Simulation of internal water pressure loads for HPP penstock pipes under seismic impacts

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Abstract. The article provides an analysis of various methods for determining the increase in internal water pressure on the lining of penstock pipes of hydro power plants (HPP) under seismic impacts using static and dynamic theories. The main factors affecting the amplitude of vibration are analyzed.

Keywords. Dynamic model for seismic impact calculation, velosigram of an earthquake, pressure conduit, hydrodynamic pressure increase.

1 Introduction

The methodology for determining loads from internal water pressure under seismic impacts was developed in the works of Sh.G. Napetvaridze [1], I. Nikagava [2]. Napetvaridze’s formula for the maximum pressurization has been included in all editions of SPs for construction in seismic areas [3]. In the works of J.N. Kilasonia [4] and Sh. Okamoto [5], a linear model was proposed for the distribution of pressure peaks along the penstock pipe route under seismic pressure rise at the water inlet side. The fundamentals of the dynamic theory as applied to penstock systems are described in the works of N.F. Mandzhavidze [6].

According to the current SPs [7], seismic impact is classified as a special load combination. The Medvedev–Sponheuer–Karnik scale, also known as MSK-64 is standards-compliant. In addition to describing the effects of earthquakes, the MSK-64 scale contains values of displacements, velocities, and accelerations on the ground surface corresponding to a particular score. These parameters are particularly important in the calculation of engineering structures. Each score corresponds to a particular range of acceleration values.

However, the applied methodology for determining the additional pressure from seismic impacts, based on a simplified model of seismic impact description, does not take into account a number of factors that significantly affect the results, such as accelerograms of actual earthquakes, the design of penstock pipelines, the boundary conditions in the

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hydraulic turbine assembly, the ratio of frequencies of forced and free vibrations, the duration of seismic impact.

2 Materials and methods

The applied calculation methodology for determining the additional pressure in penstock pipelines from seismic impacts is based on the applicable MSK64 model for describing seismic impact. The formula for determining the hydrodynamic seismic pressure rise according to SP 358.1325800.2017 [3] is

\[ P_{se} = \frac{AK_i}{2\pi} \rho \omega^2 \]

where \( A \) – seismicity coefficient, the values of which it is recommended to take equal to 0.1; 0.2; 0.4 respectively for estimated seismicity score of 7, 8, 9; \( K_i \) – the coefficient correcting for tolerable damage to buildings and structures (equal to 0.5 for hydraulic structures); \( \rho \) – sound velocity in water 1485 m/s; \( \omega \) – prevailing period of seismic ground vibrations, the value of which is adopted as 0.5 s.

A typical earthquake is simulated by an accelerogram approximated by the cosine function at 2 Hz frequency

\[ a = a_{max} \cos(\omega t), \]

where \( \omega = 2\pi f_o \) – angular frequency of vibration, \( f_o \) – frequency taken equal to 2 Hz, corresponding to the prevailing period of seismic vibrations [3].

Eq. (1) is based on Joukowski formula for determining the hydraulic shock by the known change in the average mean velocity in section \( \Delta V \) in a pipeline [8]

\[ \Delta H = \frac{c \cdot \Delta V}{g}, \]

where \( c \) – the velocity of the hydraulic shock wave, \( g \) – gravity acceleration.

The maximum change of velocity \( \Delta V \) occurs at the time interval \( T/4 \ldots 3T/4 \). Integration of (2) within these limits gives a formula for the velocity change

\[ \Delta V = \frac{2a_{max}^2}{\pi} \left[ \frac{\sin(\omega t)}{\omega} \right] = \frac{2a_{max}^2}{\pi} \left[ 1 - \cos(\omega t) \right] = \frac{2a_{max}^2}{\pi} \left[ 1 - (-1) \right] = \]

\[ = \frac{a_{max}^2 \cdot 2 \cdot T}{2\pi} = \frac{a_{max} \cdot T}{\pi} \]

Substituting the solution (4) into formula (3), we deduce:

\[ \Delta H_{se} = \pi g \frac{a_{max}^2 T}{4}, \]
After switching from head to pressure, introducing a seismicity coefficient \( A = a_{\text{max}} / g \) and a decreasing coefficient \( K_{1/2} \) in (5), the equation (5) results in the form (1). The issue is discussed in more detail in [9].

The influence of seismic impact on pressure fluctuations in penstock pipelines is considered in more detail when performing calculations of transient processes in time using the theory of waves of N.E. Joukowski and boundary conditions, in the assemblies where hydraulic turbines, control valves, as well as offset bends of surge tanks and pool joints are located. We consider the most dangerous case of seismic wave propagation along the axis of the pipeline, when its walls move together with the ground with the velocity of \( V_{\text{sei}} = f(t) \). In this case, the velocity of water relative to the walls of the pipeline will be \( V + V_{\text{sei}} \) [6]. The specified velocity component is introduced into the differential equations of the unsteady head fluid motion, as well as into the boundary conditions characterizing the change in turbine flow rate. This expands the capacity of basic calculation models for hydro-mechanical transient processes in considering the combined influence on processes in penstock pipelines of hydraulic turbine control modes and velocigrams of specific earthquakes.

