IMPLICATIONS OF FISH BEHAVIOR FOR VERTICAL SLOT FISHWAYS DESIGN

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Fish are confronted to a challenging hydrodynamic environment when they swim upstream vertical slot fishways. Nevertheless, the knowledge of fish behavior in these conditions is limited, particularly for coarse species such as cyprinids. The goal of the present study is to analyze fish swimming behavior in these artificial environments and to explore its implications in the development of new fishway designs. To this end, a set of experiments has been conducted in an indoor full-scale vertical slot fishway model with different cyprinid and salmonid species. Their upstream movements have been recorded with a video camera system and their trajectory has been extracted using computer vision techniques and an artificial neural network. The results emphasize the value of achieving a deeper understanding of fish requirements in these devices and show the potential of the methodology developed to fulfill this objective. Although further research is needed, the results obtained can contribute to develop robust guidelines for future fishway designs.

1 INTRODUCTION

Fish passage over engineering constructions such as dams or weirs is an important consideration in order to maintain healthy fish populations. Well-designed vertical slot fishways can enable fish to overcome these obstructions, restoring the stream continuity and whole fish communities. As several studies have pointed out (Mallen-Cooper and Stuart [10], Silva et al. [16]), the biological objectives of building a fish pass are developing towards the accommodation of all movements of a wide range of species and sizes of fishes. Accordingly, a significant challenge of this objective is designing vertical slot fishways in accordance with the requirements of small fishes or fish species with poor swimming abilities.

Both experimental (Rajaratnam et al. [14], Wu et al. [19], Puertas et al. [13]) and numerical studies (Barton et al. [2], Chorda et al. [5]) have provided a detailed knowledge of the hydrodynamic characteristics in vertical slot fishways. Typically, these devices are characterized by varying flow velocities, with low velocity recirculation regions in contrast to high velocity main flow regions. Besides, these studies have shown that the flow field is highly turbulent with vortices of various sizes and aerated, which constitutes a challenging hydrodynamic environment for fish. Nevertheless, little is known about fish behavior in these conditions, particularly for coarse species such as cyprinids.

One of the main issues is that the fishway may form a velocity barrier to fish migrants. In these devices, fish are generally confronted to zones of high velocity flow that exceed their maximum sustainable swim speeds. Accordingly, fatigue time models are generally used to define performance and to predict passage success. Nevertheless, these models typically include the unrealistic assumption that fish swim at a constant speed regardless of the speed of flow (Castro Santos [4]). Thus, further research is needed in order to verify if poor passage in these devices can be attributed to limits of swimming capacity. Several other hydraulic characteristics such as velocity distributions, eddy size and strength, or turbulence are suspected to be important for effective fish passage, but fish response to variations of these parameters is not well documented (Katopodis [7]).

Another major concern is the large recirculation zones in the pools, characterized by low velocities and reversed flow directions. Visual observations made in large vertical slot fish passes have shown that recirculation regions, which in principle are designed to be resting areas, can become traps for small fish, by drastically increasing the transit times in each pool and thus compromising the clearing of the fish pass (Tarrade et al. [17]). Very few quantitative studies regarding this issue can be found in the literature.

The goal of the present study is to analyze fish swimming behavior in these artificial environments and to explore its implications in the development of new fishway designs. As several authors have pointed out (Silva et al. [16], Kempt et al. [8]), laboratory studies conducted on controlled conditions offer excellent opportunities to gain generic insights into fish behavior. In this case, a set of experiments has been conducted in an indoor full-scale vertical slot fishway model, with three different fish species: brown trout (*Salmo trutta*), iberian straight-mouth nase (*Pseudochondrostoma polylepis*) and iberian barbel (*Luciobarbus bocagei*). One of the main challenges is to fully track the individuals during their ascent in a non-intrusive way. In order to do so, a new technique based on an artificial neural network and computer vision techniques has been developed. With this technique, the path chosen by fish moving from one pool to another and the specific resting zones actually exploited by the fish have been identified. Besides, variables such as swimming velocities, accelerations or transit times have been evaluated for the different individuals.

