Physical modeling of a stepped spillway without sidewalls

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Abstract

The interest of a consulting company in designing stepped spillways in RCC dams led us to propose the possibility of building this type of spillway without sidewalls. Previous research on stepped spillways has focused on characterizing the complex hydraulic behavior of flow on these structures, as well as design criteria. Such studies have usually been conducted on stepped spillways with a constant width along the spillway, that is, with sidewalls.

In the present work, we report the results of the physical modeling of a generic stepped spillway without sidewalls (slope 1v:0.8h). In general terms, the lack of sidewalls produces a lateral expansion of water and therefore a non-uniform longitudinal and transversal discharge distribution. Consequently, the flow type, characteristic water depth, velocity, air concentration and pressure fields change along and across the spillway. The resulting data demonstrate that the distribution of the different variables studied depend on the specific discharge at the entrance and the spillway height.

1. Introduction

Since the early 1990s, empirical evidence on stepped spillways with sidewalls (Rajaratnam, 1990; Peyras et al. 1992) has identified two main flow types: skimming flow and nappe flow, and a transitional flow between these two. Later, different authors have proposed expressions to characterize the onset of each flow type (Chanson 2001; Meireles 2004; Sánchez-Juny et al. 2005; Amador 2005; Renna et al. 2010). Amador (2005), proposed the following expressions:

$$\frac{y_c}{h} = 0.649 \cdot \left(\frac{h}{l}\right)^{-0.175} \quad (1)$$

$$\frac{y_c}{h} = 0.854 \cdot \left(\frac{h}{l}\right)^{-0.169} \quad (2)$$

Equation **Error! No s'ha trobat l'origen de la referència.** indicates the upper limit for the existence of nappe flow and equation **Error! No s'ha trobat l'origen de la referència.** indicates the start of skimming flow. As observed, the presence of one type of flow or other depends on the geometrical characteristics of the spillway deriving from its slope (*h* is the step height and *l* is the step length) and the specific discharge at the entrance (y_c is the critical depth there). In the case of a stepped spillway without sidewalls, a crosswise change of flow type is produced depending on lateral reduction of the specific discharge.

Stepped spillways are characterized by the natural entrance of air at the so-called inception point, which is located further upstream than on conventional smooth spillways (Boes and Minor, 2001). Different authors have studied the inception point and proposed equations to characterize it (Amador et al. 2006a; Meireles et al. 2012; Hunt et al. 2013). In the case of stepped spillways without sidewalls, it has been found that the location of the inception point is practically unaffected by the absence of sidewalls. Nevertheless, downstream from the inception point, the lateral expansion of the flow affects the behavior of the two-phase flow with respect to its traditional behavior. Since the 1980s (Falvey 1980), air-water flow and self-aeration in stepped chutes has been widely studied. In these previous works, velocity profiles in uniform flow have been adjusted to a power law as in equation (**3**):

$$\frac{v}{v_{90}} = \left(\frac{y}{y_{90}}\right)^{1/N} \tag{3}$$

where y is distance, measured in the normal direction to the pseudo-bottom defined by the external edges of the steps; y_{90} is the characteristic water depth, corresponding to the perpendicular depth where air concentration is 0.90 (Matos, 2000; Boes and Hager, 2003), v_{90} is the velocity measured at this characteristic water depth and N is the adjustment coefficient. Different authors (Chanson 1994b; Matos 2000; Matos et al. 2000) define N somewhere between 3.5 and 30 depending on the specific discharge, the step length and the slope. More recently (Relvas and Pinheiro 2011), define that for skimming flows $N<9$ and for transition and nappe flows $N\geq9$.

Regarding mean air concentration, Boes et al. (2003) found that this parameter is around 0.22 at the inception point for a typical gravity dam chute of 53°, which agrees with the 0.20 found by Matos et al. (2000). Downstream of the inception point, Chanson et al. (2002) found mean air concentration to range from 0.2 to 0.6. On the other hand, air concentration distributions follow an analytical solution of the air-bubble advective diffusion equation (4) (Chanson and Toombes, 2001 and 2004; Gonzalez et al. 2005):

$$C = 1 - tanh^2\left(K' - \frac{\frac{y}{y_{90}}}{2 \cdot Do} + \frac{\left(\frac{y}{y_{90}} - \frac{1}{3}\right)^3}{3 \cdot Do}\right) \tag{4}$$

where y is the water depth measured normal to the pseudo-bottom, y_{90} is the characteristic water depth, K' is an integration constant (5) and Do is a function of the mean air concentration C_{med} (6):

$$K' = 0.32745 + \frac{1}{2 \cdot Do} - \frac{8}{81 \cdot Do} \tag{5}$$

$$C_{med} = 0.762 \cdot \left(1.043 - exp(-3.61 \cdot Do)\right) \tag{6}$$

The pressure field over the steps has been analyzed by several authors (Sánchez-Juny et al. 2003; Sánchez-Juny et al. 2007 and 2008; Amador et al. 2006b, 2009).

This paper presents empirical evidence for the behavior of a stepped spillway without sidewalls taking into account the hydraulic characteristics studied by the different authors mentioned above.

2. Experimental overview

The experimental data presented in this paper were recorded on a stepped chute model (Figure 1). This chute is 5.26 m high (from crest to toe), with a slope of 1v:0.8h and a total width of 3.0 m. It consists of 57 identical steps 0.08 m high (h), 0.064 m long (l) and 8 more steps at the top of the model fitted to a Creager profile (Estrella, 2013). The model is built of transparent methacrylate in order to allow visual inspection of the flow.

It is worth mentioning that the spill window is located on the right-hand side of the model in order to increase available expansion width. The maximum discharge tested is 260 ls^{-1}. Taking into account that the spill-width at the entrance of the chute is 1.0 m, the range of dimensionless discharge $(y_c/h)_e$ varied from 0 to 2.37. All results presented in this article correspond to the test carried out with the maximum flow rate $(y_c/h)_e$=2.37.

Additionally, a guiding wall was located at the crest of the dam. Its length approximately represents a typical supporting pile of a possible access road usually present in this type of structure, around 10 m in prototype. Hydraulically, this wall guides the flow and provides an output velocity that reduces the lateral spread of water.

