Wedge-shaped Blocks: A Historical Review

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ABSTRACT

The article aims to be an introduction to the history of the wedge-shaped blocks technology. As it is well known, the WSBs protection system was born in the middle of 20th century in the former Soviet Union. Even though its basis of operation remains, relevant studies have been yielded in order to apply this kind of protection in real cases. Besides, direct application in several case studies has shed some light on practical difficulties and the need of new technical criteria to overcome them. Thus, applied research has been developed in countries such United Kingdom, USA, Portugal, and Spain, among others. The article consists of three parts. It commences with a brief summary of some relevant research and development studies. Afterwards, a description group of case studies of stepped block spillways is included. Finally, the article ends with a short compilation of the state of the art of the current design criteria.

Keywords: Wedge block, overlapping, embankment, overtopping, protection.

1. INTRODUCTION AND BACKGROUND

The objective of this keynote paper is to provide a historical review of wedge-shaped blocks (WSBs) as a possible alternative either to protect embankment (or rockfill) dams against overtopping or to build emergency or service spillways in such type of dam. The paper is focused not only in the WSB as a single unit, but also on the concept of embankment protection and WSBs in spillways. In addition, some comments, suggestions and discussions about some critical issues for its practical application have been included herein to pose an open debate about the future of this very promising technology.

As it is well known, the applied research developed at the Moscow Civil Engineering Institute (MCEI), in the former USSR, by the Professors Gordienko, Pravdivets and Slissky, among others, is the documented origin of the WSBs. These first studies in this field established the benefits of overlapping units (wooden boards) for improving the stability of embankments against scour caused by high velocity flows (Gordienko 1967). Studies continued by testing at the Hydroproject Research Centre in Volgograd (Grinchuk et al. 1977) new protection types consisting of precast concrete slabs ($1x1m^2$ and $2x2m^2$) joined by chains.. These early efforts were the seed of the very first patented prototype of WSB and were the commencement for additional research and development accomplished around the world thus far (Grinchuk and Pravdivets 1977; Pravdivets 1980; Pravdivets and Slissky 1981; Krest'yaninov and Pravdivets 1986; Pravdivets 1987; Pravdivets and Bramley 1989). Unfortunately, the political restrictions for dissemination of any information outside the USSR during the decades of 60s and 70s prevented or delayed the publication of these initial studies. Thus, the laboratory tests, prototype applications and research studies were not available to the international technical community at that time.

Due to the *glasnost* period in the 80s, a remarkable change occurred in the former USSR. The new political state allowed occidental researchers access to the Russian studies related to WSB technology. Consequently, in August of 1989, Dr. Raymond Baker and Mr. Richard May (May and Baker, unpublished report, 1989) visited Prof. Pravdivets

in Moscow, and a stable collaboration began to deepen the knowledge about WSBs. As a consequence, new research was developed by the Construction Industry and Information Association (CIRIA) in the United Kingdom. Such work resulted in one of the most important technical reference about WSB to date: the design manual *Design of stepped-block spillways* (Hewlett et al. 1997). Prior to that time, Dr. Baker had defended his PhD Thesis that compared the behavior of different solutions to prevent scour in high velocity flows using precast concrete blocks. This research was funded also by CIRIA and involved experimental research in prototype conditions (Baker 1992). In particular, Dr. Baker concluded the following: "*Wedge shaped blocks offer the best design for primary spillways because their shape is inherently stable at very high discharge intensities. Model tests suggest that a 100 mm average thickness block could withstand 20 m³/s/m*".

In the 90s, these first advances were followed by new thorough studies in the USA that were conducted by, among others, the US Bureau of Reclamation (Reclamation) and the Colorado State University (CSU). These studies included different near-prototype scale tests and, as a result, a detailed hydraulic characterization could be done (Frizell et al. 1991; Frizell and Ruff 1995; Frizell 1992; Frizell and Ruff 1993; Frizell et al. 1990; Frizell 1997a; Frizell 1997b; Frizell et al. 1994; Slovensky 1993; Gaston 1995). The success of such investigations, conducted by the team of Mrs. Kathleen Frizell, include securing a US patent of the WSB termed *Armorwedge^TM*. A scaled WSB unit, which was designed according to this patent, was used at a service spillway of a rockfill dam for the first time (Frizell et al., unpublished manuscript, 2007).

During the last two decades, new significant knowledge advances regarding WSB performance have been achieved. In Portugal, Prof. Antonio Pinheiro from *Insituto Superior Técnico* (IST) has conducted a PhD Thesis on WSB spillways over embankment dams (Pinheiro and Fael 2000; Relvas and Pinheiro 2008) and also a specific study about considerations of the economy savings of this kind of spillways (Custódio 1999). In Spain, the SERPA research group of the Technical University of Madrid (UPM), led by Prof. Miguel Á. Toledo, has patented a new design of WSB unit in 2016. Such group is currently working on new research about topics such the dynamic response of the new block, new construction materials to improve impact resistance of the blocks and also new design criteria about drainage layers of WSB spillways (Caballero et al. 2015; Salazar et al. 2013; Moran et al. 2013).

Currently, the Federal Emergency Management Agency (FEMA) of the US Department of Homeland Security considers the WSBs system as an option for protecting embankment dams against overtopping. However, the few case studies and the lack of information about the mid- and long-term behavior suggest caution in application and to be limited to low hazard potential dams in USA (FEMA 2014). The author could not find guidelines or technical regulations about the limits of use of this technology in other countries.

Furthermore, the WSB technology has taken advantage of the studies on stepped spillways hydraulics, and many conclusions are applicable in practice (Essery and Horner 1971; Matos 1999; Pinheiro and Fael 2000; Sánchez-Juny et al. 2008; Chanson 1994; Chanson 1996a; Chanson 1996b; Chanson and Toombes 2002; Chanson 2006; Yasuda et al. 2001; Fratino 2004; Chamani and Rajaratnam 1999; Chamani 2000; Boes and Hager 2003; Mateos Iguacel 1997). However, these studies shall not be discussed herein.

In the following sections the reader will find a summary of state-of-the-art research, case studies, design criteria of WSBs with author conclusions and remarks.

