satisfactory.

Observations of the runner discharge through transparent draft tubes have revealed that at certain partial gate openings a vortex is formed which has a precession movement in the same direction as the turbine rotational movement.

<u>Fig. 7</u> This causes the vortex to alternately obstruct and then clear the water passages in the draft tube (Fig.7) and thus decrease or increase the runner discharge, causing pulsations of output which may be felt in the alternator. At full gate opening the vortex is stable, there is no precission movement and the vortex remains concentric with the draft tube. The diagram on Fig.7, which is one taken from the paper by Deriaz, gives, on the left hand side, an impression of the vortex. In the lower diagrams at the bottom of the figure the vortex is shown moving from one side of the draft tube to the other; in the first position it obstructs the passage of water through the draft tube, and when the vortex is moved to the left it assists the passage of the water, and that causes vibration of the turbine and vibration of the generator.

Deriaz calculates the precission time, which corresponds well with observations on running machines. Of the many corrective measures considered by turbine designers, Deriaz recommends a careful and correct choice of the direction of the absolute velocity C_2 in the velocity diagrams of turbines.
Turbines provided with movable blades are obviously free from these troubles.

3. <u>Resonance in large power systems under pressure</u>

The most spectacular pressure rises and the most dangerous ones are produced by auto-oscillation of the water masses causing resonance of a conduit.

The first experiments on resonance of laboratory pipelines and of large industrial pipelines go back to the years 1911-1914 when Camichel, Eydoux and Gariel, and later on Boucher and Neeser, carried out a series of bold tests. They caused resonance of the fundamental and of harmonics to occur in pipes and in penstocks, and detected two basic periods for pipelines: the theoretical period and the apparent period. The theoretical period is the period measured on a pipe formed by different sections with different diameters, when a very short wave is sent up the pipe and is reflected downwards. The travelling time of the wave measures the pipe's period. The apparent period is the period governing the fundamental resonance frequency of a compound conduit. The apparent period is shorter than the theoretical. Camichel showed that resonance occurs when the discharge at the pipe's lower end is negligible or nil and it causes the doubling of the static pressure at that point. The theory of Allievi gives some general information on resonance but the experimenters were not able to work out a theory explaining all their findings in detail. Few authors followed in the footsteps of Camichel: the names of den Hartog, Schnyder, Sacerdote, Scimeni, and Favre can be mentioned.

<u>Fig.8</u> The tragedy of the Lac Blanc-Lac Noir in January, 1934, must be mentioned now. The Lac Noir station was equipped with four Francis turbines of 40,000 h.p. each

and three 20,000 h.p. pumps (Fig.8). The head is about 100 m. The first pump was being tested at low power when exceedingly dangerous vibrations occurred in the pump which forced the test engineers to try to escape to safety. Then the penstock suddenly ruptured. A crack had started along the stool or collar of a manhole. A hole 25 ft long and 8 ft wide was torn in the pressure pipe. The pipe was torn to pieces. The water jet crushed the roof of the machine house, causing disaster and killing several engineers, including some of those who were at the time occupied with testing the pump. The late Prof. Louis Bergeron was called in as one of three expert authorities. He concluded that resonance caused by vibrations of the movable guide vanes had occurred in the pipeline and caused its rupture. A few years later, Roccard chose this Lac Noir disaster as a typical example for a theory of auto-oscillation in hydraulic systems he developed. It is interesting to mention that Roccard's theory links the vibrations of the exciter to the resonance of the pipe.

<u>Fig.9</u> Another theoretical aspect of the problem concerning the resonance of the fundamental and of the harmonics in systems of compound pipes was developed in 1936 and 1939. The basic idea of the thoery is quite simple as shown on Fig.9. The equations of Allievi for hydro-elastic waves can be written for each section of the pipe. In addition, an equation of continuity of masses has to be satisfied at each discontinuity where at any time, the pressure must be the same on both sides of the discontinuity. The boundry conditions for resonance in pipelines are: no flow at the pipe valve, and total reflection at open surfaces such as storage reservoirs and surge tanks. The same theory was adopted for a system of three pipes as shown on Fig.10. This theoretical analysis was found to agree with the measurements made more than twenty years earlier by Camichel and associates.