2 MATERIALS AND METHODS

2.1 Fishway facility

The experiments were conducted in an indoor full-scale vertical slot fishway model at the Hydraulic Laboratory of the Center for Studies and Experimentation of Public Works (Madrid, Spain) (Figure 1). The fishway model consisted of a 20 m long, 1.5 m wide and 1 m deep flume, which contains 11 pools, with the geometric dimensions that are detailed in Figure 2. At the downstream end of the flume, a chamber was designed to introduce the individuals prior to experimentation. The slope of the fishway during the tests was 7.5 % and the water discharge was fixed to 250 l/s.

Figure 1. Indoor full-scale vertical slot fishway model used in this study (left) and detail of the network of video cameras which was installed in the model (right).

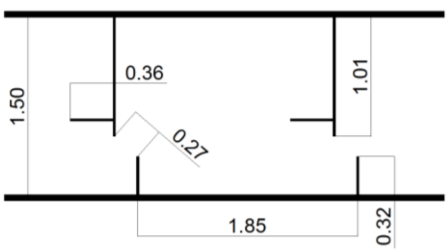


Figure 2. Geometric dimensions of a pool.

In order to continuously track the fish movements in the eight upper pools, the fishway was equipped with a video camera system. A total of 28 cameras (4 per pool) with fisheye lenses that provide a 180º viewing angle were installed. They have been placed in an overhead perspective and partially submerged (for the flow discharge of 250 l/s) so that the entire fishway is covered and turbulence and surface reflections are avoided. The location of the cameras and the structures used to fix them to the fishway are shown in Figure 1.

2.2 Experiments

Three different fish species have been tested: brown trout (*Salmo trutta*), iberian straight-mouth nase (*Pseudochondrostoma polylepis*) and iberian barbel (*Luciobarbus bocagei*) Both the trouts and nases were hatchery-reared individuals, whilst the barbels were captured at the River Cofio (tributary of Alberche River, Tagus basin, Spain).

Experiments are carried out only during the natural reproductive period of these species, i.e., December-February for trout, April-May for nase and May-June for barbel. Accordingly, fish experiments took place the 3rd of February 2010 (brown trout), the 6th of May 2010 and the 14th April 2011 (nase) and the 20th of May 2010 and 19th of May 2011 (barbel). Water temperature during the experiments was 14.4ºC (02/03/2010), 18.4ºC (05/06/2010), 19.2ºC (04/14/2011), 18.9ºC (05/20/2010) and 20.8 ºC (05/19/2011), respectively.

In each test, groups of 12-25 fish were introduced in the downstream chamber and were allowed to ascend the fishway of their own volition during 24 h, at least 6 h of which were recorded with the video camera system. The length of the fish ranged from 15 to 25 cm for trout, from 10 to 20 cm for nase, and from 30 to 35 cm for barbel. Two size-classes were considered for trout (small specimens between 15 and 20 cm, large specimens between 20 and 25 cm) and nase (small specimens between 10 and 15 cm, large specimens between 15 and 20 cm), and approximately half of the individuals corresponded to each class in the tests.

2.3 Fish behavior analysis

This section examines the method to extract the fish trajectory from the images taken by the recording system. The technique is summarized below, although a complete description can be found in Rodríguez et al. [15]. Subsequently, the procedure for obtaining other variables of interest to assess behavior, such as fish velocities or accelerations, is also explained.

The first step of the technique is the design of a projective model for the integration of the images recorded by different cameras into the global coordinate system of the fishway. Once this transformation has been defined, the images are segmented, i. e., the area occupied by the fish is separated from the rest of the image or background using a type of artificial neural network (ANN) known as Self-Organizing Map. Finally, these ANN-segmented areas corresponding to a fish in the image are identified and the fish mass center is estimated using computer vision techniques.

As a result of this process, the fish position on the fishway over time is obtained, which leads to the definition of a position vector, as follows:

$$\left[(x_{t0},y_{t0}),(x_{t1},y_{t1}),\ldots,(x_{ti},y_{ti}),\ldots,(x_{tN},y_{tN})\right]_{\min(\Delta t)=0.04s} \qquad (1)$$

Where x_{tN} is the x coordinate of the fish in the global coordinate system in time t_N and y_{tN} is the y coordinate of the fish in the global coordinate system in time t_N. The minimum time increment between two consecutives fish positions is established in 0.04 s due to the selected recording frequency (25 Hz).