Transverse discharge distribution was measured by dividing the width of the chute into three separate channels: a right channel (faced to the spill window), a central channel and a left channel. Flow distribution at the dam toe was measured for different specific discharges $(y_c/h)_e$. Transversal flow distribution was obtained at the dam toe (step 62) as well as at different heights along the spillway (steps 22, 32, 42 and 52). Note that the guiding wall reaches step 12.

Local air concentration, velocity and characteristic water depth were measured with a double fiber-optical probe (RBI Instrumentation). A single-tip of the probe detects interfaces (i.e. the instant at which the tip passes from liquid to gas and from gas to liquid). A dual-tip probe can measure the delay necessary for an interface to travel between tip 1 and tip 2. Knowing the distance between the 2 tips, the velocity of the interface can be evaluated. Supposing a homogeneous flow, liquid velocity is assumed to be equal to the bubble velocity detected by the double fiber-optical probe. The probe used in this investigation has a distance of 2.5 mm between the 2 tips. Each acquisition test was stopped after 1 min or after detection of 50000 single air bubbles per probe tip, i.e. 1 min test was the main constrain. The bubble size registered usually ranged between 1.9 mm and 4 mm. More details of the measurement technique can be found in Boes and Hager (1998). Velocity and air concentration profiles were obtained in a perpendicular direction to the pseudo-bottom, and the characteristic water depth was estimated as the position where the air concentration was 0.90.

Pressure measurements were recorded by means of piezoresistive transducers using an acquisition frequency of 100 Hz and data acquisition times of 60 secs. The range of measurement was from -1.5 to +2.0m with an error of ±0.0035m (Estrella, 2013).

3. Results

3.1. Inception point

In the case of stepped spillways without sidewalls, it has been found that the location of the inception point is practically unaffected by the absence of sidewalls. As can be observed in Figure 2, the result is similar to that proposed by Amador et al. (2006a) and Meireles et al. (2012).

3.2. Flow distribution

In stepped spillways without sidewalls, the entire dam width can be used for flow spill. As can be observed in Figure 1, downstream from the guiding wall, the flow experiences a lateral expansion (Figure 3) and the specific discharge therefore decreases across the spillway. Experiments (detailed in Estrella, 2013) have shown that this reduction is mostly dependent on the specific discharge at the entrance $(y_c/h)_e$ and the spillway height (L/L_t).

Figure 4 exemplifies the flow distribution measured in the case of $b_{0/}B=1/3$ and for the case of a dimensionless discharge at the crest $(y_c/h)_e$ of 1.14, 1.56 and 2.06. Estrella et al. (2011) present results for other conditions of $b_{0/}B$ and $(y_c/h)_e$.

The transversal flow regime can be characterized along the spillway. Figure 5 shows the transversal limits of each flow type observed for different $(y_c/h)_e$ (observed data) as well as the limits calculated with the expressions proposed by Amador (2005) for the corresponding specific discharge (adjustment). In this case, nappe flow will occur for $y_c/h<0.62$ and skimming flow for $y_c/h>0.82$.

Depending on the discharge and the dam widths at the top and at the toe, and also the dam height, the flow can reach the lateral abutments, or not. The risk of local scour there can be analyzed by the designer depending on the geology of the abutment using the estimated discharge obtained from the figure 3.

3.3. Characteristic water depth

The following figures show the evolution of normalized characteristic water depth ($y_{90}/(y_{90})_{qe}$) along the dimensionless length of the spillway (L/L_t). Results are normalized with respect to the characteristic water depth in the zone not affected by the lack of sidewalls, that is, the zone where the specific discharge is the same as that at the entrance to the chute $(y_{90})_{qe}$.

Figure 6 shows the case $(y_c/h)_e=2.37$. The dependence of characteristic water depth on transversal position (x/B) and on specific discharge (q/q_e) is presented for different values of spillway length.

Characteristic water depth decreases as the flow expands across the chute (increasing x/B) and the specific discharge decreases (q/q_e), regardless of the longitudinal position on the spillway (L/L_t). A reduction of 50% in flow rate produces a 40% reduction of the characteristic water depth with respect to that in the zone not affected by flow expansion.

3.4. Velocity field

The following figures illustrate the results of the normalized velocity profiles v/v_{90} as a function of y/y_{90}, where V_{90} is the characteristic interfacial velocity where C=0.9. Figure 7 shows the normalized velocity profiles for different flow rates $(y_c/h)_e$, at $L/L_t=0.95$ close to the spillway toe (step 58). Across the chute, profiles were obtained at sections x/B= 0, 1/10, 1/6.

Coefficients N of the equation (3) were obtained from the recorded velocity profiles. Figure 8 shows the longitudinal evolution of N for the tests with specific discharge at the entrance $(y_c/h)_e=2.37$. N increases as the flow expands, although its value ranges between 3 and 5. Close to the spillway toe, at x/B=1/6 the flow rate is within the range of transitional flow and the exponent N reaches values higher than 10. This is coherent with Relvas and Pinheiro (2011).

3.5. Air concentration

In the case of the stepped spillway without sidewalls, the area not affected by flow expansion presented mean air concentrations of between 0.32 and 0.59 in the different experiments carried out, exhibiting an increment downstream from the inception point in accordance with the findings of Chanson and Toombes (2001) for similar stepped spillway slopes. Without sidewalls, the lateral expansion also produces an increase in mean air concentration across the chute.

Figure 9 shows the evolution for normalized mean air concentration along the spillway (L/L_t) for $(y_c/h)_e=2.37$. As the flow is transversally expanding, the specific discharge decreases and mean air concentration increases, reaching maximum values of around $1.3\cdot(C_{med})_{qe}$, where $(C_{med})_{qe}$ is the mean air concentration at the spillway axis (x/B=0 and 1/30), where the flow behaves like a conventional stepped spillway with sidewalls.

Figure 10 shows measurements of air concentration profiles lengthwise ($L/L_t=0.95$ and $L/L_t=0.51$) and crosswise (x/B=0, 1/30, 1/10 and 1/6). These profiles are also compared with Equation (4) proposed by Chanson and Toombes (2001). This equation shows a good agreement in the zone close to the free surface ($y/y_{90}<0.40$), but does not fit well in the zone close to the pseudo-bottom ($y/y_{90}>0.40$). This air profile behavior was also observed in conventional stepped spillways with sidewalls by Gonzalez (2005) and Renna et al. (2005).

