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Air Entrainment and Energy Dissipation on Gabion Stepped Weirs

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Abstract: *In the last three decades the design of stepped spillways regained some interest because of their suitability with new construction methods including gabion placement. In this study, the hydraulic performances of gabion stepped weirs were investigated experimentally in terms of the air-water flow properties and energy dissipation rate. A physical study was performed in a relatively large size facility with a 26.6° slope (1V:2H) and 0.10 m step height. For both gabion and impervious stepped weirs, a detailed comparison of the air-water flow properties was performed. The visual observations highlighted the seepage flow through the gabions, including a modification of the cavity flow dynamics, especially in the skimming flow regime. In skimming flows, higher velocities were measured at the downstream end of the gabion stepped chute, associated with lesser energy dissipation rates.*

Keywords: *Gabion weirs, Stepped spillways, Energy dissipation, Air entrainment, Physical modelling*

1. INTRODUCTION

Stepped weirs have been used for more than 3,500 years (Chanson 2000-2001). The stepped design enhances the rate of energy dissipation on the spillway chute, thus reducing the size and cost of the downstream stilling structure (Chanson 1995,2001, Ohtsu and Yasuda 1998, Minor and Hager 2000). The stepped profile is particularly well-suited to the construction of gabion stepped weirs (Fig. 1). Peyras et al. (1991,1992) studied the flow patterns and energy dissipation of gabion stepped chutes. Kells (1993,1995) discussed the interactions between of seepage and free-surface flows. Chanson (1995,2001) reviewed the design of gabion stepped spillways.

It is the purpose of this contribution to study thoroughly the hydraulics of gabion stepped weirs in terms of their air-water flow properties and rate of energy dissipation. New measurements were conducted in a relatively large size facility (θ = 26.6º, h = 0.1 m), where θ is the chute slope and h the vertical step height. The results provided a new understanding of the combined effects of seepage and step surface roughness on the characteristics of overflows, as well as a systematic comparison with a flat impervious stepped chute.

Figure 1 – Gabion stepped weir at Robina, Gold Coast (Australia) in 2013 – h = 0.6 m, l = 1.1 to 2 m

2. EXPERIMENTAL INVESTIGATIONS

New experiments were conducted in a large size stepped spillway model at the University of Queensland, previously used by Felder and Chanson (2013) and Guenther et al. (2013). The test section consisted of a broad-crested weir followed by ten steps with step height h = 0.1 m and step length l = 0.2 m. The chute width was W = 0.52 m. A pump controlled with an adjustable frequency AC motor drive delivered the flow rate, allowing an accurate discharge adjustment in a closed-circuit system. The water discharge was deduced from the measured upstream head above crest using the discharge calibration results of Felder and Chanson (2012).

Two stepped configurations were tested (Table 1). The flat stepped configuration consisted of ten smooth impervious steps made of marine ply. For the gabion configuration, ten identical gabions were installed above the smooth impervious steps (Fig. 2). Each gabion was 0.3 m long, 0.1 high and 0.52 m wide, made of fine 12.7×12.7 mm^2 galvanised metallic mesh and filled with natural river pebbles. The gravels (Cowra pearl) were sieved with 14 mm square sieve. The density of the dry gravels was 1.6 tonnes/m^3 corresponding to a porosity Po $\approx$ 0.35-0.4. The hydraulic conductivity of the gabions was estimated to be K $\approx 10^{-1}$ m/s (Wuthrich and Chanson 2014).

The air-water flow measurements were conducted with a dual-tip phase detection intrusive probe. Each tip had an inner tip diameter Ø = 0.25 mm and the longitudinal separation of probe tips was Δx = 6.2 mm. The conductivity probe was mounted on a sturdy trolley and the elevation in the direction perpendicular to the pseudo bottom formed by the step edges was controlled by a fine adjustment screw-drive mechanism equipped with a Mitutoyo™ digital ruler (accuracy < 0.1 mm). The probe was excited by an electronic air bubble detector with a response frequency greater than 100 kHz. The probe signal output was sampled at 20 kHz per sensor for 45 s.

