DOI: https://doi.org/10.15407/pmach2019.03.021

UDC 532.5.032:621.22:519.633

TRANSLATIONAL WAVE IMPACT ON THE OPERATION OF THE DNIESTER PUMPED STORAGE POWER PLANT UPPER RESERVOIR

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The role of hydraulic energy as a reliable source of renewable energy to meet the ever-growing needs of society is highlighted. The uneven nature of the energy supply during the day is analyzed. The role of hydroelectric power plants (HPP) and pumped storage power plants (PSPP) in regulating the above unevenness during the operation of the integrated power system is emphasized. It is shown that the startup, operation, power control, and shutdown of PSPP units are characterized by the occurrence of unsteady hydraulic modes of flow in the forebay, upper reservoir, and corresponding canal. These modes are accompanied by the formation of translational waves, whose characteristics must be taken into account when designing and operating plant facilities. The operation of the Dniester PSPP confirmed that translational waves are generated in the upper reservoir of this plant during the operation of its units in pumping and turbine modes. The presence of such waves significantly affects the position of the marking of the crest of protective dykes and the stability of the back slope protection of these dykes under the conditions of alternating wave loads. Results of field (experimental) and theoretical studies of the parameters of the translational waves in the upper reservoir of the specified plant are given. These results were obtained for the first stage of the Dniester PSPP construction, providing the upper reservoir had a temporary separating dyke located at Pkt 7+00. The field measurements were performed with a VEGAWELL 72 diaphragm pressure sensor located in the left riser of the forebay. It is shown that the highest wave heights can be observed in pumping mode during unit shutdown. Theoretical calculations of the parameters of translational waves were performed on the basis of the Saint-Venan differential equation, using the two-dimensional method. Wave height was determined using the harmonic seiche equation for the progressive wave. It is shown that for the design case of the unit shutdown it is necessary to take into account the presence of lateral water inflow to the main flow supplied by the unit. Comparison of theoretical and experimental results showed their satisfactory convergence.

Keywords: *translational waves, pressure sensor, upper reservoir, slope, PSPP.*

Hydraulic energy is one of the main types of renewable energy that has to meet the ever-increasing production and domestic needs of society. Currently, hydraulic energy alone provides up to 76% of the world's total renewable energy.

The existing Dniester cascade consists of the Dniester Hydroelectric Power Plant (HPP)-1, the Dniester Pumped Storage Power Plant (PSPP), the Dniester HPP-2 (Ukraine) and the Dubossar HPP (Moldova). The Dniester PSPP is the most ambitious project in modern Ukraine. This plant is an integral part of the Ukraine's energy strategy until 2030. According to the initial project, the Dniester PSPP should consist of seven hydro units with a total capacity of 2,268 MW in turbine mode and 2,947 MW in pumping mode. With these parameters it ranks sixth in the world in installed capacity.

At present, the PSPP is completely ready and operates in the composition of three hydroelectric units. In turbine mode, it is capable of producing a total of 972 MW, which is almost equal to the capacity of one unit of a nuclear power plant. It is planned that the hydroelectric unit # 4 of the plant will be put into operation in 2020 [1].

As is known, the schedule of electricity consumption during the day is characterized by a large irregularity. Quite often this irregularity is managed with the help of basic units of 200-300 MW thermal power plants (TPP). In Ukraine, the number of such startups-shudowns reaches up to 3,000 per year. In addition, to overcome night time valleys in the daily schedule of loads, it is necessary to remove from operation up to ten or more TPP units per day. Such management is quite expensive and leads to significant breakdowns and failures of the TPP equipment. For nuclear power plants (NPP), this method of management is undesirable [2].

With these circumstances taken into account, power system management is usually exercised with the help of HPPs and PSPPs, which are characterized by high maneuverability. Significantly, the time necessary for the units of these plants to gain their full capacity after shutdows is 1–2 minutes, and for those running idle this time is only 15–30 s. For comparison, it is to be noted that the specified time for TPP units (after their shutdown is 90–180 minutes, for NPPs, 390–600 minutes. For the hot state, this period of time for HPPs is 20–50 minutes, and for NPPs it is 60 minutes [3].