3.6. Pressure field

In this study, pressures were obtained on the step footprint at a distance y/l=0.4 from the external edge. The main aim of this section is to determine the pressure trends along and across the spillway due to flow spread. Figure 11 shows the transversal evolution (x/B) of dimensionless mean pressure (p/γ/h) on the step footprint. Each figure provides information on longitudinal behavior (L/L_t). From the results, for larger discharges mean pressure shows an increase across a step (x/B). On the other hand, mean pressure decreases for points further away from the zone not affected by flow expansion (x/B=0) and the lower mean pressure values are found closer to the spillway toe (L/L_t=0.95).

In Figure 12, the crosswise and lengthwise evolution of mean pressures are normalized using mean pressure records for the zone that behaves like a stepped spillway with sidewalls, $(p)_{qe}$. There is a drop in the mean pressure registered across the chute due to transversal decrease in the specific discharge. A 50% reduction in the specific discharge produces a drop of 75% in mean pressure.

As expected, crosswise reduction of specific discharge is accompanied by a reduction of mean pressure over the stepped spillway. Specifically, for the maximum tested discharge $(y_c/h)_e$=2.37), a 50% crosswise reduction produces a 75% reduction in mean pressure. Similarly, the further upstream, the lower the effect of the flow’s lateral expansion for higher discharges at the entrance of the chute, and therefore the lower the pressure reduction.

4. Conclusions

This paper is framed within research work developed in response to a consulting partner’s design of a stepped spillway without sidewalls. Studying the physical model has made it possible to determine the discharge distribution across and along the spillway. The velocity profiles, air concentration and water depths obtained lengthwise and crosswise of the spillway provide a detailed description of the hydraulic effect of the water expansion as a result of the lack of sidewalls. Some results can be highlighted here:

- As the flow expands, both specific discharge and characteristic depth decrease. A 50% reduction in specific discharge means a 40% reduction in characteristic depth.
- On the other hand, as the flow expands, the specific discharge decreases, but mean air concentration increases between 1.2 and 1.3 times the air concentration in a stepped spillway with sidewalls.
- For the skimming flow regime, power N of the velocity profile law ranges between 3 and 5 and increases as specific discharge diminishes. However, if specific discharge is low enough to become a transition flow, N doubles.
- The behavior of the air concentration profiles is similar to that in stepped spillways with sidewalls. The equation (4) by Chanson and Toombes (2001) fits well in the zone close to the free surface ($y/y_{90} \geq 0.40$).
- A 50% reduction in the flow rate produces a reduction of around 75% in mean pressures on the step's center of symmetry.

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6. References

Amador, A. (2005). “Comportamiento hidráulico de los aliviaderos escalonados en presas de hormigón compactado.” Universitat Politècnica de Catalunya Barcelona-TECH.

Amador, A., Sánchez-Juny, M., and Dolz, J. (2006a). “Diseño hidráulico de aliviaderos escalonados en presas de HCR.” *Ingeniería del Agua*, 13(4), 289–302.

Amador, A., Sánchez-Juny, M., and Dolz, J. (2006b). “Characterization of the nonaerated flow region in a stepped spillway by PIV.” *Journal of Fluids Engineering*, 128(6), 1266–1273.

Amador, A., Sánchez-Juny, M., and Dolz, J. (2009). “Developing Flow Region and Pressure Fluctuations on Steeply Sloping Stepped Spillways.” *Journal of Hydraulic Engineering, ASCE*, American Society of Civil Engineers, Dept. of Hydraulic and Environmental Engineering, Technologic School of Barreiro, IPS, 2830-144 Barreiro, Portugal, 135(12), 1092–1100.

Boes, R. M., and Hager, W. H. (1998). “Fiber-optical experimentation in two-phase cascade flow.” *Proc. Intl. RCC Dams Seminar*, K. Hansen, ed., Denver.

Boes, R. M., and Hager, W. H. (2003). “Two-phase flow characteristics of stepped spillways.” *Journal of Hydraulic Engineering, ASCE*, 129(9), 661–670.

Boes, R. M., and Minor, H.-E. (2001). “Inception point characteristics of stepped spillways.” *XXIX IAHR Congress*, Beijing, China.

Chanson, H. (1994). “Hydraulics of skimming flows over stepped channels and spillways.” *Journal of Hydraulic Research-IAHR*, 32(3), 445–460.

Chanson, H. (2001). “Hydraulic design of stepped spillways and downstream energy dissipators.” *Dam Engineering*, 11(4), 205–242.

Chanson, H., and Toombes, L. (2001). *Experimental investigations of air entrainment in transition and skimming flows down a stepped chute: application to enbankment overflow on stepped spillways. Research Report No. CE158*. Dept. of Civil Engineering, The University of Queensland, Brisbane, Australia, 74.

Chanson, H., and Toombes, L. (2004). "Hydraulics of stepped chutes: The transition flow." *Journal of Hydraulic Research*, 42(1), 43–54.

Chanson, H., Yasuda, Y., and Ohtsu, I. (2002). "Flow resistance in skimming flows in stepped spillways and its modelling." *Canadian Journal of Civil Engineering*, 29(6), 809–819.

Estrella, S. (2013). "Comportamiento hidráulico de aliviaderos escalonados sin cajeros laterales en presas de HCR." UPC BARCELONATECH, Barcelona.

Estrella, S., Sánchez-Juny, M., Dolz, J., and Ibáñez de Aldecoa, R. (2011). "Aliviaderos escalonados sin cajeros laterales." *II Jornadas de Ingeniería del Agua 2011: modelos numéricos y dinámica fluvial*.

Falvey, H. T. (1980). *Air-water flow in hydraulic structures*. *Engineering Monograph No. 41, Department of the Interior, US Bureau of Reclamation, Denver Office*, Water Resources Technical Publication, Denver, CO, US, 160.

Gonzalez, C. A. (2005). "An experimental study of free-surface aeration on embankment stepped chutes." University of Queensland, Australia.

Hunt, S. L., and Kadavy, K. C. (2013). "Inception Point for Embankment Dam Stepped Spillways." *Journal of Hydraulic Engineering*, 139(1), 60–64.

De Marinis, G., Fratino, U., and Piccinni, A. F. (2001). "Flow regimes on stepped spillways." *XXIX IAHR Congress*, Beijing, China.

Matos, J. (2000). “Hydraulic design of stepped spillways over RCC dams.” *Hydraulics of Stepped Spillways*, H.-E. Minor and W. H. Hager, eds., Balkema, Rotterdam, VAW, ETH, Zürich, Switzerland, 187–194.