From the fish position vector, the observed instantaneous velocities are obtained, considering the direction vector defined by two consecutive fish positions and calculating its norm according to the following expression:

$$V_{obs} = \frac{\sqrt{(x_{ti}-x_{ti-1})^2+(y_{ti}-y_{ti-1})^2}}{t_i - t_{i-1}} \qquad (2)$$

Where V_{obs} is the fish observed speed vector norm.

However, the observed velocities are not really those which quantify the real effort made by fish to swim. In order to calculate the actual swimming velocities, the water velocity in the pools must be taken into account, as follows:

$$\overline{V}_{nat} = \overline{V}_{obs} - \overline{V}_a \tag{3}$$

Where V_{nat} is the fish swimming speed, V_{obs} is the fish observed speed and V_a is the flow velocity. It should be noted that the velocity field in the pools was computed with a numerical model based on the 2D depth averaged shallow water equations. The experimental validation of this model in 16 different fishway designs can be found in Bermúdez et al. [3].

Once the fish swimming velocities are known, their instantaneous acceleration (A_i) is calculated according to the following expression:

$$\overline{A}_i = \frac{(\overline{V}_{nat})_{ti} - (\overline{V}_{nat})_{ti-1}}{t_i - t_{i-1}} \tag{4}$$

Finally, the way fish use the different zones in the pools is discussed, focusing on the specific resting areas actually exploited by the fish during the experiments. The analysis relates the position vector of each individual (defined by Equation (1)) to the kinematic characteristics of the pools, and determines whether fish use particular zones in pools more than any other. The frequency of use and the average resting times of the different zones are evaluated.

3 RESULTS AND DISCUSSION

3.1 General performance

This section provides a general description of the behavior of the different individuals in the fishway. On the whole, both trout and barbel exhibited a high capacity to negotiate the fishway. The individuals avoided high-velocity areas and used recirculation regions, in which velocity and turbulence levels are lower, to move within the pool and for resting before ascending through the higher velocity area of the slot. Despite the high transit times observed in these recirculation regions for some individuals, no signs of disorientation and no fall back movements were detected in the recordings.

In the case of nase, however, the individuals appear to experience greater difficulties to traverse the fishway. Like trout and barbel, nases spent most of the time in recirculation areas. Nevertheless, a high rate of fall back movements, which carried them down to a previous pool, was observed for this species. This can be a response to fatigue, due to their limits of swimming performance, or other factors such as disorientation in the recirculation areas.

Overall, larger trout individuals presented a higher rate of success in ascending the entire fishway, relative to small specimens of this species (63% vs. 36%). The same is observed for nase, although the values of the success rate are much lower (8% for small specimens and 24% for large specimens). Finally, the passage success for barbel between 30 and 35 cm stands at 41%. Nevertheless, these results should be taken with caution due to the limited number of specimens and the specific conditions of the tests. In particular, Lara et al. [9], after conducting similar tests with lower flow discharges, found a higher passage success rate and contemplate the possibility that the flow discharge might have a significant influence on the results. Further research is needed to verify this point.

As explained above, the methodology is focused on identifying the path chosen by fish to move from one pool to the next one, and the use of the different zones within the pools. In the experiments with trout, a total of 24 pool ascents and 54 resting periods, corresponding to 8 different individuals, were selected from the recordings and subsequently analyzed. On the other hand, 11 pool ascents and 54 resting periods of 14 different nases, as well as 50 pool ascents and 70 resting periods of 11 barbels, were examined.

3.2 Recirculation regions

Recirculation regions are characterized by low velocity and turbulence levels, which implies that energy expenditures to maintain fish position are typically lower in these areas (Pavlov et al. [12]). Accordingly, the more limited fish swimming abilities, the higher transit times are expected in these areas. Nevertheless, it is believed that residence in an area of large scale turbulence (in this case, several times the size of the fish) for enough time will cause the fish to become disoriented, lose equilibrium and have a reduced swimming capacity (Odeh et al. [11]).

In order to evaluate fish transit time in these zones, it is necessary to define exactly the area that they cover. The separation between the main flow and the recirculation regions has been defined coincident with the 0.40 m/s contour, and it has been verified that the turbulence levels in these areas are also very low (Figure 3). Subsequently, the recirculation areas have been divided into three regions (namely A, B and C), depending on the location within the pool (Figure 4). Regions A and B are located in the upstream part of the pools, whilst region C is situated in the downstream part. An individual is assumed to be exploiting a resting zone when it remains in one of these areas for more than 5 seconds, so shorter fish displacements through these areas are not considered.