A typical example of a significant expansion of PSPP's functions is the mode of operation of the Zagorsk PSPP. The number of start-ups of the turbine units of this plant reaches 440 per month and in separate periods, about 30 per day without taking into account the startups of the units in the synchronous compensator mode [12]. The number of changes in the operating modes of a PSPP reaches up to 4,000–8,000 per year. For example, this number is 8,000 for the Drakensberg PSPP (South Africa); 6,000 for the Gilboa PSPP (USA); and 5,000 for the Dinorvig PSPP (England) [4].

The startup, operation, power management and shutdown of PSPP units are characterized by the occurrence of unsteady hydraulic flow modes in the forebay, upper reservoir, and branch duct. These modes are accompanied by the occurrence of translational waves, whose characteristics must be taken into account when designing and operating plant facilities. Ensuring the reliable operation of Ukraine's power operation is achieved by the high reliability of stations.

A specific feature of the operation of the upper reservoirs of PSPPs, compared to the reservoirs of HPPs, is a more intensive mode of their use due to regular periodic changes of the main hydrophysical fields (level of free surface, pressure distribution, flow rate, etc.), providing the operating modes change. Because of this, it is very important to take into account the dynamics of the processes occurring in the reservoir both at the stage of designing the installation and stages of its construction and operation [2–4].

In the conditions of intensive construction and operation of PSPPs in the world, and in Ukraine in particular, the problem of calculating the characteristics of translational waves in the upper reservoirs during the operation of these plants is quite urgent. It is these characteristics that determine the marking of the crest of protective dykes, taking into account the height of swash of translational and wind waves on the slope to ensure the proper reliability of the installation. The use of mathematical models allows determining the parameters of generation of translational waves under different hydraulic modes of PSPP operation. Field studies of the parameters of such waves are particularly important because they are the main reference point for confirming the correctness of existing mathematical models and their improvement [3].

There are several methods for numerically calculating the heights of translational waves at the stages of their occurrence and propagation in PSPP reservoirs. The basis of the most general mathematical model is the Navier-Stokes equation system, but its use is complicated: it requires a lot of raw data, which are explicitly difficult to describe, especially the boundary conditions, and take into account all the interacting forces; and it is difficult to perform calculations because other mathematical models with the same order of accuracy can be solved with less time and effort [4].

When studying the processes of fluid flow in open reservoirs, mathematical models of shallow-water theory are commonly used. In addition, the condition that the depth of the reservoir was small compared to the parameter of the length of the area under study and the width of the canal should be fulfilled. The models mentioned are based on the flow continuity equation, the corresponding fluid flow equation, and the law of mass conservation. The corresponding system of differential two-dimensional Saint-Venan equations, with the non-horizontality of the bottom and bottom friction taken into account, has the form

$$\frac{\partial h}{\partial t} = -\frac{\partial Q_1}{\partial x} - \frac{\partial Q_2}{\partial y},$$

$$\frac{\partial Q_1}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{Q_1^2}{h}\right) - \frac{\partial}{\partial y}\left(\frac{Q_1 Q_2}{h}\right) - gh\frac{\partial(h+Z)}{\partial x} + T_1, \quad \frac{\partial Q_2}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{Q_1 Q_2}{h}\right) - \frac{\partial}{\partial y}\left(\frac{Q_2^2}{h}\right) - gh\frac{\partial(h+Z)}{\partial y} + T_2,$$

where t is the time, s; x and y are spatial coordinates; h is the water depth, m; Q_1, Q_2 are the specific costs along the x and y axes, m^2/s; Z is the bottom mark, m; g is the acceleration of free fall; T_1, T_2 is the bottom friction along the x and y axes.

The results of field studies obtained by numerical and hydraulic modeling are of particular value because they automatically take into account the whole set of operating factors: the fluid flow laws described by differential equations in partial derivatives, especially the operation of PSPP units in turbine and pumping modes, dimensions and configuration of the upper reservoir, the effects of wind waves, etc. For example, at the Zhidowo PSPP (Poland) the translational waves during the startup of the second unit turned out to be larger than it was expected during the operation of the three units. At the same time, due to wave processes, the protective layer of the dam reinforcement was partially washed out [3]. To reduce the heights of the translational waves being generated, restrictions were imposed during the startups and shutdowns of units, taking into account the direct and inverse waves.