Matos, J., and Frizell, K. H. (2000a). “Air concentration and velocity measurements on self-aerated flow down stepped chutes.” *Joint Conference on Water Resource Engineering and Water Resources Planning and Management 2000*, American Society of Civil Engineers, Minnesota, USA.

Matos, J., and Frizell, K. H. (2000b). “Air concentration and velocity measurements on self-aerated flow down stepped chutes.” *Joint Conference on Water Resource Engineering and Water Resources Planning and Management 2000*, American Society of Civil Engineers, July 30-August 2, 2000. Minneapolis, Minnesota, USA.

Meireles, I. (2004). “Caracterizaçao do escoamento deslizante sobre turbilhoes e energia específica resiudal em descarregadores de cheias em degraus.” Instituto Superior Técnico de Lisboa, Portugal.

Meireles, I., Renna, F., Matos, J., and Bombardelli, F. (2012). “Skimming, Nonaerated Flow on Stepped Spillways over Roller Compacted Concrete Dams.” *Journal of Hydraulic Engineering*, 138(10), 870–877.

Peyras, L., Royet, P., and Degoutte, G. (1992). “Flow and energy dissipation over stepped gabion weirs.” *Journal of Hydraulic Engineering, ASCE*, 118(5), 707–717.

Rajaratnam, N. (1990). “Skimming Flow in Stepped Spillways.” *Journal of Hydraulic Engineering, ASCE*, 116(4), 587–591.

Relvas, A. T., and Pinheiro, A. N. (2011). “Velocity distribution and energy dissipation along stepped chutes lined with wedge-shaped concrete blocks.” *Journal of Hydraulic Engineering, ASCE*, American Society of Civil Engineers (Hydraulics), 345 E. 47th St.

New York NY 10017-2398 USA, and ENGECONSULT, Consultores Te\aacnicos Ltda, Rua Xavier Marques, 94, Aflitos, Recife, CEP 52050-230, Brazil., 137(3), 423–431.

Renna, F., and Fratino, U. (2010). “Nappe flow over horizontal stepped chutes.” *Journal of Hydraulic Research*, 48(5), 583–590.

Renna, F., Fratino, U., and Matos, J. (2005). “Air-water flow features in skimming flow over steeply sloping stepped spillways.” *XXXI IAHR Congress*, 11-16 September 2005, Seoul, 598–599.

Sánchez-Juny, M., Bladé, E., and Dolz, J. (2008a). “Pressures on a stepped spillway.” *Journal of Hydraulic Research-IAHR*, 46(4), 574–576.

Sánchez-Juny, M., Bladé, E., and Dolz, J. (2008b). “Analysis of pressures on a stepped spillway.” *Journal of Hydraulic Research-IAHR*, 46(3), 410–414.

Sánchez-Juny, M., and Dolz, J. (2003). “Characterization of the pressure field over a stepped spillway in roller compacted concrete dams.” *In 4th Intl. Symposium on roller compacted concrete (RCC) dams*, L. Berga, J. M. Buil, C. Jofre, and S. Chonggang, eds., Balkema, Madrid (Spain), 697–700.

Sánchez-Juny, M., and Dolz, J. (2005). “Experimental study of transition and skimming flows on stepped spillways in RCC dams: Qualitative analysis and pressure measurements.” *Journal of Hydraulic Research-IAHR*, International Association of Hydraulic Engineering Research, Hydraulic Maritime and Environmental Engineering Department, UPC, Street Jordi Girona 1-3, 08034 Barcelona, Spain, 43(5), 540–548.

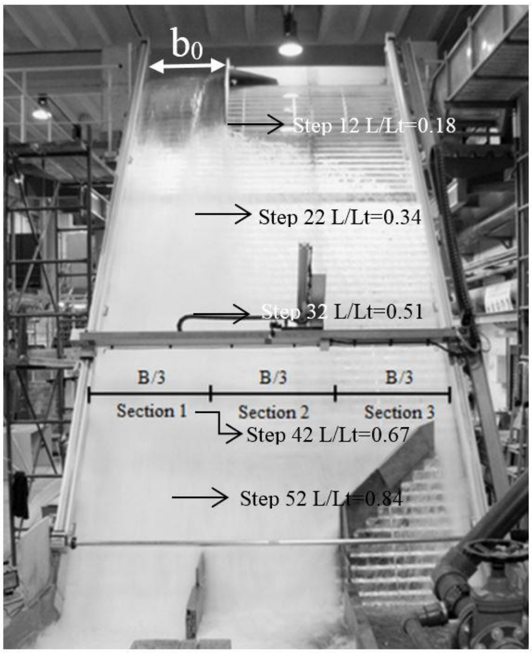

Figure 1. Front view of the stepped chute for a dimensionless specific discharge $(y_c/h)_e$=2.37 and a dimensionless spill-width b_0/B=1/3.

