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Articles

Cause of failure at Endhó dam spillway: Physical modeling

Causa de falla en la obra de excedencias, presa Endhó: modelación física

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Abstract

Over last decades, water demand has increased, and with it the need to store runoff artificially. This way reservoirs have emerged; structures considered considerable risk, in the event of failure. The work of spillway of the Endhó dam presents important water shocks in the coating slabs of the discharge channel, specifically in the final part of the rapids in relation to the trajectory, which delivers water to the buffering pond, which puts at risk the reservoir stability. According to the geological and hydraulic features of the work, it is probable that the subpressure force is the main cause of the wear, rupture and detachment of the slabs. To determine the causes that originate the failure, a 1:100 scale physical model was built. In this, the laws of resemblance (Froude) and similarity (geometric, kinematic and dynamic) were met, and the underground flow with soil from of the dam was simulated. The maximum flow that was passed on the spillway work was 11 l/s (equivalent to 1 100 m^3/s in the prototype), it was operated for 240 continuous hours. With seven pressure sensors the values were recorded in the area of interest and data up to 9 220 kgf/m^2 (prototype) were obtained. The subpressure values obtained in the physical model were higher than those estimated with Lane's methodology. The structural analysis indicates that the weight of the structure is not sufficient to counteract the subpressure in the rapid parabolic.

Keywords: Hydraulic modeling, prototype, subpressure, infiltration, sensors, slab detachment, hydrostatic thrust, structural analysis.

Resumen

En las últimas décadas, la demanda de agua se ha incrementado y con ello la necesidad de almacenar los escurrimientos de forma artificial. Así, han surgido las presas de almacenamiento, estructuras consideradas de alto riesgo en caso de falla. La obra de excedencias de la presa Endhó presenta daños importantes en las losas de revestimiento del canal de descarga, específicamente en la parte final de la rápida, en lo correspondiente a la trayectoria, que entrega el agua al estanque amortiguador, lo cual pone en riesgo la estabilidad del embalse. De acuerdo con las características geológicas e hidráulicas de la obra es probable que la fuerza de subpresión sea la causa principal del desgaste, ruptura y desprendimiento de las losas. Para determinar las causas que originan la falla, se construyó un modelo físico escala 1:100, donde se cumplieron las leyes de similitud (Froude) y semejanza (geométrica, cinemática y dinámica) y se simuló el flujo subterráneo con suelo de la presa. El gasto máximo que se transitó sobre la obra de excedencias fue de 11 l/s (1 100 m^3/s en el prototipo); se operó durante 240 h continuas. Con siete sensores de presión se registraron valores en la zona de interés y se obtuvieron datos hasta de 9 220 kgf/m^2 (prototipo). Los valores de subpresión obtenidos en el modelo físico fueron mayores que los estimados con la metodología de Lane. El análisis estructural indica que el peso de la estructura no es suficiente para contrarrestar la subpresión en la rápida parabólica.

Palabras clave: modelación hidráulica, prototipo, subpresión, infiltración, sensores, desprendimiento de losas, empuje hidrostático, análisis estructural.

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Introduction

The safety of a dam depends, among other factors, on the optimal functioning of the spillway works, which are built to allow the volumes of water that cannot be retained in the reservoir to pass through (Ramírez, 2011) and which, if not removed, could spill over the curtain, creating a major problem.

In spillway works, turbulent flows and high velocities are present, which create unfavorable conditions for the lining slabs (Khatsuria, 2013), which are used to prevent the propagation of pressures, infiltration, erosion, tubification and scour, phenomena that threaten structural stability (Del-Risco, Hurtado, & González, 2010; Khatsuria, 2013). For this reason, it is necessary to carry out a reliable design taking into account all the variables that could occur under different conditions, since a net positive reaction in the discharge and dissipation structure is not enough to ensure the stability of the work.

On the face of the slab opposite to the flow, it is inevitable that water seeps through fissures, joints, cracks and, above all, when in direct contact with the soil, giving rise to seepage (Hurtado, Del-Risco, & González, 2009). These originate negative chemical, physical and mechanical actions towards the slabs (Sahuquillo, 2010). The presence of a surface exposed to flow (due to lack of lining) generates instability and, therefore, a danger for all human beings and material assets downstream of the dam (Ochoa & Camilo, 2006).