2. RESEARCH AND DEVELOPMENT

The WSB experimental research can be grouped in three different categories. The first group studied the block as singular unit or with only a few adjacent blocks. Some studies were performed using outdoor facilities at nearly prototype scale. The second group of studies included tests of the WSBs trying to replicate the longitudinal profile of the spillway channel with different widths. Such tests were accomplished at a small scale, by placing small units (MCEI, LNEC), or in nearly prototype conditions (CSU, UPM). In some cases, like Kolyma Dam and Brushes Clough case studies, experimental tests were performed at the dam itself. Such cases will be treated in section 3. Most studies included in both groupings are focused on the hydraulic behavior of overlapping and butt-jointed WSBs, termed in this article as WSB/O and WSB/BJ, respectively. The third group of studies usually reproduce the entire spillway in laboratory conditions, at a certain model scale, to verify its correct operation as a whole: inlet structure, stepped channel, and energy dissipater. These tests usually replicated the spillway channel as a rigid stepped surface (RSS).

The main data from laboratory tests are summarized in Table 1. Such table has been performed by updating the information from previous authors (Hewlett et al. 1997; Relvas 2008) who followed an analog criteria to organize the most relevant data. The table intends to be classified chronologically. Figure 1 shows some of the parameters and variables used in Table 1. Additional parameters are subsequently identified.

Table 1. Summary of the laboratory tests

Ref.	Type	L	B	t_a	L_o	Δ	s	W	s_s	H	q	SM
MCEI	-	-	20	3-6	20	-	0.10	-	-	-	0.10	30;50
MCEI	-	-	30	5.1	40	-	0.20	-	-	-	-	100;120
MCEI	WSB/O	25	20	7*		2.5*	0.35	0.18	V	0.317	0.10	100
MCEI	WSB/O		22	8*	28	4*	0.35	0.18	V	0.317	0.10	100
MCEI	WSB/BJ	-	-	21.2	89	18	0	0.46	V	-	-	-
MCEI	WSB/BJ	-	-	22.3	79	15	0	0.46	V	-	-	-
MCEI	WSB/BJ	-	-	23.9	62	12	0	0.46	V	-	-	-
MCEI	WSB/BJ	-	-	25.4	46	9	0	0.46	V		-	-
IHE	-	-	-	-	-	-	0.25	-	-	-	-	6;10
Kolyma Dam	WSB/O	-	200	40*	200	-	0.40	-	V	5.0	2.85	10
Noori	WSB/BJ	63.5	63.5	12.5*	63.5	13*	0.20	-	V	-	0.156	-
Jiang	WSB/BJ	63	63	12*	63	12*	0.20	-	-	-	0.180	20
Jiang	WSB/BJ	53	53	18.5*	53	13*	0.25	-	-	-	0.241	40
El Kashab	RSS	-	-	-	40	4*	0.10	-	-	-	-	-
El Kashab	RSS	-	-	-	65	13*	0.20	-	-	-	-	-
El Kashab	WSB/BJ	26	24	8	24.2	3	0.21	-	-	-	0.10	-
El Kashab	WSB/BJ	26	24	8	24.2	3	0.083	-	-	-	0.10	-
Clopper	WSB/O	203	203	102	158	44	0.50	1.22	V	1.8	1.94	-
Clopper	WSB/O	203	203	102	158	44	0.33	1.22	V	1.8	2.07	-
CIRIA	WSB/BJ	50	50	17	50	12	0.40	0.60	V	4.0	0.50	6
CIRIA	WSB/O	30	25	8.5	25	4.5	0.40	0.60	V	4.0	0.50	12
CIRIA	WSB/O	60	50	17	50	9	0.40	0.60	V	4.0	0.50	6
CIRIA	WSB/O	180	150	50	150	31	0.40	0.60	V	4.0	0.50	2
CIRIA	WSB/O	240	200	60	200	40	0.286	-	V	-	-	5
Frizell	RSS	-	-	-	102	51*	0.50	0.46	V	4.72	1.09	-
Frizell	RSS	-	-	-	104	33*	0.50	0.46	V	4.72	1.09	-
Frizell	RSS	-	-	-	106	24*	0.50	0.46	V	4.72	1.09	2.7
CSU	WSB/O	373	610	92	297	64*	0.50	1.52	V	15.2	2.94	-
Kumar	RSS	-	-	-	72	12*	0.167	1.25	V	0.78	0.11	16.76
LNEC	RSS	-	-	-	-	-	0.5	0.80	0.5	0.80	0.082	25
CSU	WSB/O	457	304.8	90.5	380	75	0.5	1.22	V	9.0	3.94	-
IST	WSB/O	240	200	50	200	40	0.4	0.675	0.66	2.5	0.361	-
IST	WSB/O	240	200	50	200	40	0.4	0.60	V	2.5	0.361	-
IST	WSB/O		80	20	80	16	0.4	0.27	0.66	2.25	0.184	-
UPM CEDEX	WSB/O	243.3	165	46.55	203.3	40	0.5	0.50	V	4.7	0.24	-

*values were not measured perpendicular to the direction of the channel slope

In Table 1, Ref., is the reference or name of the facility, Type, represents the type of WSB, W is the channel width, s_s is the slope of the channel sides, V is the vertical side walls, H is the vertical drop available at the facility, q is unit discharge, and SM is geometric scale of the model (1 real: SM model). Units: L, B, t_a, L_o and Δ, in millimeters. W and H, in meters. q in m^2/s.
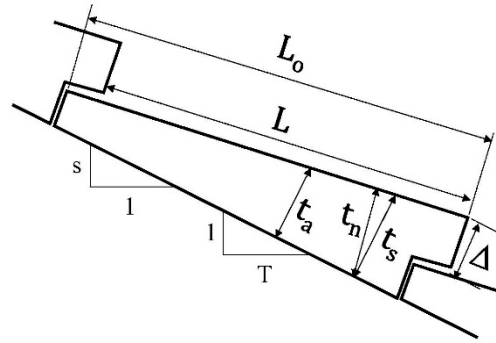
Figure 1. Main geometry parameters of a WSB unit of width B

The description of the most relevant advances achieved on experimental research are summarized in the following sections.