<u>Fig.11</u> In 1945 the tunnel of Kandergrund, Switzerland, ruptured. Water, seeping from the tunnel, accumulated between rock strata, causing a landslide. Valuable property was destroyed and two people lost their lives. This was the third tunnel rupture occurring at the same point. Geologists drew attention to poor rock conditions, which substantial repair work had not improved as expected.

Three 20 m (60 ft) long fissures, up to 3 cm (1½ in.) wide, could be seen on the concrete lining of the tunnel soffit. Hydraulic engineers thought they were caused by water hammer starting a powerful pressure rise and lifting the tunnel roof. The surge tank was an exceptionally large one and all types of water hammer waves coming from the turbine end were reflected downwards at the surge tank without penetrating the tunnel. Only a system of resonance waves could by-pass the obstacle of the surge tank: passing through the tank, the pressure variation must remain nil, but the velocity variation is at a maximum and resonance will establish itself in the whole pressure system from turbine end to power intake.

At the time is was not easy to get this explanation accepted. Vibrations of an old undamped air valve at the top end of a stand pipe were suspected.

<u>Fig. 12</u> Probably no further research would have been started on these lines if dangerous pressure rises at the Bersimis II Power Station in Canada had not been reported. Bersimis II is equipped with five turbines totalling 600, 000 kW under a head of 380 ft or 115.5 m. The main pressure shaft divides into five distribution pipes, shaft and pipes being safely built in compact granite. It was soon recognised that the pressure had been caused by dangerous resonance, and it was established that resonance had occurred some time after closing down the station. The valve in front of the turbine had been closed, too; then the water pressure in the valve seal was accidentally dropped, and seepage occurred which caused the valve to vibrate. One valve vibrated, and pressure rose rapidly, but to less than twice the static pressure.

Quebec Hydro Electric Commission, the owners of the power station, and H.G. Acres, their consultants, decided that a thorough investigation of the case should be carried out. Model tests were ordered, and the bold step was taken of repeating the conditions which had caused the resonance. A complete set of measuring devices was installed near two valves, and the resonance was caused to occur by lowering the pressure in valve seals. Periods of 0.52 secs. and 0.182 secs. were measured. A detailed paper is being submitted by Messrs Ian W. McCaig and William L. Gibson of this Congress, giving complete data on the Bersimis II incident and on another similar case at the Caland Ore Company, Iron ore mine at Atikoken, Ontario. The detailed mathematical analysis proved that resonance of upper harmonics had occurred, at Bersimis II putting the whole hydraulic system comprising the distribution pipes, the pressure shaft, the surge tank and the pressure tunnel in resonance. At the valve end, the pressure rose to just under twice the static pressure, and the same pressure rise must have happened at several points along the shaft and tunnel. The granite withstood the dangerous strain.

The tests made at Bersimis II entirely confirmed the explanation given in 1945 for the rupture of the pressure tunnel of Kandergrund in Switzerland. Harmonic oscillations of the whole pressure system can occur and waves penetrate into the tunnel.

There is information available showing that similar resonance occurred at Ffestiniog in Wales, at Guadalupe in Colombia where two pipes burst, in France, Japan, and probably elsewhere. The number of the harmonic is always an odd number like 9, 11, or even higher, and the frequency is usually a few cycles per second. It would be highly desirable for more cases to be reported and published.

Causes of the resonance can be a faulty governor, a leaking valve seal, an elastically deformable valve, vibrations of check valves or air valves, vibrations of the guide vanes, or similar causes. Water wastage at the pipe lower end is always very small.

<u>Fig. 13</u> Boundary conditions able to start resonance are those where an increase of the pressure causes a closing of the gap and a further pressure increase. This can best be seen on Schnyder-Bergeron diagrams (Fig.13). There are three cases given on this Figure 13. In the upper diagram, because of the boundary conditions at the valve resonance is established with increasing amplitude. In the middle diagram, because of other boundary conditions, resonance does not start. The lower diagram, shows stable resonance.

Once started, resonance may last for hours, unless stopped by rapid action. This consists in re-opening the valve or opening a by-pass valve. The increased flow thus drowns the resonance, which vanishes in a few seconds.

What pressure systems are likely to enter into resonance ? This question is of obvious importance.