A large number of farmers benefit from the operation of the Endhó Dam, since agriculture is the main economic activity in the region; another use is for flood control during the rainy season, coming from Mexico City and the basin itself (Conagua, 2009).

To determine the causes that originate the detachment of slabs, emphasis was placed on geotechnical and hydraulic factors, such as: infiltration, subpressure and physical dimensions. By knowing which phenomenon threatens the stability of the work, it is possible to give solution alternatives to rehabilitate, with efficient works at the lowest cost (González, 2016; Iñiguez-Covarrubias, Ojeda-Bustamante, & Díaz-Delgado, 2015). Therefore, the objective of this article is to know the distribution of pressures of the spillway work template, by means of pressure sensors, placed in the lower part of the physical model, and to define the distribution of forces, stresses, moments, displacements and deformations of the structure, taking into account the stiffness effects of the foundation and soil, by means of a structural analysis.

Hydraulic modeling is a tool which helps to select the optimal design of any structure; it is a reliable instrument, where it is possible to inspect, measure, analyze, evaluate, observe, verify and optimize resources (Del-Risco *et al.*, 2010; Jiménez-Castañeda, Berezowsky-Verduzco, Hernández-López, & Caballero-Coranguez, 2020; Lopardo, 2010), to visualize as a whole the phenomena throughout space and continuously in time, accurately reproducing the boundary conditions (Arteaga, 2012).

If the conditions of similarity are not satisfied, the so-called "scale effects" may appear, where due to the magnitude of the transformation adopted, there are forces that become important, mainly molecular forces, which are generally insignificant in the prototype, but become relevant due to the reduced size of the model. Such forces are mainly associated with capillary forces derived from surface tension and viscous or internal friction forces (Chanson, 2009).

Sensors are an accurate instrument for recording pressure values, however, these must be properly calibrated to obtain reliable data (Gonzalez & Giraldo, 2014).

Materials and methods

Prototype description

The Endhó dam is located in the municipality of Tula, Hidalgo (20° 08' 15" N, 99° 21' 45" W and 2 023.5 m altitude). On the left bank of the reservoir there is an overflow work. This consists of a free-crested half-fan spillway, which discharges excess water into the discharge channel, and two stilling basin located at the end of the spillway; it is then incorporated into the Tula River.

The crest has a height of 3.5 m and was designed for a flood of 1,700 m^3/s, with a crest length of 200 m and a maximum head of 2 m. The discharge channel is of variable width, from 138 m at the foot of the crest to 20 m at station 0 + 400, continuing with that width until the end, where there is a rapid, which at the end of it, in the part corresponding to the trajectory (parabolic profile), has three teeth, flow dividers. The entire structure is lined with reinforced concrete, with transverse and longitudinal drains (Conagua, 2009). In the first buffer pond, which was the original design, there are two rows of deflectors formed by longitudinally alternating teeth and then, after its original construction,

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due to inadequate flow dissipation, the next pond had to be designed (Figure 1 and Figure 2).