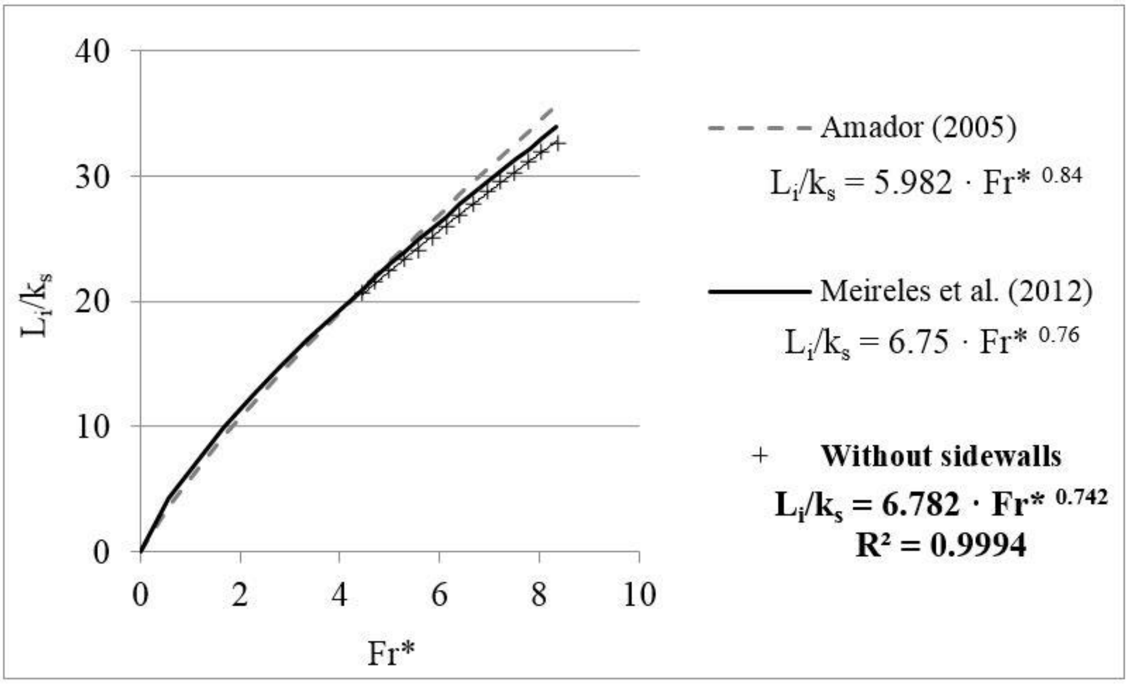

Figure 2. Comparison of the inception point observed without sidewalls and the equations proposed by Amador et al. (2006a); Meireles et al. (2012) for the case with sidewall

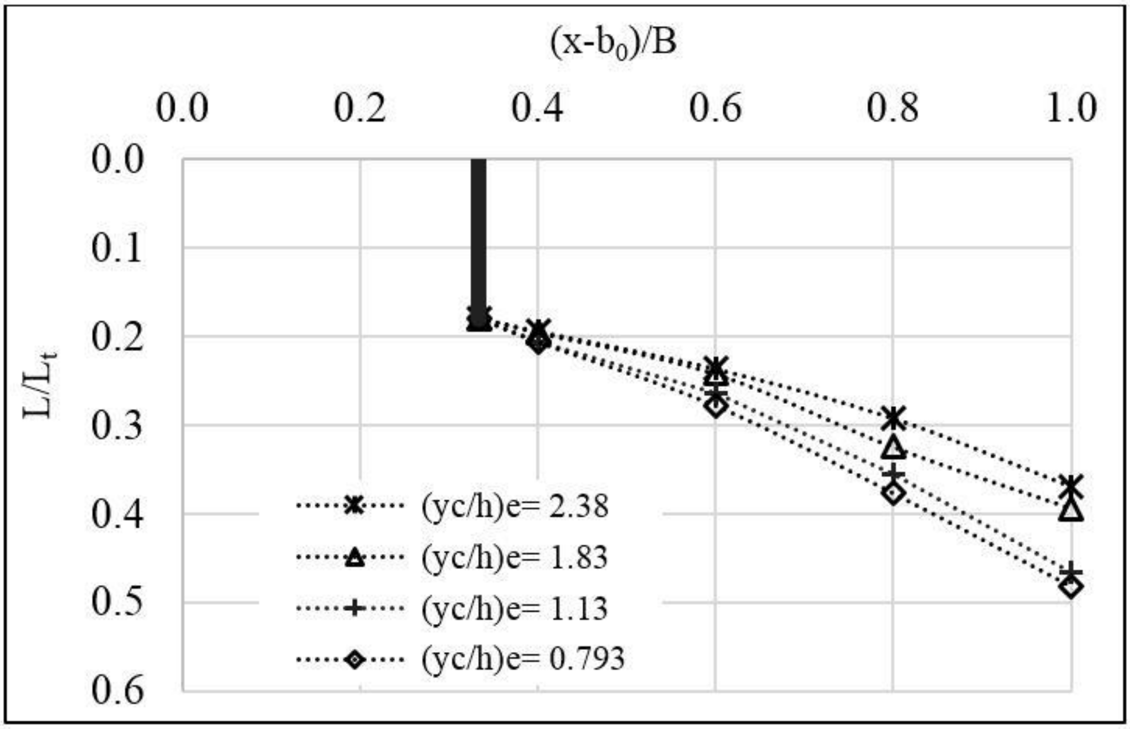

Figure 3. Lateral spread characterization along the spillway for different specific discharges at the entrance

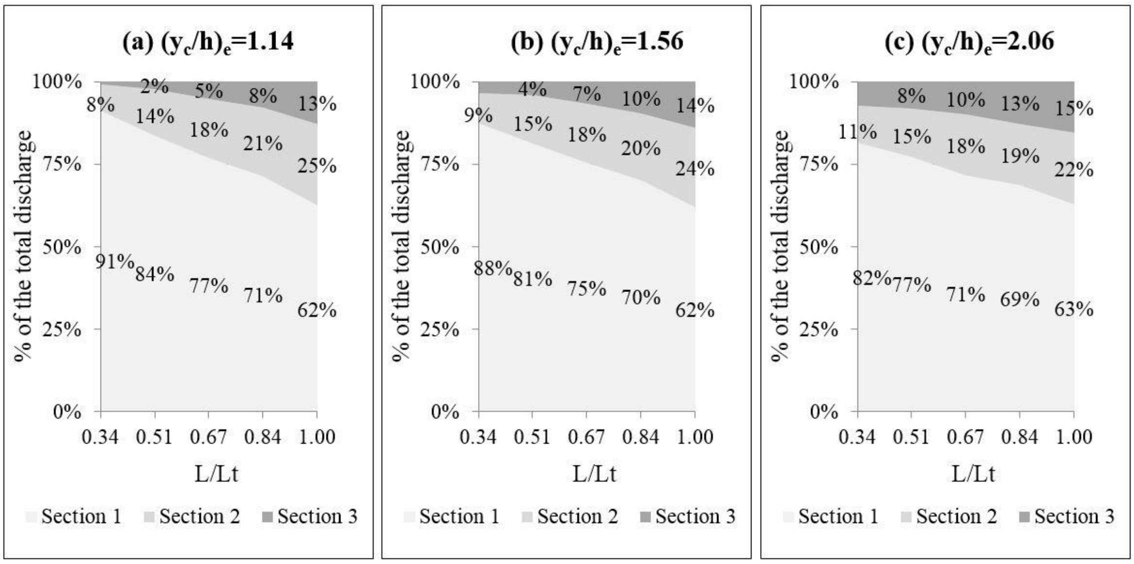

Figure 4. Flow distribution at a dimensionless distance along the chute obtained as the ratio between the distance from the corresponding step to the crest (L), and the whole length of the chute (L_t), for the case $b_0/B=1/3$. (a) $(y_c/h)_e=1.14$, (b) $(y_c/h)_e=1.56$, (c) $(y_c/h)_e=2.06$