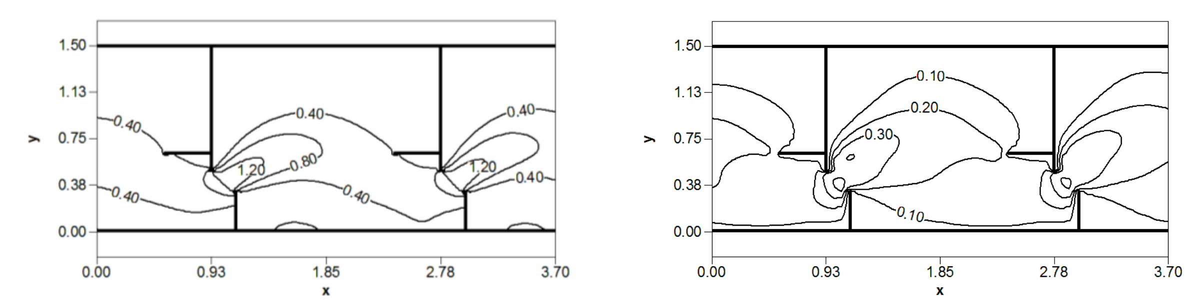


Figure 3. Velocity field (in m/s, left) and turbulent kinetic energy field (in m^2/s^2, right) in the pools computed by the 2D numerical model

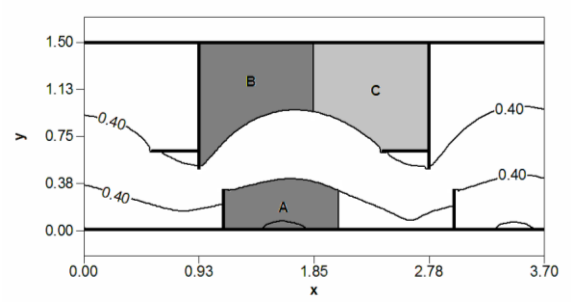


Figure 4. Definition of the recirculation regions. Dark grey areas are the upstream regions A and B, while the light grey area is the downstream region C

Low-velocity areas were not frequented uniformly by fish, which stayed most frequently in the zone located just downstream from the slot and behind the small side baffle (zone A). The frequency of brown trout using zones A and B was 57.4 % and 42.6%, respectively, with an average residence time of 411 s and 413 s. The individuals of trout do not remain in the zone C for more than 5 seconds, so it is assumed that they are not using this zone as a resting area. In the experiments with nase, resting periods were mainly only observed in zone A, with an average residence time of 389 s, and zones B and C were rarely used (only one resting period was analyzed in each area). Finally, the frequency of barbel using zones A and B was 51.4 % and 44.3 %, respectively, with an average residence time of 118 s and 179 s. As in the case of trout and nase, the individuals almost never remain in the zone C for more than 5 seconds.

Table 1. Exploitation of resting areas for the three species. Note: σ is the standard deviation.

	Frequency of use (%)			Resting time (s)							
	Zone A	Zone B	Zone C	Zone A		Zone B		Zone C		Global	
				Average	σ	Average	σ	Average	σ	Average	σ
Trout	57.4	42.6	0	411	424	413	406	0	-	412	412
Nase	96.3	1.9	1.9	389	419	11	-	52	-	376	417
Barbel	51.4	44.3	4.3	118	188	179	334	36	5	141	261

As shown in Table 1, the standard deviation values for the resting times are high, regardless of the species. In the experiments, the resting times for trout vary from only 23 s up to 2053 s. Similarly, resting times in the range 6 s - 2084 s and 5 s - 1668 s have been analyzed for nase and barbel, respectively. Despite these high transit times, no signs of disorientation were observed in the recordings for trout and barbel, which continue their ascent without significant problems once they leave these areas. However, in the case of nase, several fall back movements were observed, which could be attributed to this cause.

Both the trout and barbel showed an almost identical frequency of use of zones A and B. In the case of trout, the distribution of resting times between both areas was very similar. Although barbel also used more frequently zone A, their average resting time was slightly lower in this zone than in zone B. Finally, de individuals of nase used almost exclusively zone A to rest, with an average resting time in accordance to the values obtained for trout.