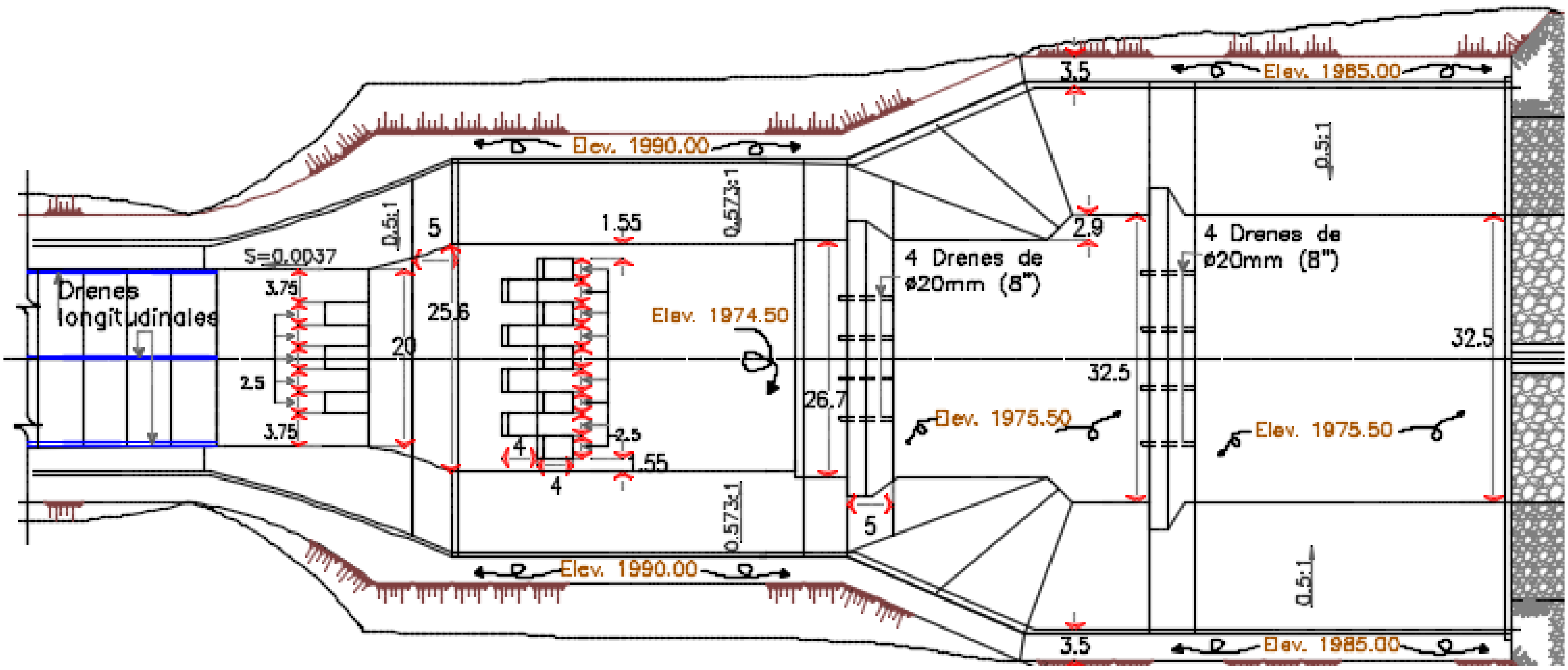

Figure 1. Plan of the parabolic profile rapid and stilling basin.

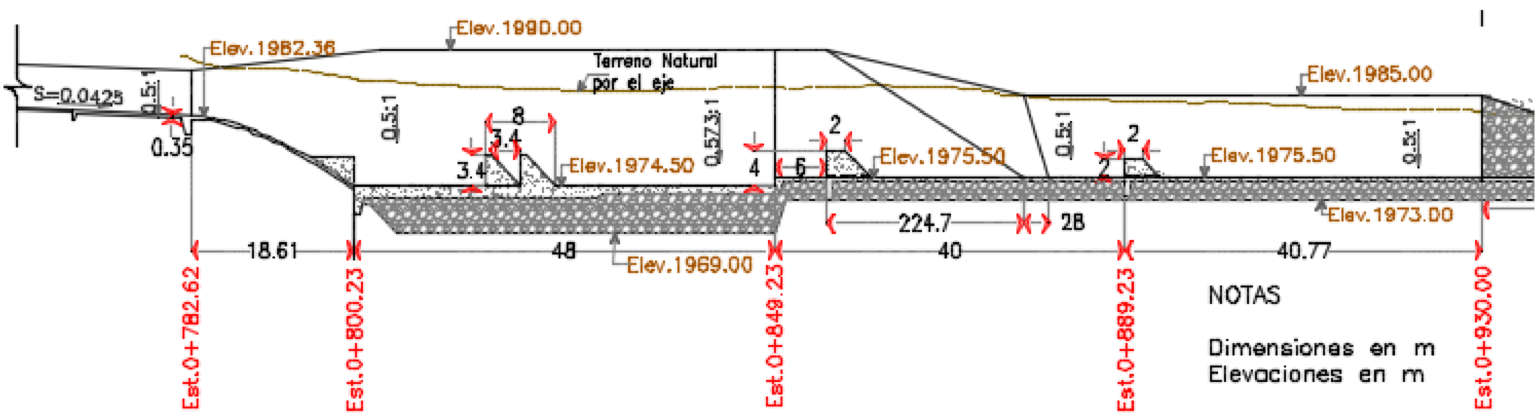

Figure 2. Plan of the parabolic profile rapid and stilling basin.