3 Results

The use of the dynamic model for seismic impact calculation resulted in a more comprehensive analysis of the processes in the penstock systems of HPPs. The peak seismic pressure in a penstock pipe is reached when the frequency of free pressure fluctuation with the frequency of seismic impact, when the phenomenon of resonance occurs. Comparison of the range of prevailing frequencies of earthquakes with the range of free pressure fluctuation frequencies in turbine pipelines of real hydrostructures has shown that any penstock pipe up to 350 m long can get the resonance, regardless of the lining material (Fig. 1).

Comparison of pressure peaks along the pipeline route upon real earthquakes, scaled for a certain score, and analytical model with harmonic change of seismic impact velocity allowed to determine the duration of harmonic input equivalent to real earthquakes, which is 2-3 periods of seismic vibrations (Fig. 2).

The value of seismic pressure is significantly affected by the steepness of the regulator capacity line in \( Q-H \) coordinates. At a fully open turbine (gate), when the flow rate is close to maximum, the head pulsations arising from seismic effects are negligible. With reduction of flow rate to the level of turbines idle running (8...20% nominal) the value of seismic pressure at scale 7 earthquake increases to 5...10 m, which is less than the maximum hydraulic shock at emergency load dump at power plants at the toe of the dam and diversion type power plants.

In case of zero flow rate in the pipeline, the seismic pressure change does not depend on the head. The pressure rise is limited only by the duration of the seismic impact when it is defined by a harmonic law.

In turbine pipelines of HPPs located at the toe of the dam, the case of zero flow is unattainable due to leakages through the guide apparatus, which make up at least 1% of the maximum flow rate according to operational data. This circumstance provides limitation of the pressure peak rise during seismic impact.
4 Discussion

The analysis of the methodological issues of deriving the calculation formula for determining the maximum pressure rise under seismic impact made it possible to evaluate the included parameters and compare them with the characteristics of specific earthquakes. Modern methods for assessing the dynamic stress state of pipeline shells require a more detailed description of the perturbing effects without limitation to the maximum value [10].
Generalized data of calculations for transient processes in time under seismic impact using the dynamic model demonstrated that the lower the initial flow rate is, the higher the limit of additional pressure is, but a greater number of cycles of seismic vibrations is required to achieve it (Fig. 3). Thus at the initial flow rate equal to 5% of the maximum, the value of additional pressure from a 5-intensity degree earthquake can be 15 m, and this value will be achieved in 2 or 3 periods of seismic impact. At the same time, at the initial flow rate equal to 0.5% of the maximum, the value of additional pressure from a 5 intensity degree earthquake can be as much as 35 m, but this value will require 10...12 cycles of seismic vibration at a constant frequency and amplitude.

The simulation results showed that the attenuation of free pressure fluctuations after seismic impact stops also depends on the initial flow rate. The limit amplitude of pressure fluctuations is directly related to the value of the logarithmic decrement of the oscillation attenuation. The higher the initial flow rate, the higher the value of the free vibration attenuation decrement is, and therefore the lower the value of pressure rise from seismic impact is.

![Graph](image1)

![Graph](image2)
Fig. 3. Dependence on the initial flow rate and on the maximum velocity of the characteristics of the vibration process in a penstock pipe with a period of free pressure fluctuations of 0.5 s under a 5-intensity degree earthquake, an initial head of 100 m and the velocity of the hydraulic shock wave of 720 m/s.

5 Conclusion

The development of mathematical model approach makes it possible to create effective algorithms based on dynamic theory, which allow to consider the specifics of seismic impact and response of the penstock pipeline in a more comprehensive and reasonable way. The dynamic model provides means for calculations on the basis of real earthquake velocigrams, revelation of more complex systems specifications including long headrace and surge tanks of different types, determination of the conditions for reducing the dynamic load from internal water pressure under seismic impact taking into account the operation modes of hydraulic turbines.

The range of prevailing frequencies of seismic vibrations 0.7...5 Hz coincides with the frequency range of most turbine pipelines up to 350 m long. In case of resonance, the seismic pressure component can reach values of 50 m and more already with a 5 intensity degree earthquake, significantly depending on the opening of turbine control elements.

With increasing length of turbine pipelines, the ratio of free and forced vibration frequencies also increases, moving away from resonance values. At the same time, the peaks of the additional pressure are reducing. Therefore, the longer the pipeline is, the weaker the response to seismic impacts and the lower the pressure rise from seismicity is.

Comparison of the values of additional seismic pressure obtained as a result of calculations based on reduced (scaled) velocigrams and analytical models showed that the equivalent to real conditions result is obtained at the harmonic input of two-three periods (4-6 shocks).

Analysis of the vibration process under resonance conditions has shown that the attenuation of pressure fluctuations in a penstock pipe is conditional upon the change in flow rate of the turbine or penstock. Leaks can limit the pressure rise in the pipeline even at prolonged resonance due to the damping effect of the reflection from the turbine assembly of the wave with a negative sign.

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