Model tests have shown that a minimum of leakage is required to start resonance and then to reach the doubling of the pressure. When the leakage is less, resonance is not fully established and the pressure rises are less spectacular. It can be assumed that a minimum of energy must be released at the lower pipe end to balance the friction losses along the whole system of conduits. A balance of energy must be established. It may be interesting to note that all the known pressure conduits where resonance occurred were relatively short. The longest is the Kandergrund tunnel with a length of 4 km. The problem of balance of energy must be looked into in more detail.

<u>Fig. 14</u> In order to by-pass difficult calculations, a Schnyder-Bergeron diagram with axes q and y can be used showing which relation must exist between the elastic shock lines, the valve characteristics and the pressure losses for resonance to be established. The three curves can be replaced by their tangents, α being the angle of the elastic shock lines with the horizontal q axis, δ that of the valve characteristic with the vertical y axis, and β the angle of the tangent to the pressure loss curve with the horizontal axis. The condition for damped oscillations excluding resonance is :

$$\frac{2\cos(\alpha-\delta)}{\cos(\delta+\beta)} \leqslant \frac{\sin 2\alpha}{\sin(\alpha-\beta)}$$

High friction losses, expressed by a larger angle β, cause the damping of the pressure waves.

In the case of resonance we assume that there is balance of energy between generated energy and losses, and no energy is transmitted from one end of the system to the other. It is not impossible to conceive a system where the free surface end of the conduits would be replaced by an arrangement able to absorb energy, for example a pump. The pressure at the end would then be variable and not nil, and energy could be transmitted. This is more or less the system visualised in 1918 by Constantinescu.

Reversing the proposition, it is possible to think that systems designed to transmit energy could cause the whole system to enter into auto-oscillation and resonance, when the period of vibrations happens to be an acceptable harmonic of the whole system and the energy large enough to maintain resonance. There is, therefore, an obvious link between the story of dangerous resonance as told here and the effects to use sonic waves in pipes to transmit energy. There may be many technical problems still to be solved when passing from laboratory tests to full scale design.

Some conclusions could be drawn from all this.

On the one hand, hydro-power engineers have been trained to avoid vibrations. They know the damage done to gates or valves, they know the loss of efficiency caused by vibrations in pumps and turbines, they have witnessed the effects of resonance on huge hydro-power systems.

On the other hand, no less well-informed scientists are endeavouring to create vibrations, to send sonic waves up pressure conduits with the aim of transmitting signals or transmitting energy, or of pumping water.

Somewhere there is a danger line, not to be crossed, frequencies which are dangerous, energy levels which should not be reached. For the time being, the limits are not clearly known and only guesses can be made. It may be that the frequencies used and the energy levels considered for sonic wave transmission were not those which were dangerous; a warning may nevertheless be useful. Practical full scale designs will have to face all eventualities.

These remarks are inspired by incidents which occurred on conduits. Similar remarks apply to gate vibrations. Little information on incidents or accidents having occurred to large gates is available.

A bolder invasion of these somewhat forbidden fields of practical experience, incidents, is one of the recommendations which the 10th Congress should consider.

To the surprise of many, the subject "Hydro-Elastic Vibrations" covers an extremely wide field, ranging from the analysis of streams of eddies to vibrations of large gates, auto-oscillations of large power conduits, or the breathing of elastic containers filled with liquids. Papers have been submitted to this Congress on nearly all these topics.

In the past, work on the subject has been widely scattered. Few attempts have been made to co-ordinate research or to produce inspiring summaries of important sub-chapters. Such efforts are indispensable if a comprehensive theory on Hydro-Elastic Vibrations is ever to be developed.

This lecture does not pretend to cover all the vast subject of Hydro-Elastic Vibrations. It is hoped, however, that enough has been said to establish that here is an important chapter of hydro-dynamics which has been somewhat neglected in the past and which requires more attentive consideration.