Model description

The physical model was built in the annex of the hydraulics laboratory at the Universidad Autónoma Chapingo. It is 12 m long and of variable width, 2.5 m at the beginning and 0.8 m at the end. Water was made to flow for 240 h over the overflow work, with a flow rate of 11 L/s, without interruption. The water supply was made with two tanks, one of constant charge that supplies the second one, from this it passes to the vessel, through a velocity reducing screen; subsequently, the water circulates over the crest, going through the overflow work. At the end there is a 90° thin-walled triangular spillway, which allows gauging the flowing water and discharges it into the laboratory's recirculation channel system (Figure 3).

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Figure 3. A) Physical model, complete view of the overflow works; B) velocity reducing screen, vessel, crest, initial part of the discharge channel; C) streamlines in the compacted soil profile; D) transverse and longitudinal drains, placed in the lower part of the discharge channel; E) triangular 90° weir.

A length scale l_e=100 was selected. The shape of the overflow work was achieved with the use of more than 100 laser-cut medium density fibroboard scantlings.

It is necessary to highlight that the joints were not taken into account, since the work was built in one piece, however, as mentioned by Gonzalez and Posada (2016), it is important to take into account such divisions. The model was filled with 18 m^3 of pumiceous tuff, coming from the study area (Hidalgo); this soil was tested for compaction and granulometry.

The drainage network was placed at the bottom of the lining slabs, with porous hose of 8 mm diameter, with an arrangement of 14 × 8 cm. Sensors were also placed over the axis of the discharge channel, in the rapid parabolic and in the first buffer pond.

Similarity and resemblance

The theoretical basis of the physical modeling is the similarity and resemblance laws. The similarity law used in the model is Froude's law, which relates inertial forces and gravitational forces (JiJian & JinDe, 2008) (Equation (1)). The scales used for the model are presented in Equation (2):

$$Fr = v\,(g\,L)^{-1/2} \quad (1)$$

where v:: velocity, L: characteristic length and g: gravity:

$$A_e = {l_e}^2;\ v_e = {l_e}^3;\ Q_e = {l_e}^{\frac{5}{2}};\ t_e = {l_e}^{\frac{1}{2}};\ F_e = \gamma_e\,{l_e}^3\ P_e = \gamma_e\,l_e \quad (2)$$

where A_e: area scale, v_e: volume scale, Q_e: volume flow scale, t_e: time scale, F_e: force scale, γ_e: specific weight scale and P_e: pressure scale.

The laws of resemblance that were accomplished are geometric, dynamic, and kinematic; in the geometric resemblance, the lengths, in the kinematic, the velocity magnitudes and, in the dynamic, the forces exerted by the fluid are homologous between the prototype and the model.

Measuring instruments

The equation describing the amount of flow (m^3/s) passing over the triangular spillway was obtained volumetrically (Equation (3)); the head over the spillway (m) was measured with a hooked limnimeter:

$$Q = 1.37\ H^{2.48} \quad (3)$$

where Q: flow rate, and H: head on the spillway.

Piezometers were installed at the level of the excess work template (on the axis) to record the water flow. The velocity was estimated with the Prandtl tube, in this equipment the difference between the total pressure and the static pressure was visualized.

In the physical model, subpressure was measured with seven piezoresistive sensors (MPX5100DP), distributed under the axis of the discharge channel, the parabolic rapid and the first stilling pool (Figure 4).