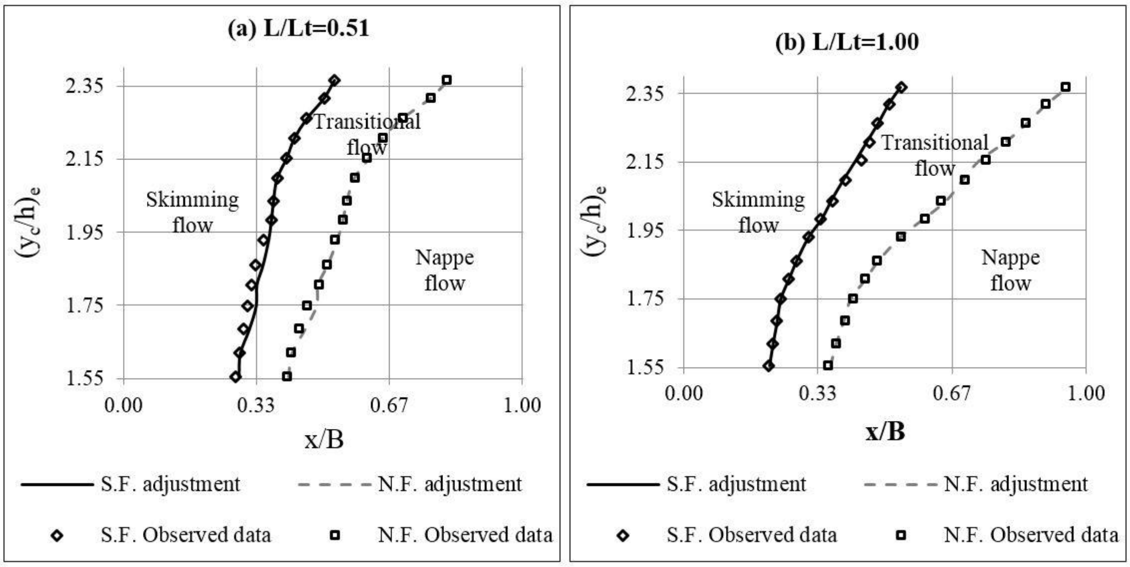

Figure 5. Crosswise flow regime characterization for $(y_c/h)_e$ ranging between 1.55 and 2.37. S.F. = inferior limit of skimming flow, N.F. = superior limit of nappe flow. (a) At the middle of the spillway (L/L_t=0.51), (b) At the spillway toe (L/L_t=1.00)

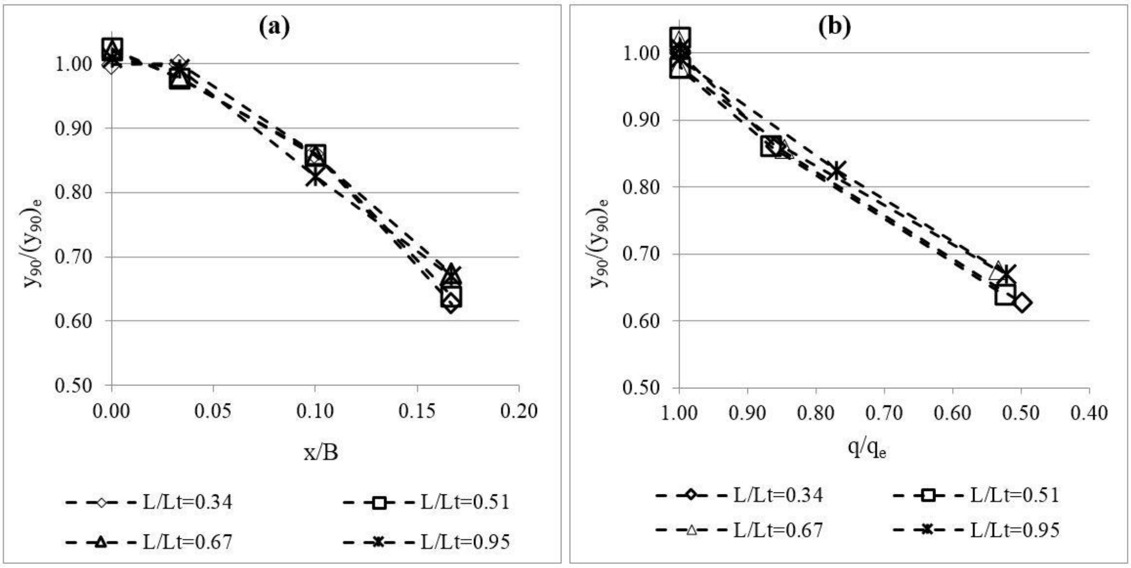

Figure 6. Evolution of normalized water depth along the spillway (L/L_t), for $(y_c/h)_e$=2.37. (a) Depending on transversal position (x/B). (b) Depending on specific discharge (q/q_e)

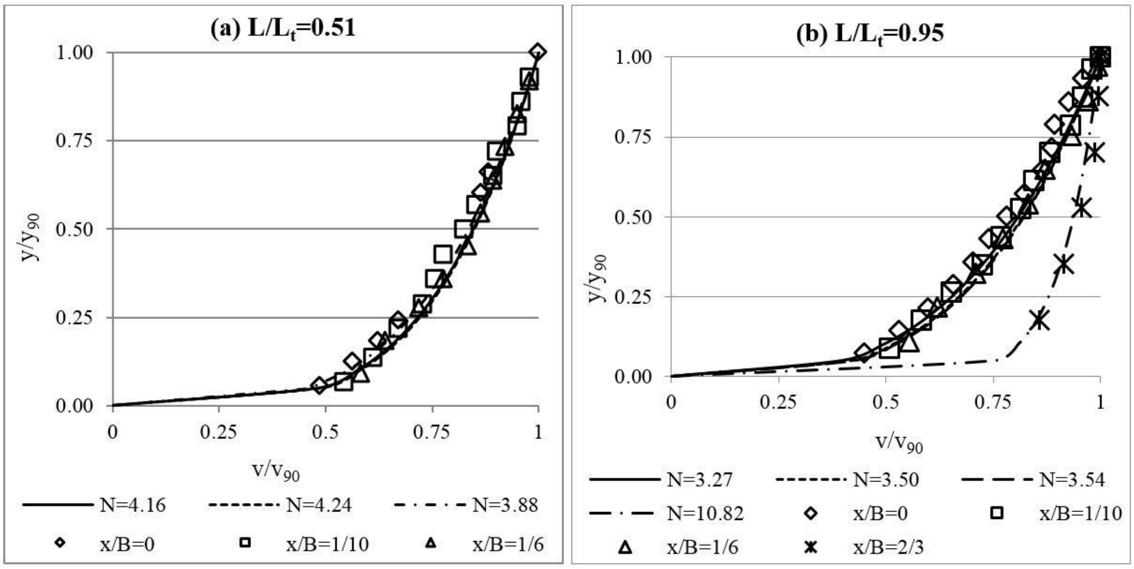

Figure 7. Normalized velocity profiles for $(y_c/h)_e$=2.37 at (a) L/L_t=0.51 and (b) L/L_t=0.95.