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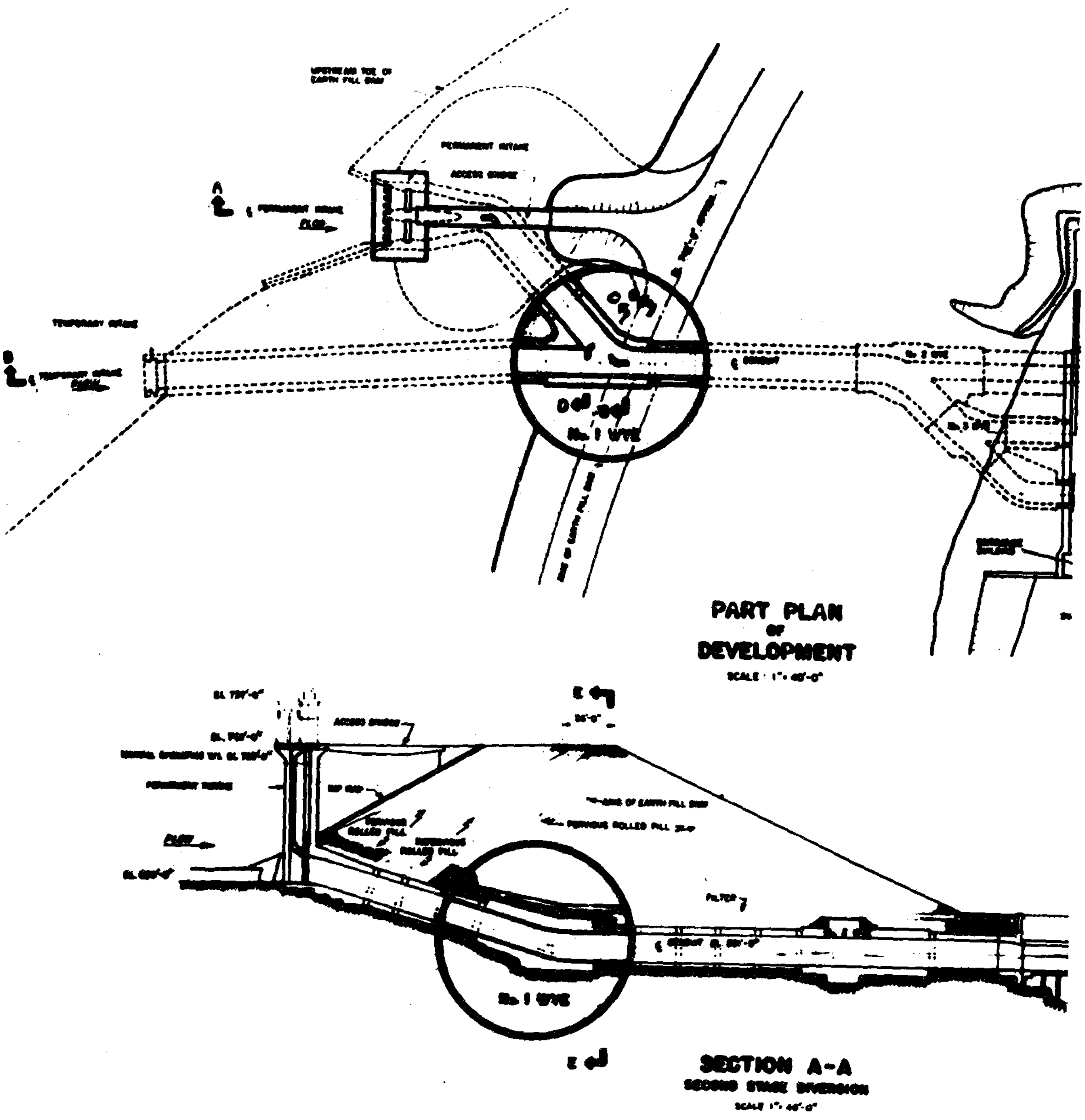

Fig. 1 General layout of a steel-lined penstock.