The translational waves formed in the upper reservoirs of PSPPs during unit shutdown in pumping mode show quite clearly their presence by the destruction of the protective layer of dam reinforcement from the sand-gravel mixture at the marks of the normal banked-up water level (BWL) (Fig. 1).

Fig. 1. Destruction of the protective layer of sand-gravel mixture reinforcement

The heights of translational waves were calculated for the first stage of the Dniester PSPP with an intermediate dam on the Pkt 7+00 picketage of the upper reservoir. The measurements were made by a WEGAWELL 72 membrane pressure sensor located in the left riser of the intake camera.

The calculations and field studies performed show that translational waves are generated in the reservoir during the startup, operation and shutdown of the unit in pumping mode. Their greatest heights can be observed during the shutdown of the unit. The mathematical model describes the formation and propagation of waves by wave phases rather qualitatively, but there are large differences in altitude in the case of unit shutdown. The unit shuts down when the flow is perturbed, which picks up the lateral inflow of water, and partially deflects to the left riser of the forebay.

According to the results of field studies, the lateral water inflow to the main stream is harmonious in nature, the period of which can be determined from the results of measurements. The translational wave crest height, after the unit shuts down, which was calculated by the two-dimensional method based on the Saint-Venan equation, can be described by the harmonic seiche equation for the progressive wave, and a correction factor was introduced to take into account the lateral water inflow to the main stream. Then the harmonic seiche equation will take the form

$$\eta = He^{\beta k} \cos\left(\frac{2\pi}{T\sqrt{gd}} x - \frac{2\pi}{T} t \right)$$

where *H* is the wave height, *T* is the wave period, *d* is the depth of the reservoir at a certain point with a certain mark of the water level.

The factor $e^{\beta k}$ takes into account the increase in the height of translational waves, caused by the lateral water inflow to the main stream. The determined coefficient of the lateral water inflow in the upper reservoir of the Dniester PSPP during the operation of one unit in pumping mode is in the range of 1.79–1.87 at water levels close to the BWL=222,500 m. Taking this value into account in the boundary conditions of the left boundary of the mathematical model for calculating the heights of translational waves in the basis of the two-dimensional differential Saint-Wenan equation, we obtain the following graph (Fig. 2).

After considering the lateral water inflow to the main stream, the height value for the first translational wave coincides in phase and height. For further calculation, it is necessary to take into account the change of the period of waves and their attenuation in time with the help of the coefficient *k*.

After further investigations of the parameters of the translational waves in the upper reservoir of the Dniester PSPP for the full volume, their parameters have not significantly decreased. Fig. 3 shows the results of field measurements with 4 sensors.

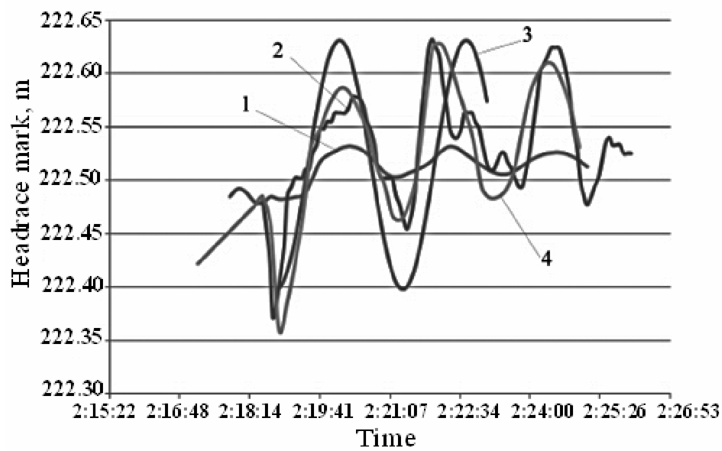

Fig. 2. Graph of comparison of the results of mathematical calculation and field studies at the shutdown stage of the Dniester PSPP unit in pumping mode:
1 – mathematical modeling using the two-dimensional Saint-Venan method, 2 – field studies, 3 – calculation with taking into account the lateral water inflow correction, 4 – calculation with taking into account the lateral water inflow correction in the mathematical model