The experimental study was conducted on both stepped weir configurations. Flow visualisations were carried out for a wide range of discharges: $0.005 \le Q \le 0.114$ m^3/s. The air-water flow properties were recorded mostly in the transition and skimming flow regimes, for a range of dimensionless discharges between $0.5 \le d_c/h \le 1.7$ corresponding to Reynolds numbers Re between 1.40×10^5 and 8.78×10^5. Herein d_c is the critical flow depth, Q the water discharge, Re the Reynolds number defined in terms of the equivalent pipe diameter and W the channel width. The experimental flow conditions are summarised and compared with previous studies in Table 1.

Figure 2 – Gabion stepped weir experiment – h = 0.1 m, d_c/h = 1.25

Table 1 - Experimental investigations of gabion stepped weirs

Reference	θ (°)	h (m)	Geometry	Flow conditions	Instrumentation
Stephenson (1979)	18.3, 26.6, 33.7, 45	0.10, 0.15	Gabion steps (1 to 4 steps) W = 0.10 & 0.38 m	d_c/h = 0.18 to 2.05	Pointer gauge.
Peyras et al. (1991,1992)	18.3, 26.6, 45	0.20	Gabion steps (3 to 5 steps) W = 0.80 m	Q = 0.05 to 0.2 m^3/s Re = 2.5×10^5 to 1.0×10^6	Pitot tube array.
Present study W = 0.52 m	26.6	0.10	Gabion steps Flat impervious steps	Q = 0.02 to 0.11 m^3/s Re = 1.4×10^5 to 8.8×10^5	Double-tip conductivity probe (Ø=0.25 mm)

3. BASIC FLOW PATTERNS

On the gabion stepped spillway, a porous seepage flow regime was observed for very small discharges ($d_c/h < 0.3$). In the porous flow regime, the water seeped through the gabion materials. On the first gabion box, some infiltration was observed. A short horizontal seepage face was observed on each step and there was no overflow past the step edges. For the smallest discharges, no vertical seepage was observed through the step vertical face. With increasing discharge, some small water jets came out of the gabions. The transition between porous and nappe flow regimes occurred once some overflow took place at the first gabion. The nappe flow ($0.3 < d_c/h < 0.6$) exhibited a succession of free falling nappes from one step edge to the next one. The cavity behind the nappe was filled with a superposition of seepage jets coming out of the upstream gabion (Fig. 3, Left). In the lower part of the cavity, an oscillating recirculating flow region was observed. The recirculation motion in the step cavity exhibited a different flow pattern compared to that observed on flat impervious stepped spillways. A transition flow regime was observed for $0.6 < d_c/h < 0.9$. The hydrodynamic instabilities and splashes appeared less intense than on flat stepped spillways. For the largest discharges, a skimming flow was observed ($d_c/h > 0.90$). The flow pattern was generally similar to that observed on the flat stepped configuration. However a different streamline pattern was seen next to the stagnation point on the horizontal step face (Fig. 3 Right). Some bubbly flow and air bubble entrainment into the gabions were observed, mostly in the upper corner of each gabion box downstream of the inception point of free-surface aeration. Further differences were found in terms of cavity flow motion as a result of seepage flow effect. Detailed string studies were carried out to visualise the cavity flow (Fig. 4). A vertical flow of air bubbles was observed close to the vertical step face (Fig. 3 Right). In the centre of the cavity a clear water core was seen in all cavities downstream of the inception point for all discharges (Fig. 4). The existence of a similar clear water core was previously reported by Gonzalez et al. (2008) for rough impervious steps. On the gabion stepped weir, some continuous interaction between the cavity and the gabion was noted. The behaviour of the flow inside the cavity is schematically sketched in Figure 3 (Right).