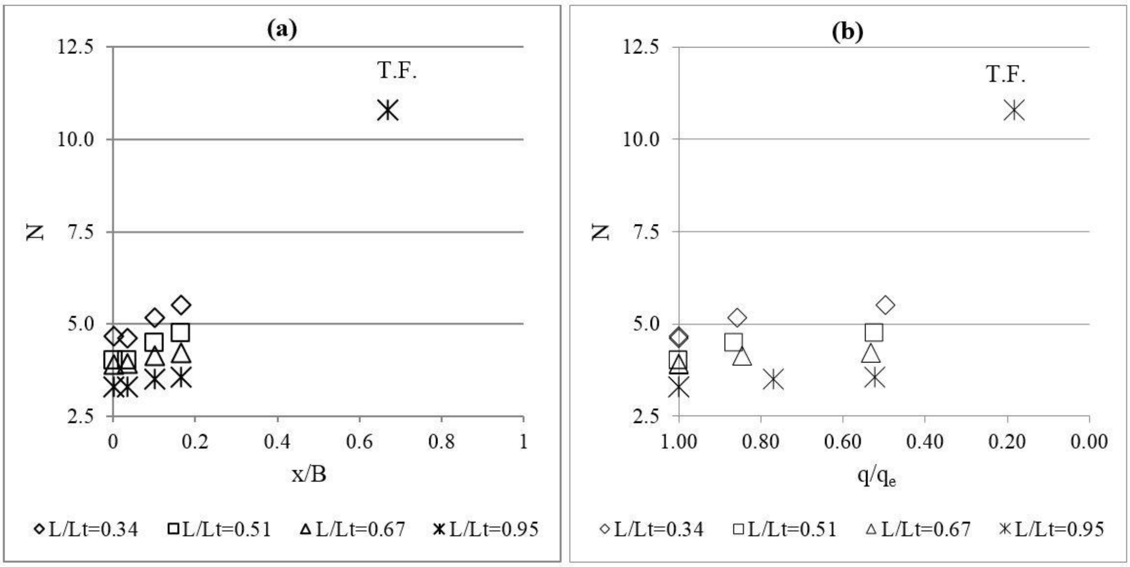

Figure 8. Lengthwise evolution (L/L_t) of fitted coefficient N. $(y_c/h)_e$=2.37. T.F.=Transitional flow.

(a) Depending on transversal position (x/B), (b) Depending on specific discharge (q/q_e).

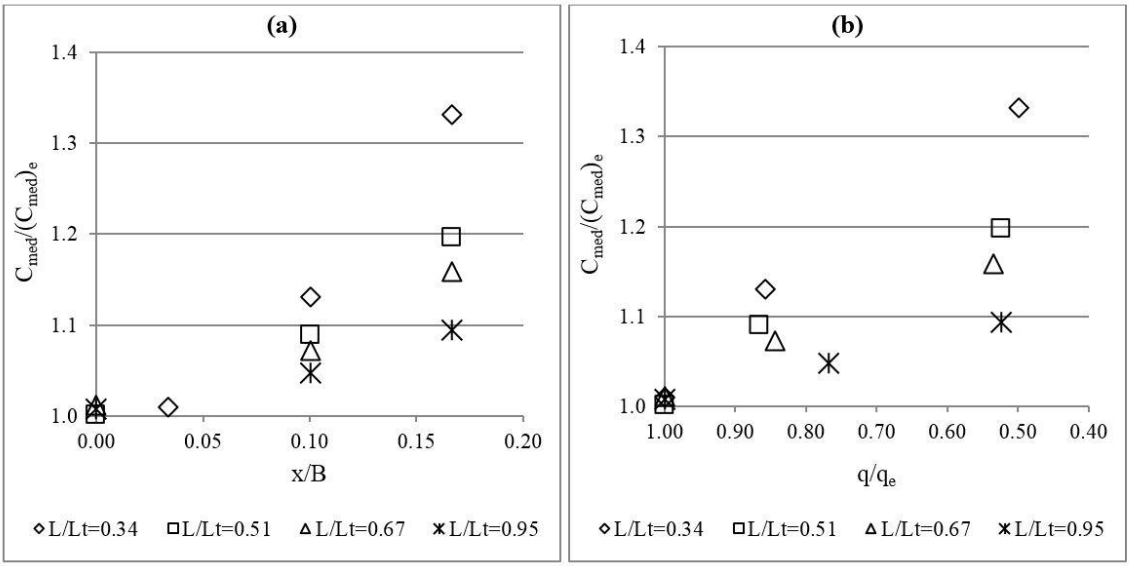

Figure 9. Lengthwise (L/L_t) evolution of mean air concentration, $(y_c/h)_e$=2.37. (a) Depending on transversal position (x/B), (b) Depending on specific discharge (q/q_e)