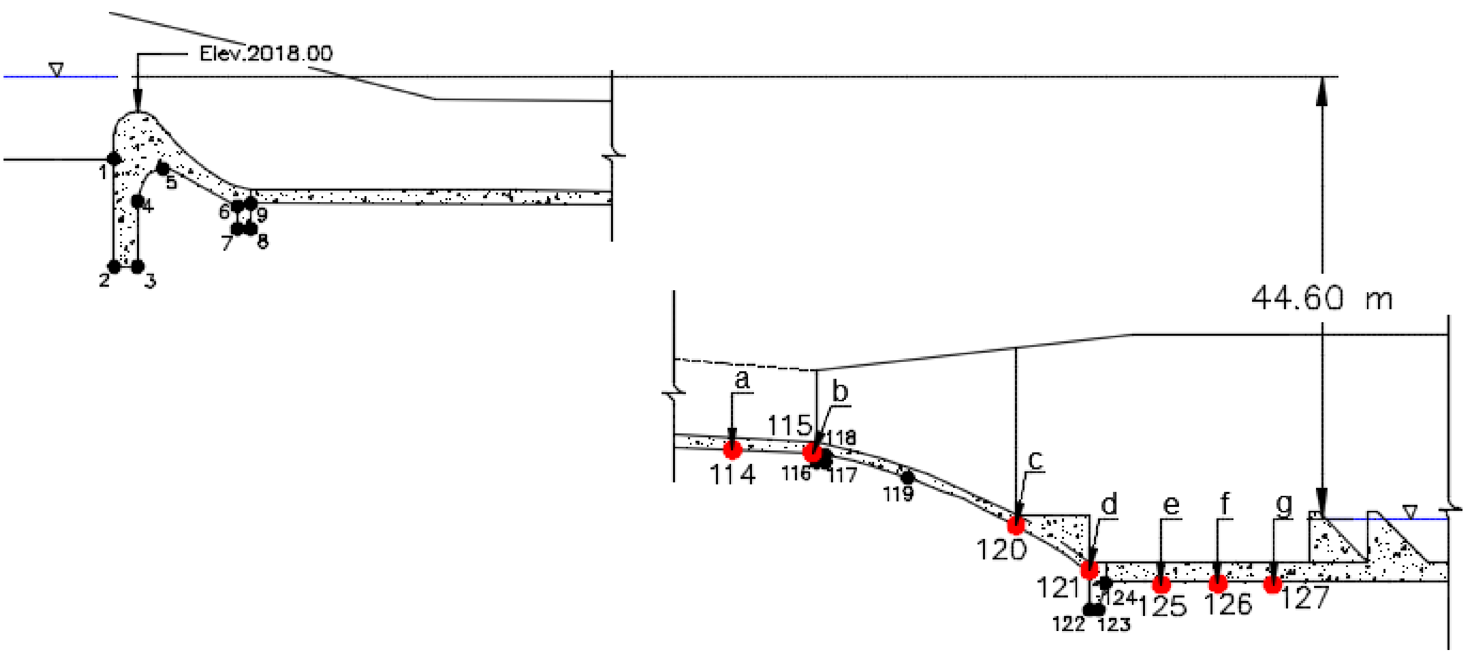

Figure 4. Location of sensors in the model (letters) and numbering for Lane's methodology.

The microcontroller of the data acquisition system was programmed to record the subpressure values every half minute, these values are the average of the measurements obtained with a frequency of one second, in a language that is part of the Arduino platform (free hardware). Each of the sensors were calibrated by verifying the accuracy with piezometers, before placing them at the bottom of the lining slabs, and the equations resulting from the calibration were integrated into the programming code. The recorded values were obtained in centimeters of water column, which were subsequently converted to kgf/m^2, the unit corresponding to the subpressure in the prototype.

Lane’s method

Determining the subpressure values by Lane's method (Equation (4)) involves using the filtration path criterion, where the total compensated filtration length of the structure is equal to the sum of the vertical filtration lengths plus one third of the sum of the horizontal filtration lengths. The distances that presented a slope greater than 45° are considered as vertical and those that had a slope less than 45° were considered as horizontal distances (Arteaga, 2012):

$$Sp_x = \omega_a \, B' \, c' \, [\varphi_x - (\varphi \, L^{-1}) \, L_x] \quad (4)$$

where Sp_x: subpressure at any point "x", ω_a: volumetric weight of water, B′: width of the base of the section where the subpressure acts, c′: subpressure factor, φ: effective hydraulic head, φ_x: hydraulic head or potential at point "x", L_x: compensated filtration length up to point "x", and L = total compensated length.

At each break in the structure (bottom) a consecutive number was assigned, as control points, to apply the methodology in each of them, starting at the top and ending at the boundary of the lining of the second buffer pond (Figure 4).

Structural analysis

For the analysis, the self-weight of the structure, the weight of the water prism, the water thrust, the subpressure and the impact of the mantle on the floor were considered. A characteristic section of the study area is shown in Figure 5. To estimate the soil reaction at the floor slump, Equation (5) (Arteaga, 2011) was applied:

$$R_T = \frac{Wa_p + Wc_p + 2\,V - Sp_x}{B'} \quad (5)$$

where R_T: soil reaction in the floor slab, Wa_p: weight of the water prism in the floor slab, Wc_p: self-weight of the floor slab, V: vertical component of the resultant of the tangential forces in the lateral walls, Sp_x: subpressure at the point of study and B´: transverse length of the floor slab of the bottom panel.