On the flat impervious stepped weir, a nappe flow regime was observed for the smallest discharges ($d_c/h < 0.5$). The flow consisted of a succession of free falling nappes from a step to the following one (Chamani and Rajaratnam 1994, Toombes and Chanson 2008). Below each falling nappe, a recirculating pool of water was formed with an air cavity above. A schematic representation of the cavity pattern can be found in Figure 5 (Left). For a range of intermediate discharges ($0.5 < d_c/h < 0.9$), the flow was characterised by strong hydrodynamic instabilities associated with a well developed spray region and a large amount of splashes. The step cavities were almost completely full, with a small air pocket under the step edge, while for larger discharges the cavities became filled with water (Chanson and Toombes 2004). For the larger discharges ($d_c/h > 0.9$), the flow skimmed as a coherent stream above the pseudo-bottom formed by the step edges. Substantial air entrainment occurred downstream of the inception point of free surface aeration, and an energetic recirculation pattern was observed in the step cavities (Chanson 1994, Chamani and Rajaratnam 1999, Boes 2000) (Fig. 5, Right). Overall the flow pattern observations and flow conditions for the changes between flow regimes were in agreement with the literature for a similar chute slope.

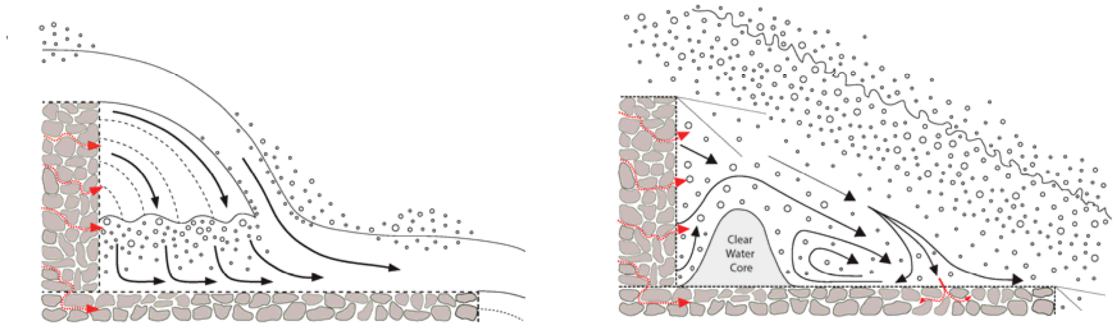

Figure 3 – Definition sketches of nappe (Left) and skimming (Right) flows on the gabion stepped weir – Red arrows highlight the air-water seepage motion

Figure 4 – Cavity flow pattern in a skimming flow on gabion stepped weir - Flow conditions: step cavity 7-8, $d_c/h = 1.25$, $Re = 5.5\times10^5$ - Note the clear water core in the step cavity

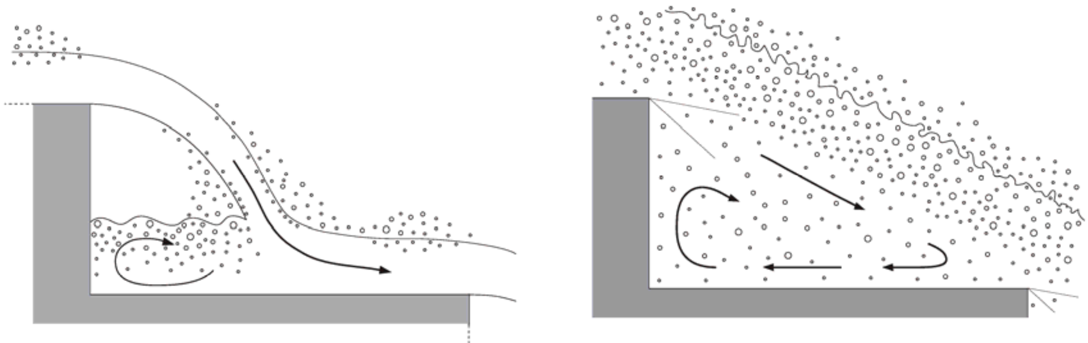

Figure 5 – Definition sketches of nappe (Left) and skimming (Right) flows on the flat impervious stepped weir