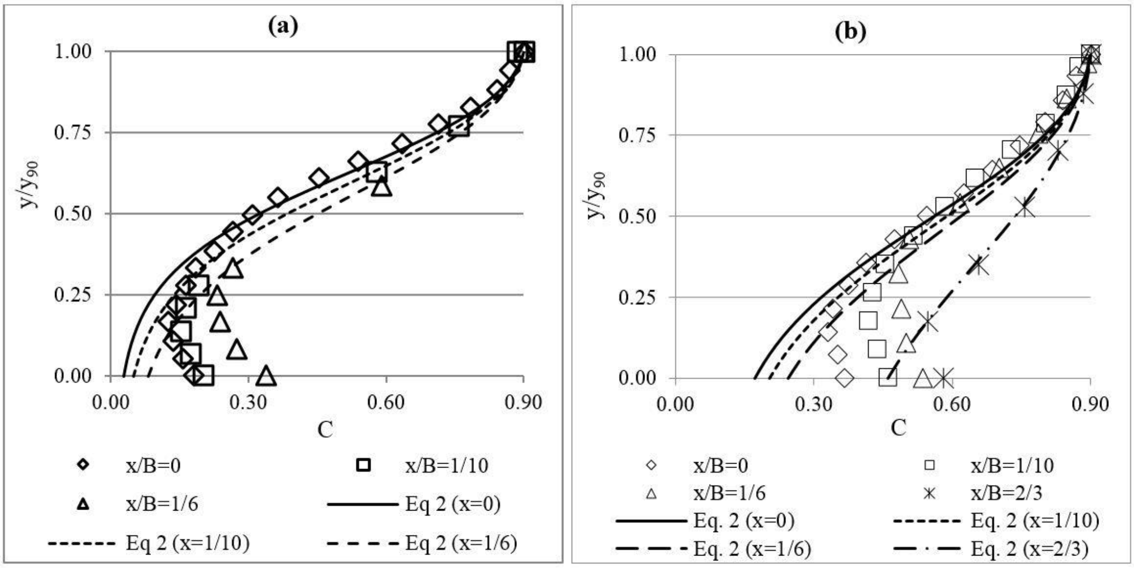

Figure 10. Air concentration profiles for $(y_c/h)_e$=2.37, and comparison with the Equation (4) proposed by Chanson and Toombes (2001). (a) L/L_t=0.51, (b) L/L_t=0.95

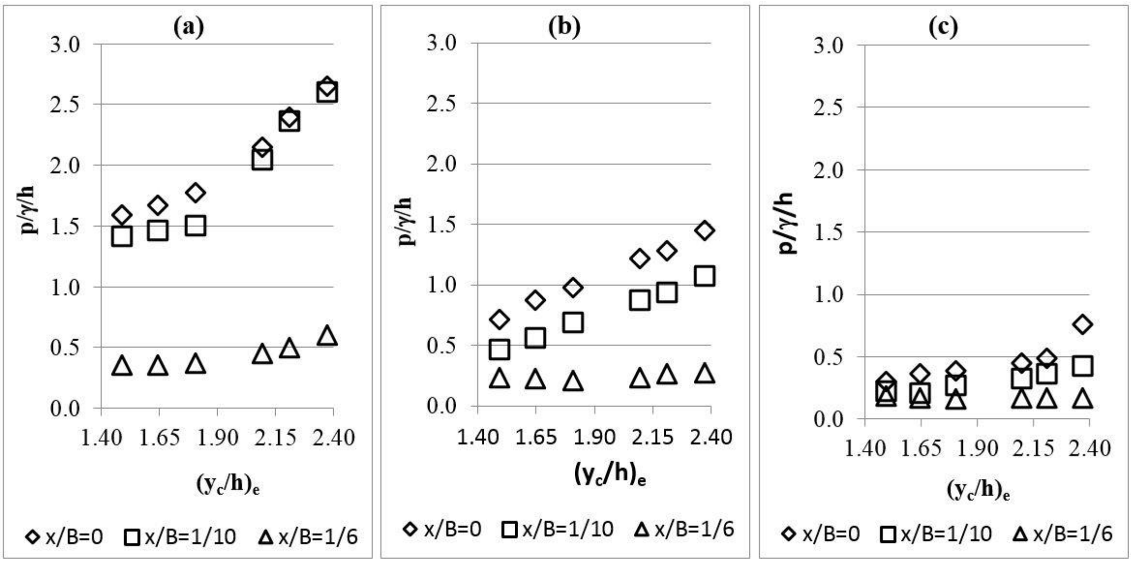

Figure 11. Evolution of dimensionless mean pressures lengthwise (L/L_t) and crosswise (x/B) the spillway. (a). L/L_t=0.34, (b). L/L_t=0.67, (c). L/L_t=0.95.

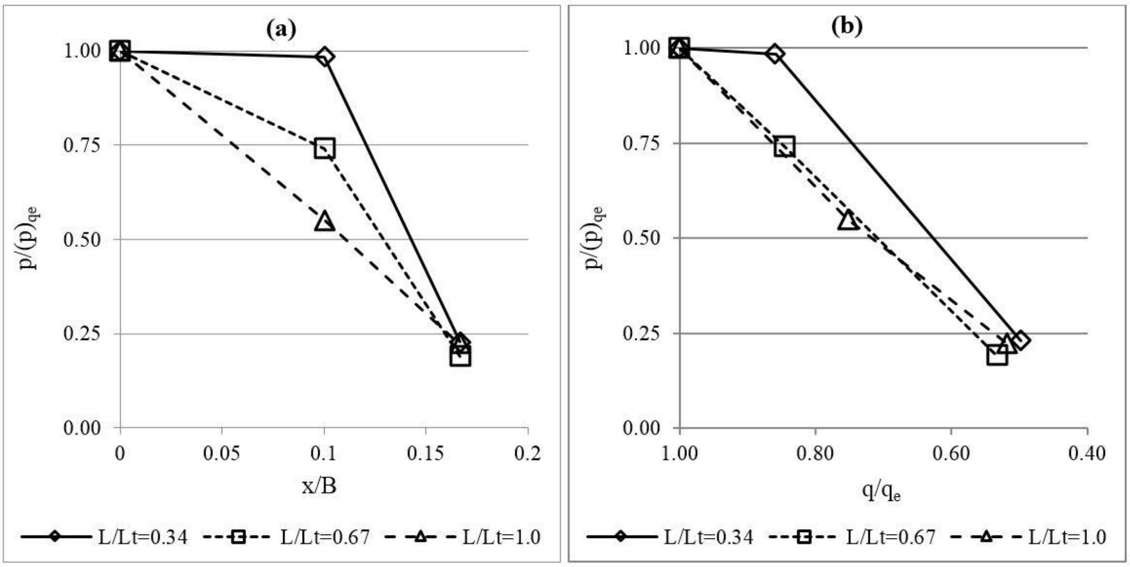

Figure 12. Evolution dimensionless mean pressures for $(y_c/h)_e$=2.37 at the spillway crest, for the different heights L/L_t. (a) Crosswise evolution (x/B). (b) Depending on q/q_e.