Consequently, the recirculation regions located in the upstream part of the pools seem to play an important role in fish passage. More precisely, the area located downstream the small lateral baffle shows a very high frequency of use for the three species. By contrast, fish transit times in the recirculation regions located in the downstream area are minimal and, in general, these areas are barely used by the individuals.

3.3 Pool ascents

In this section, the pool ascents of the three species have been analyzed. It should be noted that, given the limited number of pool ascents and the complexity of the phenomenon which is being studied, the main objective of this section is to show the potential of the proposed methodology. Thus, the values and parameters obtained must be taken with caution.

In general, two modes of successful ascents were observed, depending on the location of the individual within the pool before traversing the slot (Figure 5). In mode 1, fish are located in the resting area A before passing through the slot to the next pool upstream. In some of these cases, fish remain stationary in zone A during a short period, while in the remaining cases they just use this area to approach the slot. In mode 2, fish are located in the recirculation area B, in which they usually have spent several seconds or minutes before moving closer to the water jet and passing through the slot.

In the case of brown trout, mode 1 is the most frequent (it is observed in 66.7 % of the pool ascents which are analyzed), generally with a previous resting period (in 75% of the cases). The same applies in the case of nases, which only rest in recirculation zone A. Finally, the preferred option for barbel is also mode 1 (it is observed in 56.0% of the pool ascents which are analyzed), with a resting period before traversing the slot in 60.0 % of the cases.

Once the trajectory followed by the individuals has been identified, their observed speed, swimming speed and acceleration have been calculated as described in section 2.3. Figure 6 shows an example of results, in which velocities and accelerations (in modulus) are represented as a function of the traveled distance and time spent.

Table 2 shows the average values for the maximum swimming velocities and accelerations, as well as their standard deviation. The maximum swimming velocities are obtained in the slot region, due to the high water velocities that the fish is confronted to in this area. In the case of trout, the average maximum swimming velocity is 1.51 m/s, with a standard deviation of 0.21 m/s. If the maximum swimming velocity is expressed as a function of the fish body length (BL), a range between 10.0 BL/s and 6.0 BL/s is obtained. For nases, the average maximum swimming velocity is 1.47 m/s, with a standard deviation of 0.20 m/s, and the maximum swimming velocities vary from 7.4 to 14.7 BL/s. In the case of barbel, the average maximum swimming velocity is 1.53 m/s, with a standard deviation of 0.29 m/s. If the maximum velocities are expressed as a function of fish body length, the range of variation obtained is 4.4 - 5.1 BL/s.