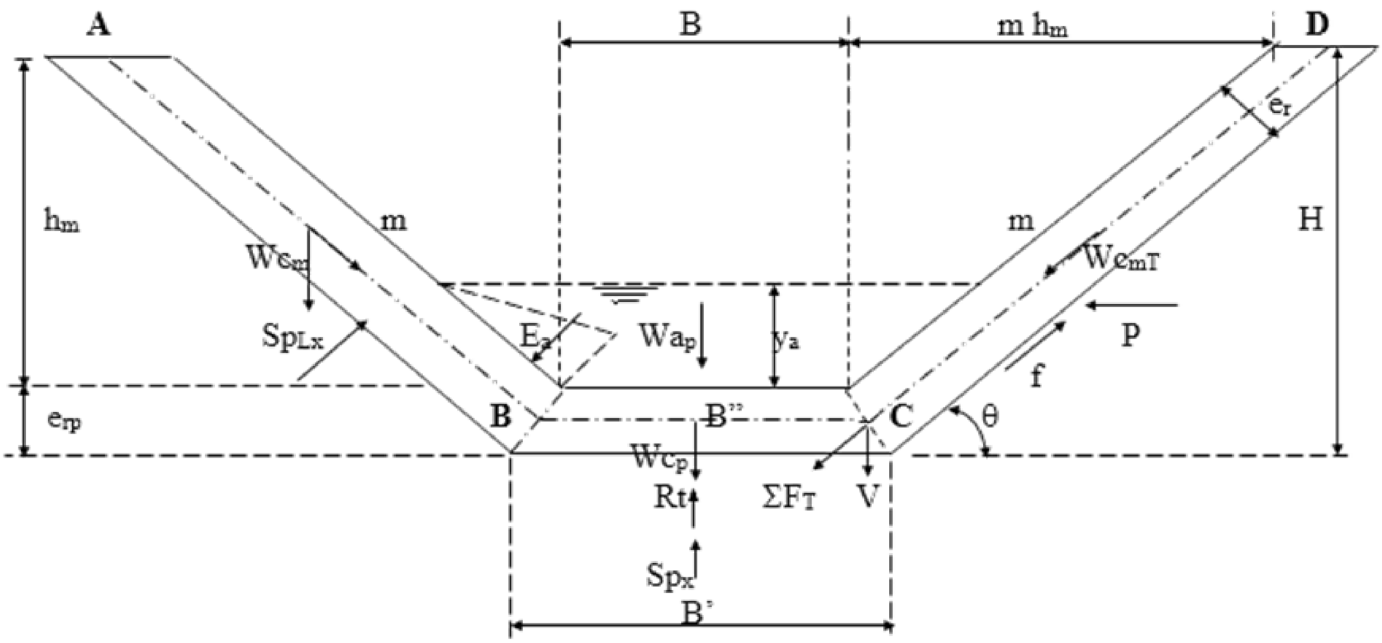

Figure 5. Cross section at point "x" for the force analysis. Source: Arteaga (2011).

The section was analyzed for the critical point, determining the moments and shear at the axis, by using the Cross method, the structure was

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checked for bending, adhesion, length of development, required camber, and for shrinkage and temperature.

Results and discussion

After 60 h of continuous operation, the first record of subpressure was obtained in the sensors; however, these values correspond to the pressure exerted by the water that circulated from the final part towards the stilling basin. After 135 h of recording, all the sensors stabilized with an average value of 1 350 kgf/m^2, this value corresponds in prototype to the subpressure exerted by the river water towards the structure.

After 140 h, an accelerated increase in the values was noticed, the seepage in the direction of the flow reached the area of interest. The sensor located at position "a" rose to 4 350 kgf/m^2, maximum subpressure for this position; while the sensor located at "d" reached 9 220 kgf/m^2, maximum pressure of all sensors (Figure 6).