2.1. MCEI (Russia)

Experimental testing began at the Hydraulics Laboratory of the MCEI. The general aim was to explore cost-effective alternatives for conventional spillways of embankment dams. According to first estimations, the cost saving of a WSB spillway could be as much as 60% from a typical solution built with reinforced concrete at the abutment of the dam. After the visit to Moscow, Prof. Baker briefly describes the work of research and development undertaken by Prof. Pravdivets from 1974 (May and Baker, unpublished report, 1989). This work included hydraulic and hydrodynamic model studies of embankment dams protected by scaled WSBs (1:30, 1:50, 1:100 and 1:120) with prototype unit flow up to 100 m^2/s and average thickness of the WSB up to 0.50 m (Figure 2). As a direct result, the very first design curves of the WSB units were accomplished (Figure 3). Such curves estimate the average WSB thickness, t_a, for different embankment slopes (s) (see Figure 1) depending on the design unit flow, q. They were applicable for WSBs placed on the spillway channel under conventional skimming flow conditions for a safety factor of about 1.5.

Figure 2. Test of WSBs protecting a coarse sand embankment under overtopping and seepage flow at the laboratory of MCEI (courtesy of Dr. Raymond Baker)
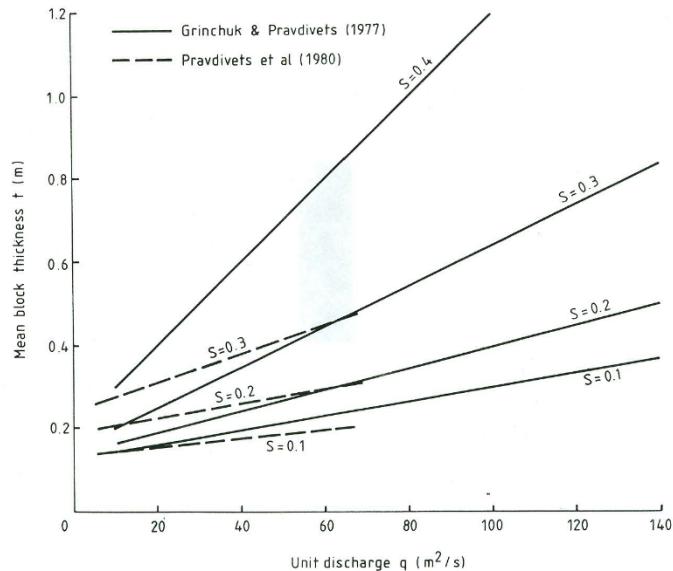
Figure 3. Design curves developed in Russia for WSBs under skimming flow conditions (Bramley et al. 1989)

Prof. Pravdivets also supervised research studies by students Mr. N.D. Shon and Mr. M.E. Lunatsi (unpublished). Both students focused on the performance of the WSBs under hydraulic jump conditions. As it was observed, the combination of the high turbulence developed in the hydraulic jump as well as inadequate drainage (subgrade flow under the WSBs) made the protection system unstable. Therefore, different criteria should be followed to size the WSBs at the toe of the embankment in order to withstand hydraulic jumps. Mr. Shon tested two different types of WSB over a slope of 0.5 with a horizontal bottom at the toe. Meanwhile, Mr. Lunatsi tested a double WSB unit in a horizontal channel for Froude numbers between 4.5 and 5.6 and concluded that this longer block improved stability and a reduction in stilling basin length could be achieved.

As it will be showed in the section dedicated to case studies, the theoretical and experimental conclusions obtained at model scale at the laboratory could be validated in prototype conditions, which gave the work at MCEI a significant value as well as reliability about its eventual application.

2.2. Universities of Southampton (UK), Tong Ji (China) and King Faisal (Saudi Arabia)

The first studies outside USSR were developed by Mr. B.M. Noori for his PhD Thesis at Southampton University (Noori 1985). According to Relvas (Relvas 2008) and Slovensky (Slovensky 1993) he performed two sets of experimental tests. The first consisted of a rigid stepped surface to obtain conclusions regarding the friction factor. The second was aimed to test WSB without overlap but joined by metallic connectors. These blocks failed for a unit discharge of 0.156 m^2/s due to the mass slide of the saturated sand where they were placed.

There is a reference of a research study at the University of Tong Ji (Jiang 1985); however, available information is limited. According to CIRIA and Relvas (Relvas 2008; Hewlett et al. 1997) the tests made by Jiang were performed on WSBs without overlap using aluminum units.

The research studies at King Faisal University (El-Khashab 1986; El-Khashab et al. 1987) compared different types of protection against scour induced by high velocity flows. The performance of concrete blocks were based on tests with fixed strips and three different block shapes, namely: cylinders, rectangular prisms, and a particular geometry of WSB without overlapping. Such WSBs were vertically chamfered at upstream corners and interlocked between consecutive rows (Figure 4). The main conclusion of this study was that the WSB system was the most reliable among all tested protections. The available discharge at the laboratory was not sufficient to produce scour on the tested slopes (*s*) of 0.08 and 0.21 with this type of protection.
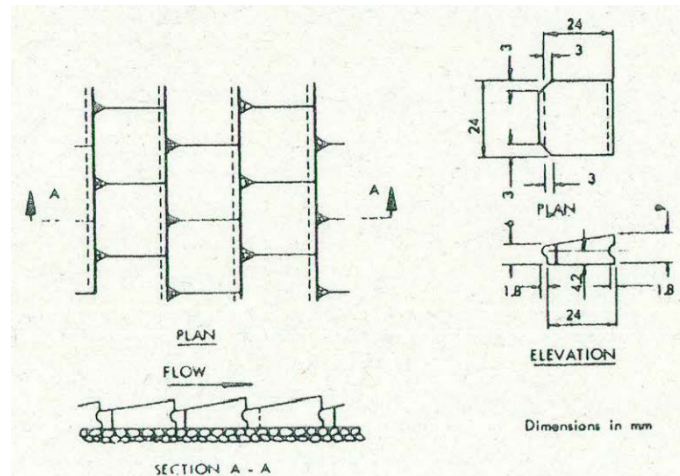
Figure 4. WSB protection tested at King Faisal University (El-Khashab et al. 1987)

2.3. University of Salford and CIRIA (UK)

The successful application of WSBs in USSR garnered interest from researchers at the University of Salford and at CIRIA. This fact was determinant to maintain the effort of technical development as well as disseminate the technology all around the world. The PhD Thesis of Prof. Baker mentioned the state-of-the-art at that time. It consisted in a literature review (Baker 1992) of the papers translated from Russian by Mr. Richard May and Reclamation and a personal contact between Prof. Pravdivets and British researchers (May and Baker, unpublished report, 1989). Thus, a new research effort was made, including new laboratory tests at Salford and large scale tests in Fort Collins at CSU. Previously, Prof. Baker had performed full-scale tests of different type of protections (none of them was WSB) in nearly prototype conditions at the reservoir called Jackhouse site (Figure 5).