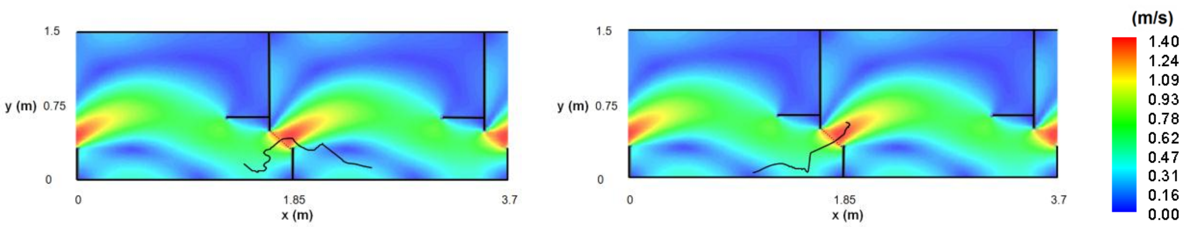
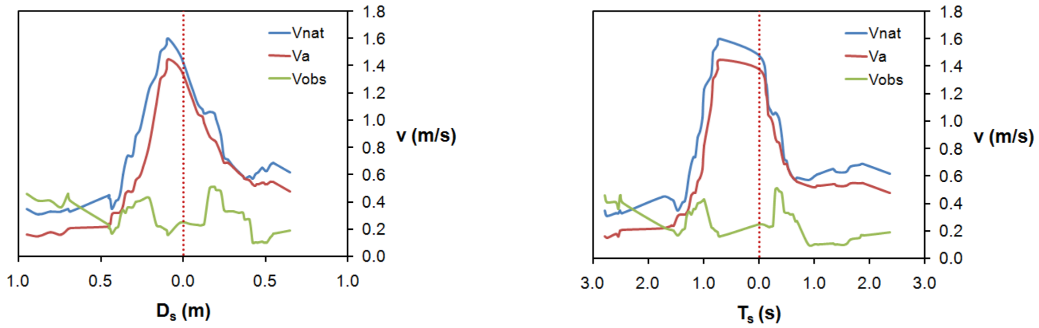
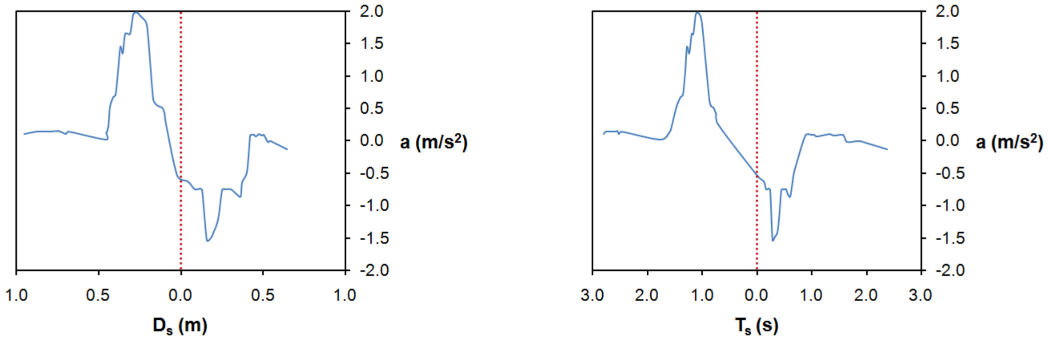


Figure 5. Two examples of successful pool ascents of the tested brown trout, projected onto the map of flow velocities: mode 1 (left) and mode 2 (right).



(a) Fish swimming velocity V_{nat}, fish observed speed V_{obs} and water velocity V_a



(b) Fish acceleration a

Figure 6. Velocities and accelerations calculated for the fish which followed mode 1 trajectory in Figure 5. Note: D_s is the traveled length from the slot section and T_s is the time since the fish traverses the slot.

Table 2. Average maximum swimming velocities and accelerations for the three species.

	Swimming velocity (m/s)		Acceleration (m/s^2)	
	Average maximum	Standard deviation	Average maximum	Standard deviation
Trout	1.51	0.21	1.11	0.68
Nase	1.47	0.20	1.33	0.66
Barbel	1.53	0.29	1.05	0.53

These results are consistent with observations made by other authors on burst speed of salmonids and cyprinids. In the tests with trout and barbel, the value of 10 BL/s proposed by Bainbridge [1] or Cowx [6] as a general rule for fish burst capacity is not exceeded (6.0 – 10.0 BL/s is obtained for trout and 4.4 – 5.1 BL/s for barbel). On the contrary, in the case of nase, the high velocity values that are needed to traverse the slot in relation to their body length (up to 14.7 BL/s, well above the burst speed range between 4 and 9 BL/s proposed by Webb [18] for cyprinids) could explain their difficulties in negotiating the fishway.

4 CONCLUSIONS

In this study, we propose a methodology to analyze fish swimming performance in an experimental full-scale vertical slot fishway model. The methodology, which uses an artificial neural network and computer vision techniques, is applied to five different experiments with brown trout, iberian straight-mouth nase and iberian barbel, respectively. In the tests, the methodology allowed reconstructing the fish trajectory and identifying the zones actually exploited by the fish. Additionally, it was possible to calculate fish velocity and acceleration when moving from one pool to the next one.

Thus, the results show the potential of the methodology to explore the implications of fish swimming behavior in the development of new fishway designs. Although further research is needed (larger number of fish and species, variations in flow discharges, etc.), this approach can contribute to the evaluation of fish response to different hydraulic characteristics, the definition of key factors on fish movements, and the improvement of the existing models used to predict passage success. Essentially, the results provided by this methodology can facilitate development of biological response curves between fluid properties such as velocity or turbulence shear stress and possible biological effects such as disorientation or passage success. Consequently, they can contribute to develop robust guidelines for future vertical slot fishway designs.

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