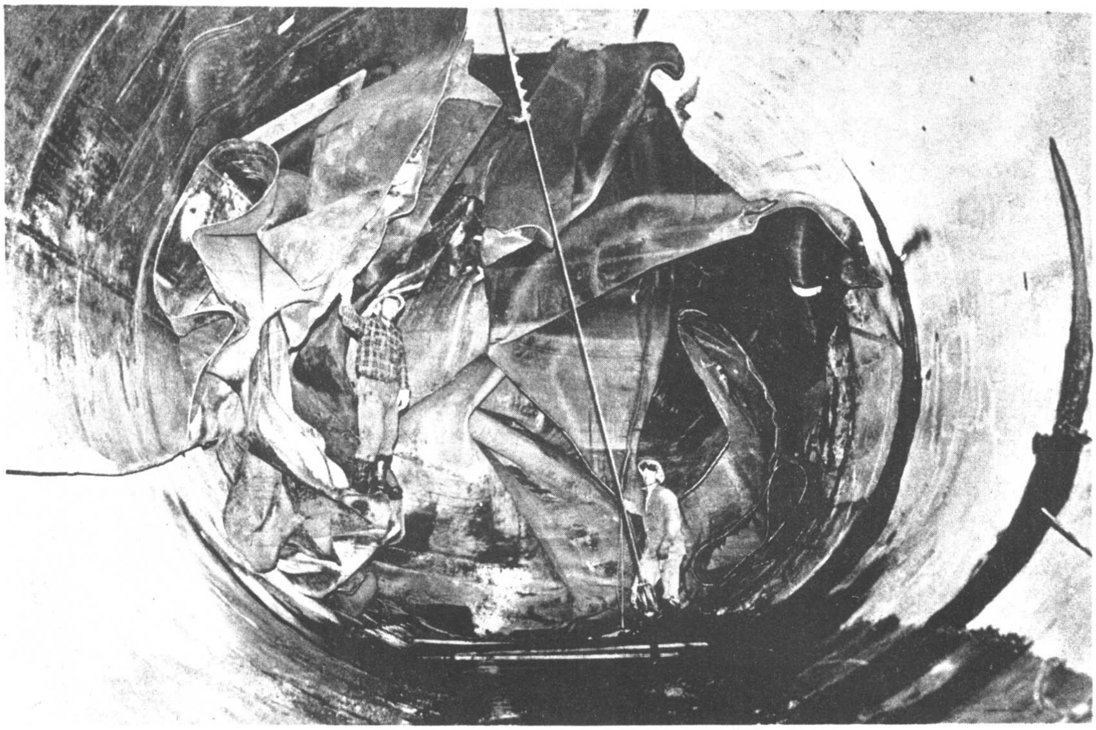

Fig. 2 Ruptured steel lining seen from the downstream end of the penstock.