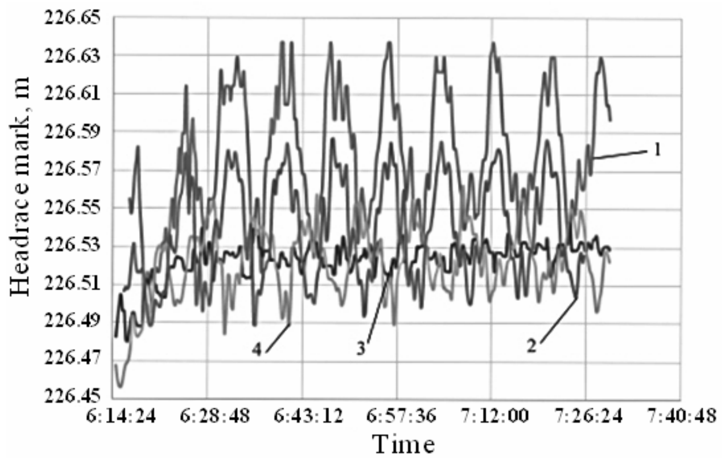

Fig. 3. Graph of measurements of the parameters of translational waves by sensors:
1 – in the forebay of the water intake, 2 – at Pkt 63+63; 3 – at Pkt 52+01; 4 – at Pkt 38+01

Conclusions

1. In the conditions of intensive construction of PSPPs, the problem of calculating the translational waves in the upper reservoir during the operation of these plants in pumping mode is relevant, as they are a benchmark for checking the accepted markings of the crest of protective dykes.

2. The use of state-of-the-art measuring and control equipment allows us to accurately measure the necessary parameters of translational waves and predict their influence on hydraulic structures.

3. The obtained values of wave heights during the operation of one unit do not pose a particular threat to protective dykes, but to some extent destroy the reinforcement of slopes.

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Received 06 June 2019

Вплив хвиль переміщення на роботу верхньої водойми Дністровської гідроакумулюючої електростанції

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Висвітлюється роль гідравлічної енергії як надійного джерела відновлюваної енергії для забезпечення постійно зростаючих потреб суспільства. Аналізується нерівномірність характеру енергопостачання протягом доби. Підкреслюється роль ГЕС та ГАЕС у регулюванні зазначеної нерівномірності під час роботи об'єднаної енергосистеми. Показано, що пуск, робота, регулювання потужності та зупинка агрегатів ГАЕС характеризуються виникненням в аванкамері, верхній водоймі та відповідному каналі неусталених гідравлічних режимів потоку. Ці режими супроводжуються утворенням хвиль переміщення, характеристики яких потрібно враховувати під час проектування та експлуатації споруд станції. Експлуатація Дністровської ГАЕС підтвердила, що у верхній водоймі цієї станції під час роботи її агрегатів у насосному і турбінному режимах утворюються хвилі переміщення. Наявність таких хвиль істотно впливає на положення відмітки гребеня огороджувальних дамб та стійкість кріплення верхового укосу цих дамб в умовах дії знакозмінних хвильових навантажень. Наводяться результати натурних (експериментальних) та теоретичних досліджень параметрів хвиль переміщення у верхній водоймі зазначеної станції. Ці результати отримані для першого етапу будівництва Дністровської ГАЕС за наявності у верхній водоймі тимчасової роздільної дамби, розташованої на ПК 7+00. Натурні вимірювання були здійснені датчиком тиску мембранного типу VEGAWELL 72, який розташований у лівому стояку аванкамери. Показано, що найбільші висоти хвиль спостерігаються у насосному режимі під час зупинки агрегату. Теоретичні розрахунки параметрів хвиль переміщення виконувалися на основі диференціального рівняння Сен-Венана за двовимірною методикою. Висоту хвиль визначали за допомогою гармонійного рівняння сейші для прогресивної хвилі. Показано, що для розрахункового випадку зупинки агрегату необхідно враховувати наявність бокового притоку води до основного потоку, що подається агрегатом. Порівняння теоретичних і експериментальних результатів показало їх задовільну збіжність.

***Ключові слова**: хвилі переміщення, датчик тиску, верхня водойма, укіс, ГАЕС.*

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