Figure 5. Experimental setup of field tests of different scour protections at Jackhouse site (Baker 1992)

Specifically, the WSB system was studied by Baker in laboratory conditions at Salford University (Figure 6 left). The ramp of the testing facility was 0.6 m wide and 4 m high with a slope (*s*) of 0.4, i.e. 2.5H:1V. The setup of the bottom of the upstream part of the testing channel was built with fixed strips in order to accomplish a flow pattern of a stepped bottom. So, the testing area for WSBs was at the downstream portion of the channel. The maximum available flow was 0.5 m^2/s. Three different sizes of overlapping WSBs (Figure 6 right) were used.

Figure 6. Experimental set up (left) and sizes of the WSBs (right) tested in Salford University (Baker 1992)

The main conclusions can be summarized (Hewlett et al. 1997) as follows:

1. Every block was tested up to the failure discharge according to Russian criteria, but such failure did not occur.
2. An average pressure map was obtained through the pressure measurements in 14 different locations in one of the larger tested blocks (Figure 7)
3. The specific tests carried out to obtain conclusions about the surface of spots and holes on the WSB and the drainage capacity showed that 2.5% of the upper surface produced low uplift pressures. No remarkable differences were found in the test results performed with an open surface of 5%.
4. Lifting tests showed that for increasing unit discharge, a larger uplift force was necessary to lift the blocks from its original positions.
5. The gap size in the longitudinal joints was also studied and it was concluded that minimizing the gap was desirable. It was observed that a higher gap opening induced lower suction effects, reduced friction forces between the blocks, and increased drainage flow.
6. Sliding tests of a panel of blocks without toe restrictions were also performed. It was observed that instability occurred only for low unit discharges. However, it was stable when the discharges were raised quickly from zero. This also occurred for the tests with a missing row of WSB (Figure 8) at high unit discharges: the blocks failed as the discharge decreased.
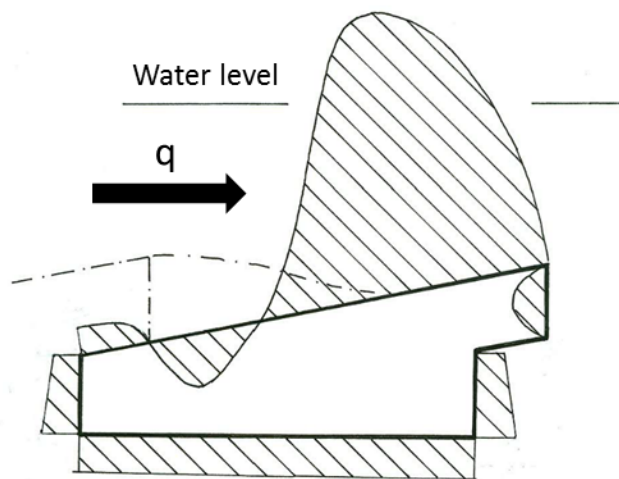

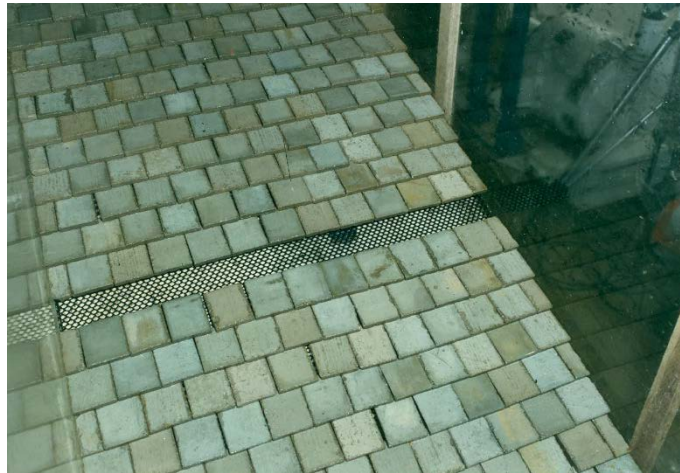Figure 7. Mean pressure distribution around a WSB (adapted from Baker 1992)

Figure 8. Missing row ready for a sliding test (Baker 1992)

7. The length to height step ratio ($L/\varDelta$) was tested as well. The results of the average pressure on the block confirmed the Russian recommendation which posed an optimum value for this ratio between 5 and 6.5. Thus, higher ratios did not allow to develop the roller zone downstream the riser preventing the development of stabilizing low pressures. On the contrary, smaller ratios, made the skimming flow to jump over the downstream rows.

8. The tests carried out under hydraulic jump conditions showed two different failure modes (Figure 9): "*individual blocks vibrating normal to the embankment surface and groups of blocks waving up and down as a panel*". Once again these results confirmed the recommendation of Pravdivets to not allow the formation of hydraulic jumps in blocks designed for free flow conditions.

9. New design curves were posed for blocks under a hydraulic jump. Naturally, the size of such blocks were considerably higher than the units (Figure 3) working under conditions of free surface flow (Figure 3).