4. AIR-WATER FLOW PROPERTIES

All the void fraction profiles showed a substantial flow aeration. Overall the nappe flows over gabion steps were slightly less aerated than the flow on the flat impervious stepped weir. However the air concentration at y = 0 (i.e. at the gabion edge) was non-zero because of the bubbly flow inside the gabions. In the skimming flows, the void fraction data exhibited a S-profile (Fig. 6A). In Figure 6, y is the distance normal to the pseudo-bottom formed by the step edges, C is the void fration, F is the bubble count rate, V is the time-averaged interfacial velocity, Tu is the turbulence intensity (Tu = v'/V) and V_c is the critical flow velocity. The flow aeration tended to be lesser on the gabion stepped chute than on the smooth impervious stepped chute for the same flow rate. The void fraction distributions were successfully compared with the advective diffusion equation (not shown). The bubble count rate distributions on both flat impervious and gabion stepped configurations showed a marked maximum corresponding to a local void fraction between 0.4 and 0.5 (Fig. 6B). The results were consistent with previous studies of stepped spillways. For all discharges, the bubble count rate was consistently smaller on the gabion stepped weir compared to the flat impervious stepped chute. In the skimming flows, some difference was noted between smooth and gabion stepped chutes in the lower part of the flow. Namely, significantly less bubble count rates were recorded in the gabion stepped configuration (Fig. 6B).

The velocity distributions showed some self-similar profiles which compared well with a 1/10th power law for $y < Y_{90}$ where Y_{90} is the characteristic distance normal to the pseudo-bottom where C = 0.90. In the nappe flow regime, the interfacial velocities were smaller on the gabion steps for the same flow rate. Some typical results in the skimming flow regime are presented in Figure 6C, illustrating that the gabion stepped chute flow exhibited faster velocities than the smooth impervious stepped chute flow, for the same discharge at the same location downstream of the inception point of free-surface aeration. The finding was counter-intuitive, although a similar trend was previously observed on rough impervious steps by Gonzalez et al. (2008) and Bung and Schlenkhoff (2010). For completeness, the velocity data were comparable in transition flows for both stepped configurations. For both configurations, a local maximum in turbulence intensity was observed at the location where the bubble count rate was maximum. Typical results are presented in Figure 6D for a skimming flow. Overall the level of turbulence was higher above the flat impervious stepped weir. The relationship between bubble count rate and turbulence intensity showed a monotonic increasing trend for both flat impervious and gabion stepped configurations as reported by Chanson and Toombes (2002).

The porosity of gabion steps induced some seepage through the gabions, thus reducing the overflow discharge above the steps. The overflow discharge per unit width above the gabions was estimated by applying the equation of conservation of mass using the void fraction and velocity data. The results showed that the proportion of seepage flow was a function of the flow regime and flow rate. In skimming flows, it was about 15% down to 5% of the total flow rate with increasing discharge.

5. ENERGY DISSIPATION

The energy loss down the stepped chute may be calculated as

$$\Delta H = H_{max} - H_{res} \tag{1}$$

where ΔH is the head loss, H_{max} is the upstream total head and H_{res} is the residual head. Herein the residual head was calculated based upon the air-water flow properties:

$$H_{res} = \int_0^{Y_{90}} (1 - C) \times dy \times \cos\theta + \frac{q^2}{2 \times g \times \left(\int_0^{Y_{90}} (1 - C) \times dy \right)^2} \tag{2}$$

where C is the void fraction, g is the gravity acceleration and q is the water discharge per unit width. The results are presented in Figure 7 in terms of rate of energy dissipation and residual head at the downstream end of the chute, where $\Delta z_o/d_c$ is the dimensionless drop in elevation between the broad crested weir and the sampling location. Note that the gabion stepped data were calculated using the overflow discharge estimate (Wuthrich and Chanson 2014).