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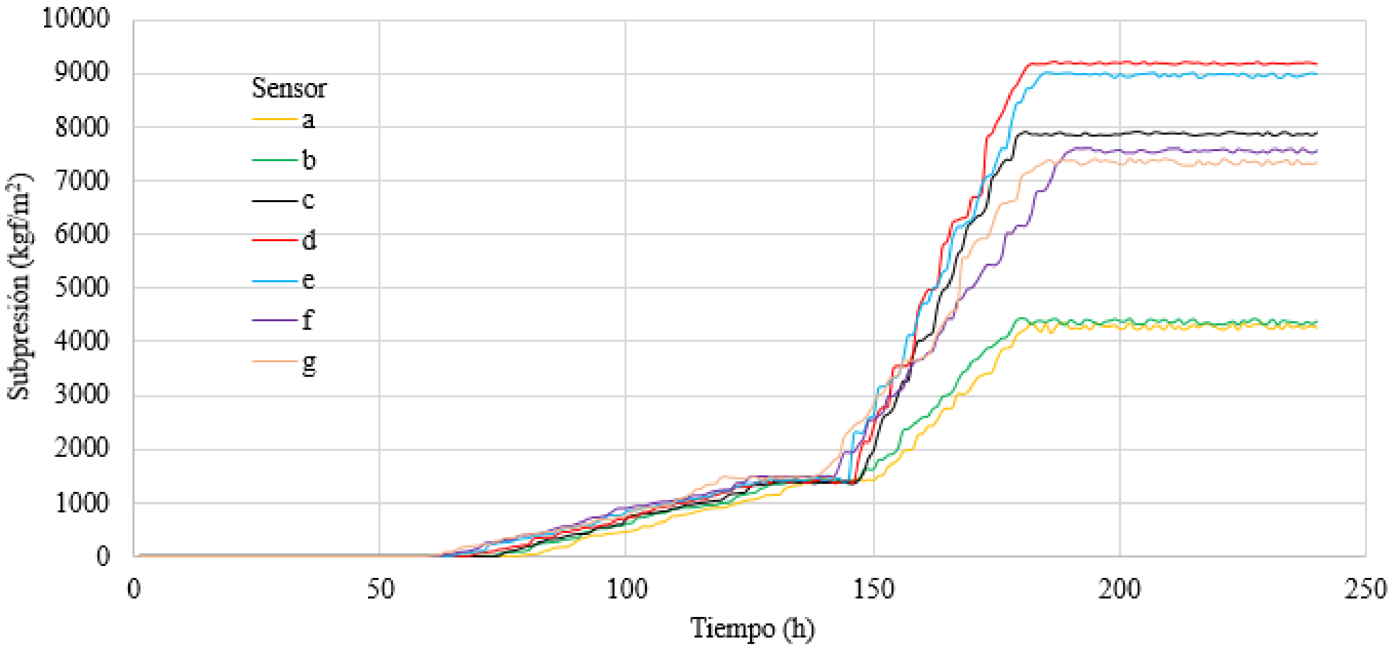

Figure 6. Subpressures recorded with the MPX5100DP sensors in the physical model.

When applying Lane's methodology (Arteaga, 2012), a loss per meter of 0.1183 m was obtained, a filtration load reaction of 8.19 m and a necessary infiltration path length of 379 m, so the proportion of elements proposed for the structure is considered incorrect. The maximum value of subpressure (considering the existence of drains) is located at point 121, whose value is 7 343.47 kgf/m^2, in comparison with the homologous point "d" represents 20.35 % error. However, for point 114, whose value is negative and homologous with point "a", presents an error of up to 140 % (Figure 7).