10. Additional tests were carried out to study the deflector block at the toe of the WSB channel recommended by Pravdivets. They confirmed the appropriate functioning of this element as long as the tailwater level do not cause a hydraulic jump on the stepped blocks.
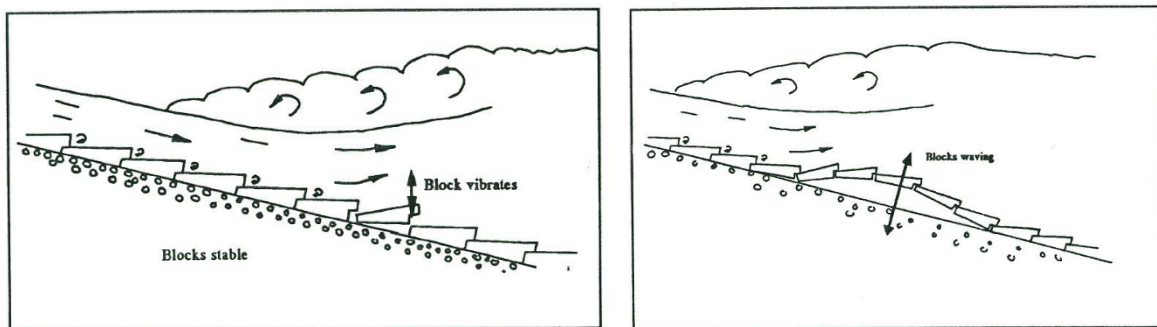

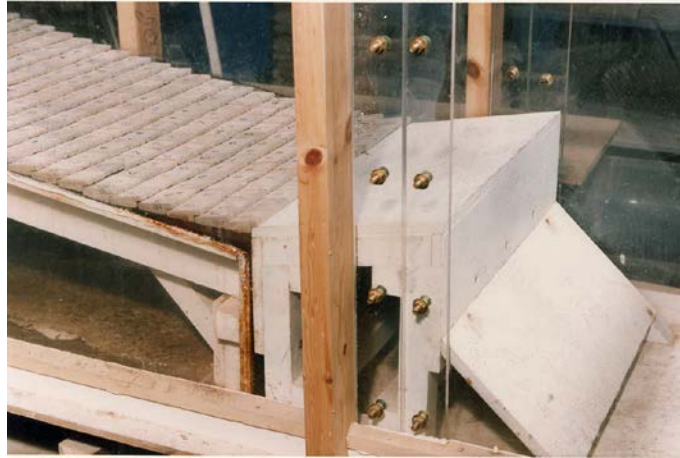Figure 9. Failure modes of WSB under hydraulic jumps (Bramley et al. 1991)

Figure 10. Toe block ready to be tested (courtesy of R. Baker)

All of the abovementioned conclusions, as well as the practical guidelines for design, are thoroughly included in the *CIRIA Special Publication 142. Design of stepped-block spillways* which is still the most complete technical manual for practical applications of the WSB system.

Finally it is known (Meldrum 1995) that the scaled model of the WSBs emergency spillway at Wadi Sahalnawt Dam, which was built in 1991, was also tested at the hydraulics laboratory of the University of Salford but, unfortunately, the author could not find references or details of that study.

2.4. CSU and RECLAMATION (USA)

One of the first experimental research studies with WSBs in USA was promoted by the Federal Highway Administration and performed by Simons, Li and Associates, Inc (Clopper 1989). This work, co-sponsored by Reclamation, USDA Soil Conservation Service, and Tennessee Valley Authority, involve tests performed at the CSU hydraulics laboratory in Fort Collins for different overtopping protections, including WSBs. The channel facility utilized for studies was 1.22 m wide and the protected embankment had the following features: upstream slope 0.5 (2H:1V), downstream slope 0.33 (3H:1V), height 1.8 m and crest length 6.1 m .
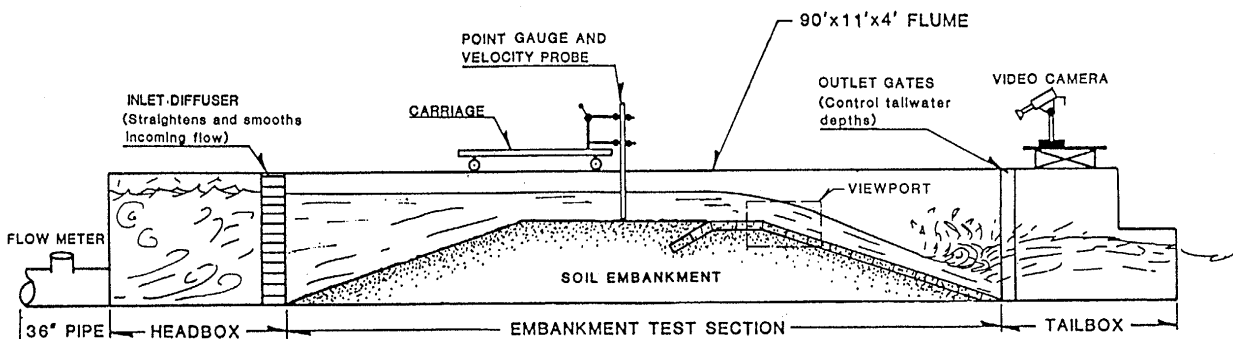

Figure 11. Sketch of the hydraulic testing facility at CSU (Clopper 1989)

The WSBs were placed over geotextile and a geogrid, for drainage purposes. The WSBs were designed according to Russian criteria and tested for hydraulic heads of 1.2 m, which corresponded to a unit discharge of approximately 2.07 m^2/s approximately. Clopper (Clopper 1989) concluded that WSBs were stable under such conditions, i.e. a velocity of 5.2 m/s and a shear stress of 5.2 kN/m^2. However, vertical movements from -2 mm to 3.5 mm were measured after

the tests. According to Relvas (Relvas 2008), citing Bramley and Slovensky (Bramley et al. 1989; Slovensky 1993) these movements could be caused by low value of the ratio (L/Δ) of WSBs: 3.6. After this research, Clopper published a methodology, based on the published by Simons and Sentürk for riprap (Simons and Şentürk 1992), to analyze the stability safety factor of different protecting systems of articulated concrete blocks, including WSBs (Clopper 1991).