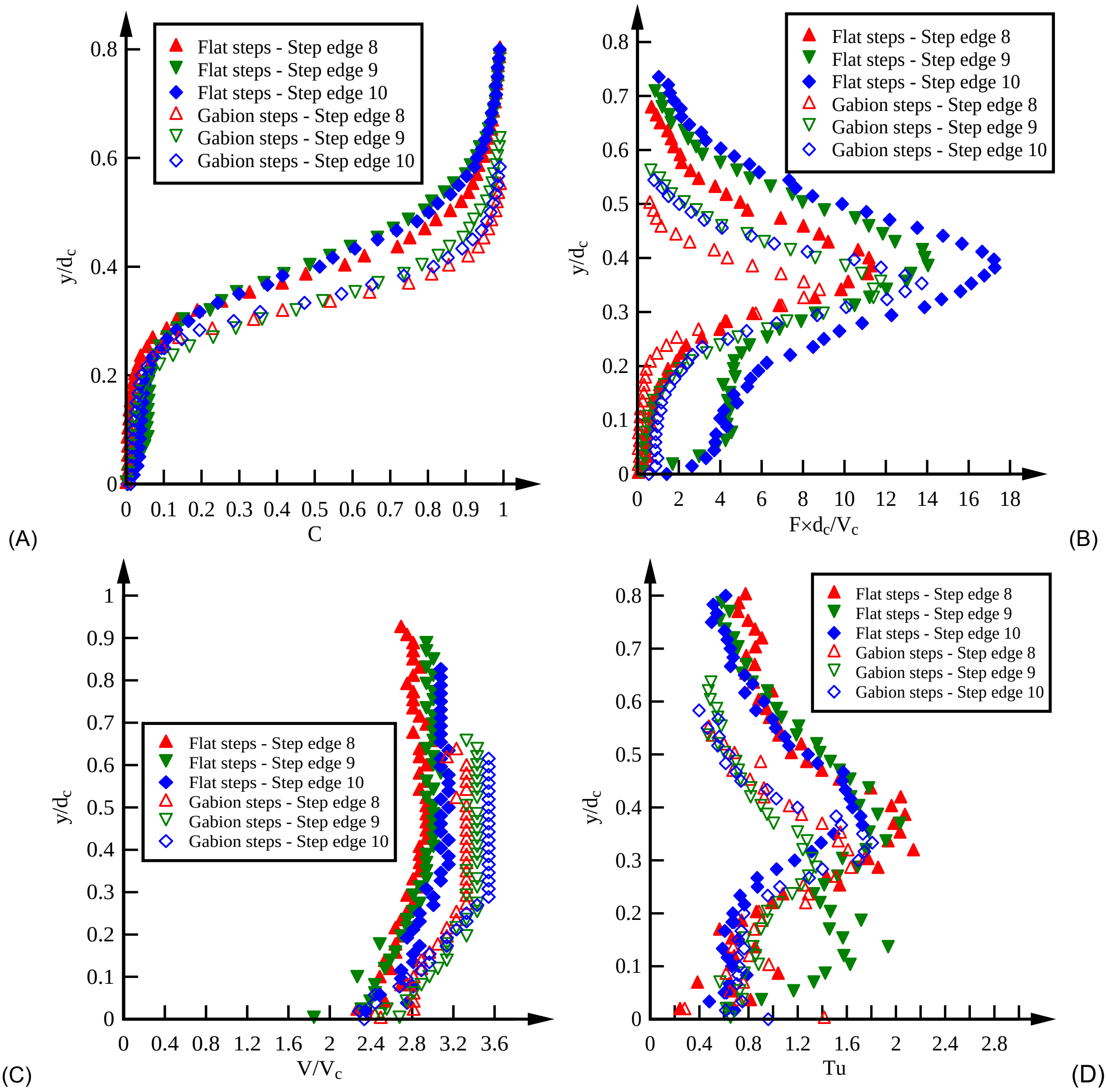

Figure 6 – Dimensionless distributions of void fraction (A, Top Left d_c/h = 1.5), bubble count rate (B, Top Right d_c/h = 1.7), interfacial velocity (C, Bottom Left d_c/h = 1.3) and turbulence intensity (C, Bottom Right d_c/h = 1.5) on stepped weirs

Altogether the experimental results showed that the gabion stepped weir was the least efficient in terms of energy dissipation but for the smallest discharge (Fig. 7A). For the smallest discharges (d_c/h = 0.5), the energy dissipation of the gabion stepped chute was slightly larger than that on the flat impervious stepped configuration. The residual head data showed the largest residual head for the gabion stepped chute in skimming flows (Fig. 7B). The results were overall consistent with the interfacial velocity measurements (Fig. 6C)