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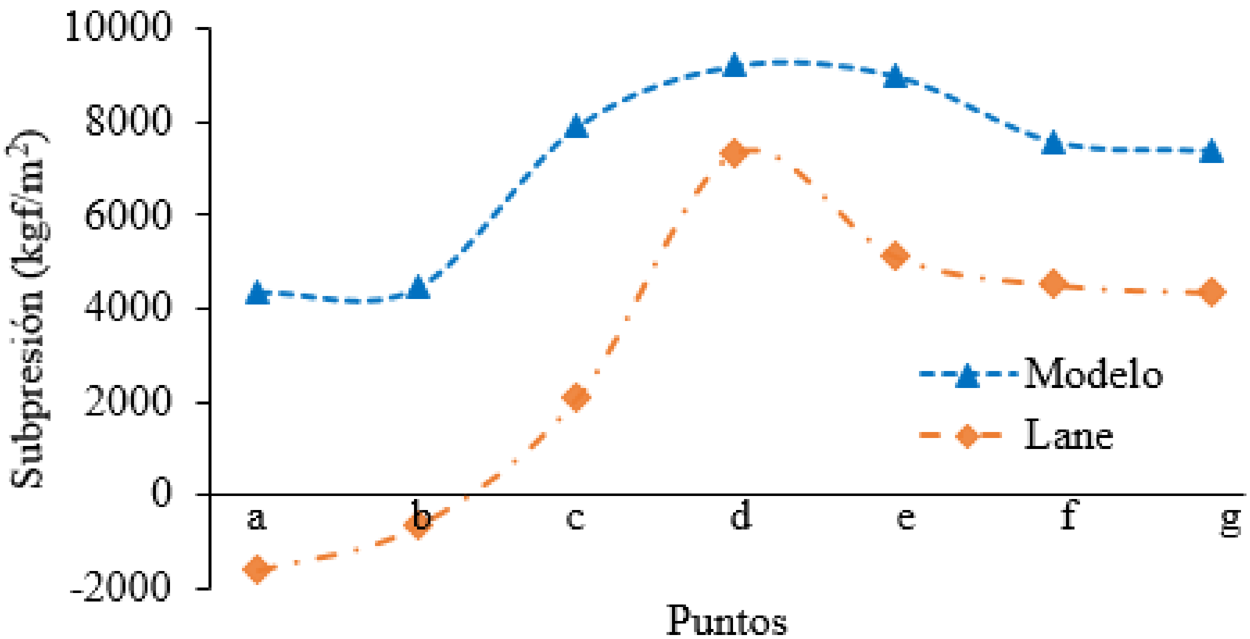

Figure 7. Subpressure recorded by the sensors and that obtained by Lane's methodology for the homologous points of the structure.

The soil reaction with negative values indicates that subpressure forces predominate, even considering all the variants acting in each of the sections. Point "d" or 121 is the most critical, with values of -8 085 kgf/m^2, obtained experimentally, and -6 209 kgf/m^2 generated by Lane's method (Table 1).

Table 1. Soil reaction.

Puntos	Rt LANE	Rt MODELO
	kgf/m²	kgf/m²
a	2 439	-3 655
b	1 359	-3 747
c	-1 09	-6 926
d	-6 209	-8 085
e	-1 222	-3 132
f	-608	-2 026
g	-443	-1 878

For the section at point "d", it was obtained that the moment at the axis (isostatic) of the BA and CD bars is -79.13 kg - m. In the review of the required cant, a cover of 7 cm was taken, since the bed is in contact with the ground (American Concrete Institute, 1977), it was found to be deficient with 7.3 cm, so it is necessary to increase this minimum cant to 81 cm. The allowable shear stress for this structure is 3.55 kg/cm^2 (American Concrete Institute, 1977); according to the calculations, the section is higher (4.38 kg/cm^2), therefore, it is not acceptable. As for the revision for adhesion, length of development and shrinkage and temperature, they are within the permissible values.

Conclusions

According to pressure measurements when the spillway was not in operation, subpressure values were present that put the stability of the structure at risk. These measurements confirm that the pressure is capable of lifting the chute blocks and the lining slabs, structures weighing several tons, which were placed to dissipate the energy and protect the lining slabs.

Upon performing the structural analysis and obtaining the distribution of forces, moments, stresses, displacements and deformations of the structure, it was ratified that with the characteristics present in the spillway works it is not possible for it to support such a magnitude of subpressure. Likewise, the soil reaction in the floor slump (measured in the model and calculated by Lane's method) shows negative values, which confirms the instability of the structure and, therefore, the detachment of the chute blocks and lining slabs, observed in the spillway works of the Endhó dam, Hidalgo.

When comparing the upward pressure obtained experimentally and that calculated by Lane's method, it is concluded that the most critical point coincides in both methods, occurring at the end of the trajectory that joins the rapid of the discharge channel with the buffer pond, which caused the deterioration and detachment of the chute blocks and the lining slabs of the template, causing this effect to propagate due to the weakness that existed at this point.

However, it is important to study and analyze the work under different situations and not only an empty dam, to determine in which scenario the most unfavorable condition for the work occurs, since a result that is within the acceptable ranges (under certain conditions) does not guarantee a safe and stable operation with the different phenomena that may occur throughout the useful life of the hydraulic structure.

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