After the research studies of Clopper and considering the evidences of the benefits of WSB protection system, not only technically but also economically, both Reclamation and CSU decided to continue focused research efforts. Thus, new experimental research was conducted by Slovensky (Slovensky 1993) and Gaston (Gaston 1995) supervised by Prof. James F. Ruff and technically supported by Mr. Brent Mefford and Mrs. Kathleen Frizell. This new research involved tests in two facilities. The smaller facility was a 0.46 m wide, 4.6 m high channel, with an available unit discharge of 1.3 m²/s. The bigger was an outdoor, near prototype facility, in order to minimize the scale effects (Figure 12). This facility was composed of a 0.5 (2H:1V) slope channel, 15 m high with a maximum unit discharge of 2.94 m²/s. The aims of the research were to study the stability of the blocks as well as to deepen the knowledge of the specific hydraulic conditions of the flow over WSBs. So, it was found the minimum velocity head to develop negative pressures downstream the riser of the WSB. In addition, Frizell (Frizell 1992; Frizell and Ruff 1993) and Slovensky (Slovensky 1993) quantified the benefits of drainage for the WSB stability and the predominant effect of the channel slope on the energy dissipation, being greater dissipation for lower channel slopes (*s*). The near prototype tests showed the increase of the stability as the unit discharge increased. Furthermore, hydrodynamic pressures and air concentrations were measured in such tests. Thus, Gaston concluded that the average air concentration of the flow was 33% for a channel slope of 0.5 (2H:1V) with a reduced influence of the macro-roughness of the stepped bottom. In addition he found that the distribution of the air concentration along a cross section of the stepped channel is independent of the unit discharge, for uniform flow regimes.
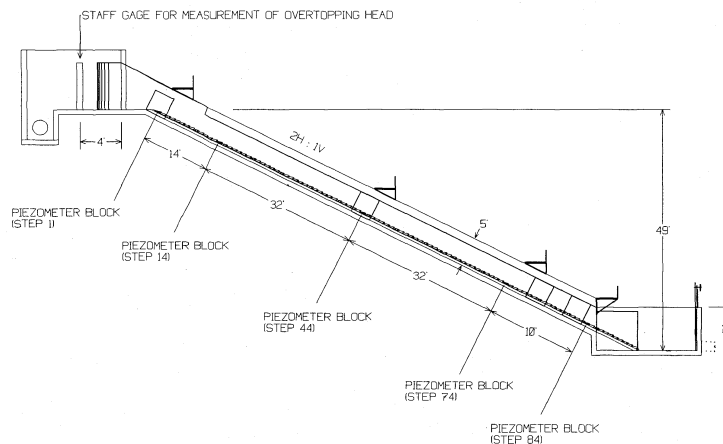

Figure 12. Profile of near prototype facility of CSU (measures in ft) (Slovensky 1993)

Further investigations continued at Reclamation which made possible to obtain in 1996 the so named *Concrete step embankment protection* (U.S. Patent No 5,544,973), commercially termed as Armorwedge™ and initially held by the company Contech®. This company and PYPSA S.L. funded additional research studies in 2006 about this particular WSB (Thornton, unpublished, 2006). However the results of the experimental testing were not published since they were classified as confidential and proprietary by contract.

2.5. IST and Laboratorio Nacional de Engenharia Civil (LNEC) (Portugal)

Prof. Antonio Pinheiro (IST) has conducted research about stepped spillways and hydraulics of WSBs. He also supervised research studies (Custódio 1999) to obtain a numerical model to compare the construction costs between a traditional reinforced concrete spillway, separated from the dam body, and a non-conventional one, using WSBs. The main conclusion of the case studies analyzed was that the WSB spillways achieve a reduction of the cost from 40% to 60% in comparison with the traditional alternatives.

The PhD Thesis of Dr. Antonio J. Relvas, supervised by Prof. Pinheiro, included a detailed state of the art of the technology, plenty of technical references about the WSB system. The research was focused on the characterization of the flow including results about aeration, velocity distribution and friction resistance and comparisons with the formulations of other authors. The experimental facility was composed of two trapezoidal channels (termed C1 and C2. C1R indicated a rectangular cross section of the channel) composed of WSBs of different sizes (C1 bigger than C2) in order to study the scale effect. In addition the Thesis include conclusions about the relation between the spillway discharge, q, and the drainage flow, q_d, and the saturation level, depending on the unit discharge on the spillway. The tests proved that q_d decreased as the values of q were higher.

In addition to this, LNEC has participated in some of the IST research projects holding the experimental facilities in its hydraulic laboratory. LNEC collaborated as well in the Barriga Dam scale model. Such model included the whole spillway, with fixed strips to simulate the stepped bottom of the WSB channel at a geometry scale of 1:25 (Couto et al. 2007). The aim of this model was to study the inlet conditions, the performance of the flip bucket and also to estimate the potential scour downstream, at the river bed.

2.6. UPM and CIMNE (Spain)

During the last 5 years, the UPM, through the SERPA research group (led by Prof. Toledo) in collaboration with CIMNE, has been working in additional research (currently ongoing) on WSBs. The first direct contact of the group with this technology was the technical supervision of the Barriga Dam project. After that experience, it was detected a lack of research work which was considered necessary to deepen the knowledge and so, reduce the uncertainties of this protection system. This research has been funded by the Spanish Government.

The research work has combined experimental and numerical testing (Caballero et al. 2015; Salazar et al. 2013). The experimental facility was located at CEDEX laboratory (Madrid) and included a 0.50 m wide steel and methacrylate testing channel constructed on a 0.5 slope (2H:1V), which provides a 4.7 m vertical drop. Walls were 0.85 m high, measured normal to the base. The facility had a maximum unit discharge capacity of 0.24 m^2/s. On the other hand, CIMNE provided the numerical modeling expertise which complemented the experimental approach. The main result of the first stage of the research was a patent of a new model of WSB (Figure 13), held by the Spanish company PREHORQUI, S.A., CIMNE and UPM. This model is designed to optimize the aeration process, transmitting the negative pressures from the upper zone of the riser to the backside of the block. This patent is being tested at this particular moment to have all the information regarding the pressure distribution along the block surface and the conditions of stability.
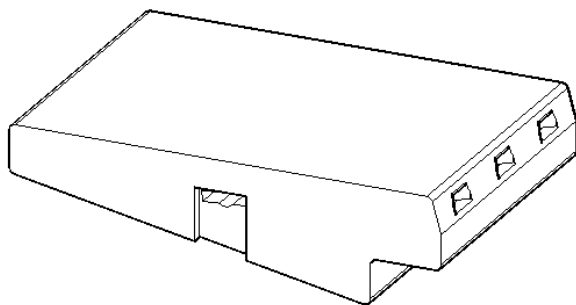

Figure 13. Left, UPM facility at CEDEX laboratory. Right, sketch of the WSB patented in Spain

The second stage of the research, which will be initiated soon, has two general objectives. The first is to study the operation conditions of the drainage layer as well as proposing detailed design guidelines according to its seepage

capacity and the flow balance for the hydraulic conditions of each part of the spillway channel. The second goal is to characterize the hydrodynamic response of the new block and to look for different versions of it, adapted to each part of the spillway channel, depending on the critical combination of flow depth, velocity and pressure distribution.