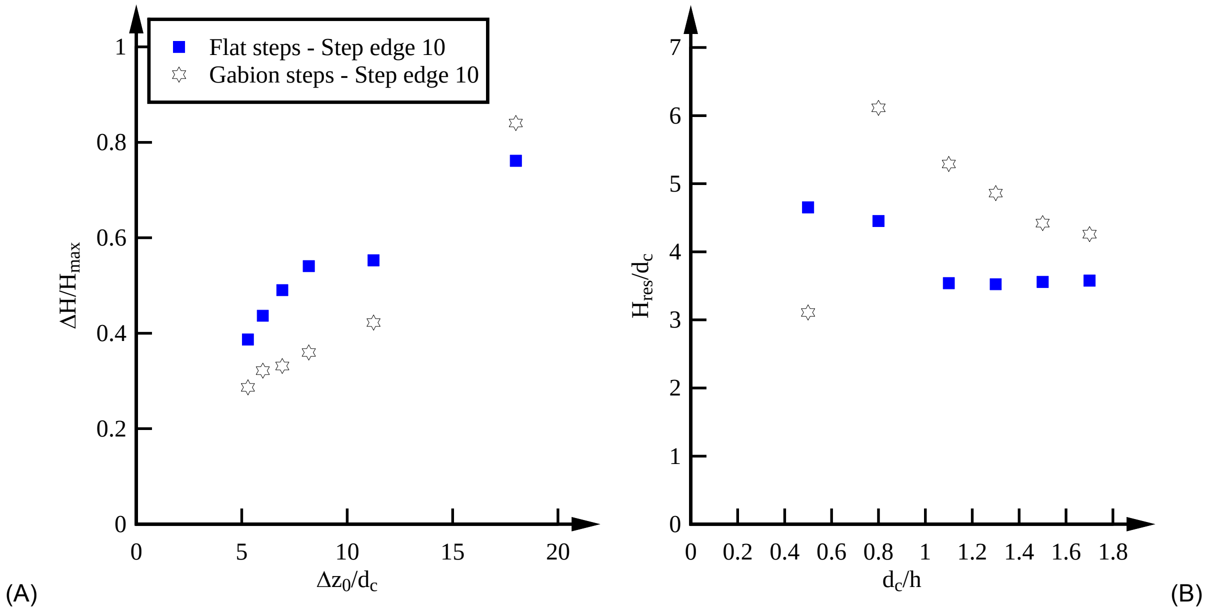

Figure 7 – Dimensionless rate of energy dissipation (A, Left) and residual head (B, Right) at the last step edge (Step 10) - Same legend for both graphs

6. CONCLUSION

The hydraulic performances of a gabion stepped weir were investigated experimentally through a comprehensive physical study based upon a Froude similitude. A gabion stepped chute and a flat impervious stepped chute were tested comparatively in a large size facility with a chute slope of 26.6° (1V:2H) and step height of 0.1 m. On the gabion stepped chute, a porous regime was observed for the smallest discharges: there was no overflow and the water seeped through the gabions. For larger discharges, the main overflow regimes included the nappe, transition and skimming flows with increasing discharges. The interactions between seepage flow and overflow were functions of the discharge, gabion configuration and flow regime. They resulted in a modification of the step cavity flow and recirculation patterns.

Some detailed air-water flow measurements were conducted at all step edges downstream of the inception point of free-surface aeration. The results showed comparable trends for both stepped weirs, although with some quantitative differences. The gabion stepped chute was less aerated. The bubble count rate and turbulence intensity were also lower on the gabion stepped weir. In skimming flows, larger velocities were measured at the downstream end of the gabion stepped chute. The rate of energy dissipation and residual head were calculated based upon the air-water flow properties. In skimming flows, the rate of energy dissipation was the lowest on the gabion stepped weir. While the finding might appear counter-intuitive, it was consistent with earlier experimental results on rough impervious stepped chutes, highlighting the importance of sound physical modelling in the investigation of hydraulic structures.

Finally it must be added that the laboratory experiments were conducted with new gabion boxes. The weir structure was possibly more rigid than older gabion structures and it was not affected by any form of damage.

7. ACKNOWLEDGMENTS

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