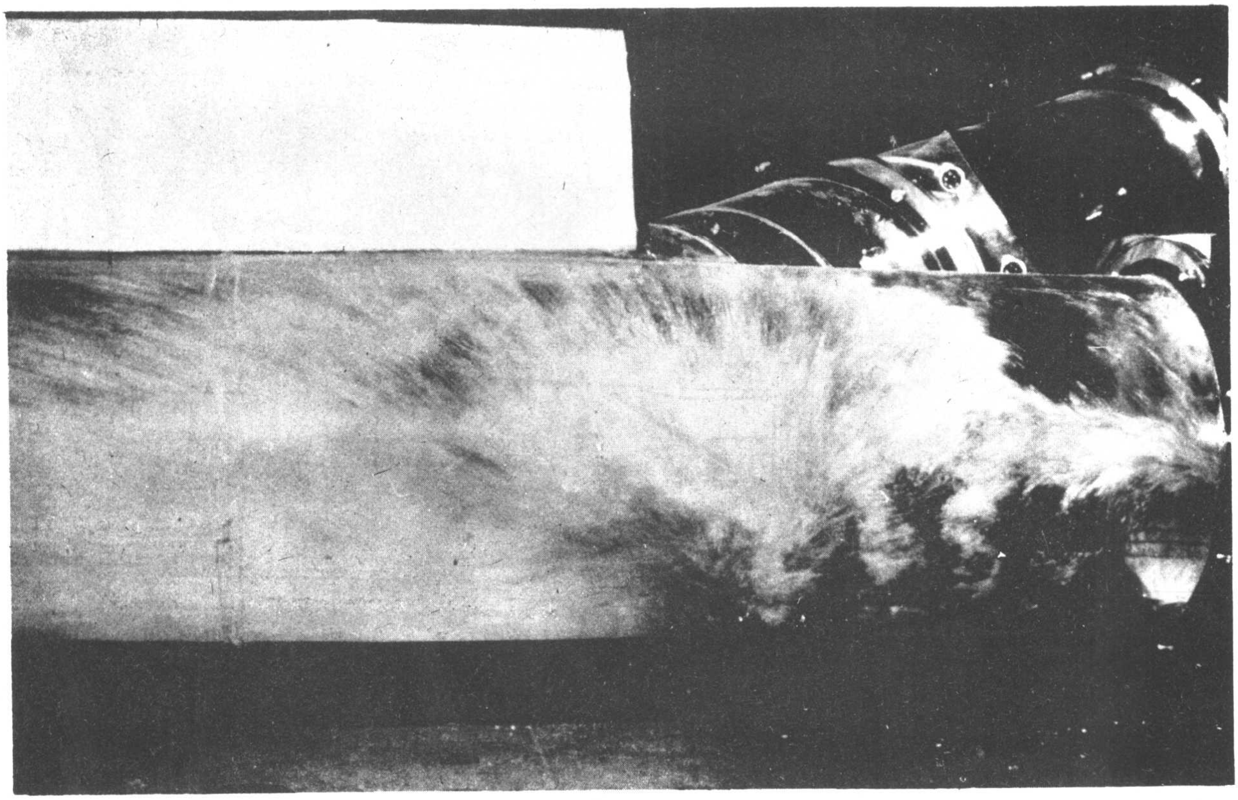

Fig. 3 Model tests showing the high turbulence of the flow in the penstock Y-piece.

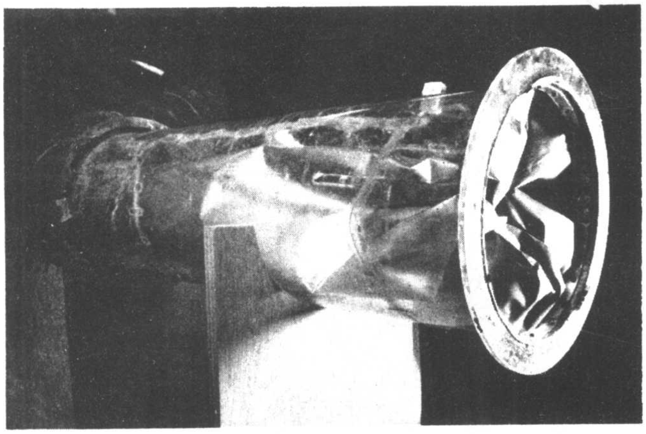

Fig. 4 General arrangement of the model tests reproducing the rupture of the lining.

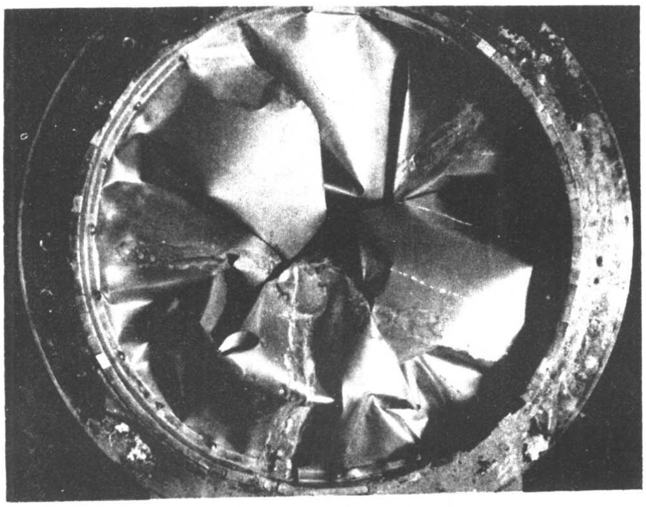

Fig. 5 Model test: ruptured lining shown from the downstream end (To be compared with Fig.2).

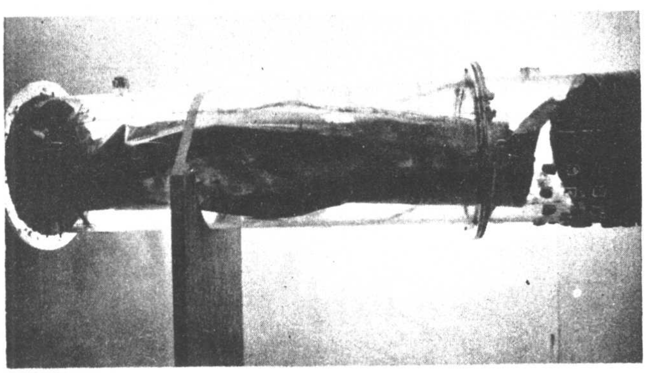

Fig. 6 Model lining showing the sharp circular line of rupture at the upstream end of lining.