3. CASE STUDIES

The case studies presented herein consists of emergency (or service) spillways and diversion channels of hydropower installations with high velocity flows. Such cases are divided in two groups. The first corresponds to the prototypes constructed for testing purposes, even though they had an additional use or exploitation. The second one includes case studies of dam spillways which are in service without an explicit interest for research or testing. All the case studies are summarized in Table 2, where more information about them can be found. In the following text only the most relevant cases with available information or pictures are cited explicitly.

The author did not find evidences of case studies of overtopping protection of the entire (or part) of the downstream slope of embankment dams with WSBs.

Table 2. Summary of WSB case studies (geometric units in m, unit discharge in m^2/s)

Case (country)	Type	L	B	t_a	L_o	Δ	s	W_s	s_s	H_s	q_s
Dneiper (Russia)	WSB/O	3.0	3.0	0.8	2.6	0.5	0.154	14.2	0.33	37	-
Dneister (Russia)	WSB/BJ	-	1.0	0.25	1.0	-	0.222	2020	V	7	-
Kolyma (Russia)	WSB/O	-	2.0	0.40	2.0	-	0.5	6.0	0.33	20	5.0
Transbaikal (Russia)	WSB/O	-	-	-	-	-	0.4	115.0	0.33	13	18.0
Jelyevski (Russia)	-	-	-	2.0	0.35	3.0	-	0.125	12.0	0.33	20	-
Jiangshe Wanan (China)	WSB/BJ	2.12	2.12	0.74	2.12	0.52	0.2	-	-	-	-
Wadi Sahalnawt (Oman)	WSB/O	1.2	1.0	0.2	1.0	0.2	0.286	980.0	V	23	5.1
Brushes Clough (UK)	WSB/O	0.725	0.4	0.212	0.59	0.125	0.333	2.0	0.5	17	1.5
Barriga (Spain)	WSB/O	0.73	0.50	0.14	0.61	0.12	0.5	20	0.5	17	7.3
Bruton Dam (UK)	WSB/O	1.20	0.955	0.34	1	0.18	0.25	48	-	9	3.1 to 4.2
Friendship Village (USA)	WSB/O	0.457	0.305	0.09	0.38	0.075	0.5	5 to 2.75	-	18	3.1 to 4.2
Odgen Dam (UK)	WSB/O	1.00	1.00	-	-	-	0.333	32	-	15	-

In Table 2, Case is the name of each case study, Type represents the type of WSB, W is the channel width, s_s, slope of the channel sides, H_s is the vertical drop at the spillway, q_s is the design unit discharge. Units: L, B, t_a, L_o, Δ, W_s and H_s, in meters. q_s in m^2/s.

3.1. Prototypes

Dneiper Power Station (Russia). The spillway chute was placed downstream of a hydraulic gate that regulated flows (Hewlett et al. 1997). The slope of the chute was 0.15 (6.5H:1V). The WSBs withstood a unit discharge of 60 m^2/s. The measured WSB movements were from 2 to 3 cm at zones without loss of filter material of the drainage layer, and

from 50 to 70 cm where the underlying granular material was removed. The measures of maximum hydrodynamic forces were 4.5 t (vertical) and 2 t (horizontal).
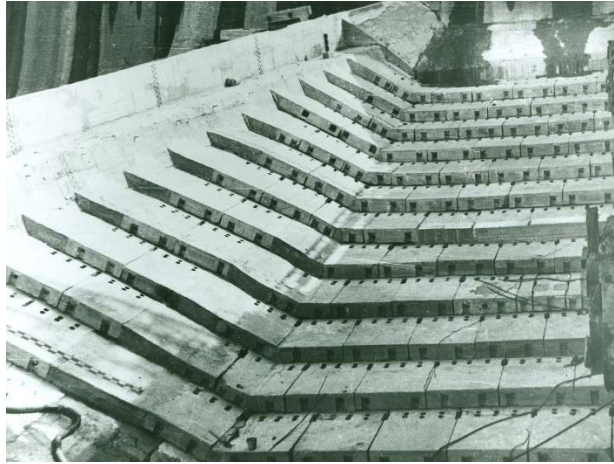

Figure 14. Picture of the chute of the Dneiper Power Station (courtesy of R. Baker)

Dneister Power Station (Russia). A temporary spillway was installed at the cofferdam of the main dam with a protection of WSBs that were 1m x1m and 0.25 m thick. The rest of the downstream slope of the cofferdam was protected by large (4.5m x 10.0mx0.5 m) concrete slabs, anchored to each other. The cofferdam spillway passed a unit discharge of 13 m^2/s successfully (Pravdivets and Slissky 1981).

Auxiliary spillway at Kolyma Dam Project (Russia). The Kolyma Dam is a 135 m high rockfill dam used to generate hydropower (Hewlett et al. 1997). At the time of construction, a project to protect the dam against overtopping was proposed. The design unit discharge was 90 m^2/s. Protection via WSBs was tested but ultimately was not selected for the main dam. Nevertheless, a WSB spillway was built in a small embankment dam that was included in that project (Figure 15). The design unit discharge of this smaller dam was 5 m^2/s.

Figure 15. Picture of the spillway at embankment dam in Kolyma Project (courtesy of R. Baker)

Brushes Clough (UK). Brushes Clough Dam is a small reservoir that is currently out of service. The WSB spillway was intended to be a permanent waterway to avoid storage. It was designed for a unit discharge of 2.2 m^2/s (Figure 16, left). The slope of the channel was 0.33 (3H:1V). The slopes of the trapezoidal channel were built with stone pitching instead of WSBs. The WSB dimensions were 0.4 m wide, 0.56 m long exposed length, with an average thickness of 0.21 m and a riser height of 0.12 m. The upstream face of a single block had a specific geometry to facilitate aeration at the end of the downstream block. Despite the small size of the spillway, the relevance of this case

study is high given that it is the first installation designed with the guidelines and recommendations published by CIRIA (Hewlett et al. 1997). Furthermore, the spillway has been tested and thoroughly monitored to document performance. This case showed one of the important issues to be faced by this technology which is the vandalism. Some of the WSBs were seriously damaged and had to be repaired (Figure 16, center and right) even though their thickness were overdesigned.

Figure 16. Brushes Clough Spillway. Left, downstream view. Center and right, WSBs with damages caused by vandalism (courtesy of R. Baker)

The stepped invert of the spillway channel at its toe was made of reinforced concrete just before the stilling basin (Figure 16, left: first 10 rows from downstream). Testing and monitoring work with controlled discharges (Figure 17) were funded by CIRIA for a period of two years. During this time, the spillway was operated for total discharges up to 1 m^3/s. The tests included measures of WSB movement, pressures, aeration, and flow depths.

Figure 17. In site tests at Brushes Clough spillway (courtesy of R. Baker)

3.2. Service and Auxiliary Spillways

State Farm dams and Jelyevski Dam (Russia). This group of cases involves a several small dams for agricultural supply in Russia with spillways composed of overlapping rectangular slabs but they were not wedge-shaped. The name of these dams were Bolshevik, Maslovo, Sosnovski, Zaraysk and Klinbeldin (Figure 18).

Figure 18. Downstream view of Klinbeldin Dam (courtesy of R. Baker)

The spillway of Jelyevski Dam was the first reported failure case study. This spillway was not built on the downstream slope of the dam but at one of the abutments of the dam site. According to the failure analysis prepared by Pravdivets (Hewlett et al. 1997), the cause of this failure was the undermining of the subsoil composed by clay and sand of poor quality. The diagnosis of Pravdivets was that the material was washed away due to an incorrect design of the filter and drainage layers. He also concluded that quality of subsoils of the WSBs spillways should be controlled.

Wadi Sahalnawt (Oman). The spillway was built on a 23 m high permeable rockfill dam constructed for flood control. It was an auxiliary spillway with a design unit discharge of 5.2 m^2/s (Hewlett et al. 1997; Meldrum 1995). The spillway chute was a 980 m wide rectangular channel limited by vertical concrete walls. The service spillway was a conventional type, constructed with reinforced concrete and its design unit discharge is 12 m^2/s.

This case study is unique due to the high permeability of the material of the dam and also due to the operating conditions, which include seepage flows through the rockfill. The spillway was physically modeled at Salford University to test that no uplift pressures due to seepage could affect the stability of the WSBs. The WSB's dimensions were 1 square m in plan and their average thickness was 0.2 m. They had a specific design to permit a lateral interlock between adjacent blocks within a row.

Barriga Dam (Spain). This was the first installation of a scaled version of the *Armorwedge*[TM] patent (only applicable to installations within the USA) in a service spillway (Morán and Toledo 2014; Morán and Toledo 2015) and the first WSB spillway in Spain. The unit discharge for the design flood was 8 m^2/s while the unit discharge for extreme flood was 11.4 m^2/s. The trapezoidal WSB channel was constructed over the rockfill material of the dam body on a 0.5 slope (2H:1V). Two drainage layers of gravel material of different sizes were placed between the dam body and the WSBs. The crest was composed of a reinforced concrete slab. The toe structure was a flip bucket with large drainage holes in order to isolate the turbulence generated at the plunge pool from the flow in the WSB's channel. The dam has been in operation since 2007 and the spillway has passed some small floods with a maximum unit discharge of approximately 0.5 m^2/s without damages reported so far. The project involved scale models tested at CSU and LNEC (Couto et al. 2007). The CSU tests were performed with smaller units hydraulically scaled to 1.6 geometry factor at the prototype. Moreover, some additional modifications to the WSB were incorporated into the final design used at the dam. An interior hole was added transversely to the block to allow a cable to be introduced into it, to join each WSB with the ones in the same row. This made an additional restriction for the blocks to be pulled out of the revetment due to unforeseen causes. In addition, this hole was useful in the transportation and placement of the blocks in the spillway site. A small convergence of the lateral surfaces were adopted to improve the demolding of the units. The LNEC

scaled model was used to design the inlet and the toe block with hydrodynamic shapes. These tests also estimated the potential scour downstream the flip bucket.
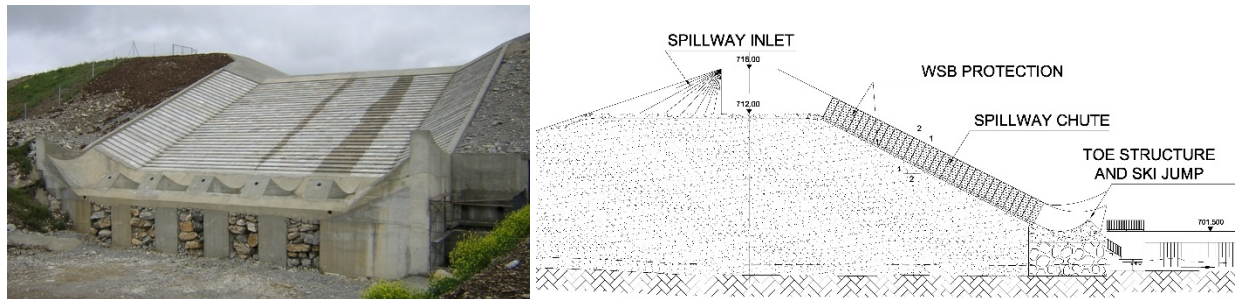

Figure 19. Barriga dam. Left, view from downstream. Right, vertical cross section through the spillway axis.

Friendship Village (USA). The auxiliary spillway of Friendship Village Dam was constructed in 2008 using the *Armorwedge* patent (FEMA 2014). The design unit discharge was 0.92 m^2/s. According to the description included in the FEMA manual "*the ArmorWedge block spillway has a trapezoidal shape with a conventional concrete crest and toe block for stability. The spillway height is about 59 feet. The ArmorWedge blocks were placed over a layer of gravel, underlain by a geotextile placed on the graded earthen slope. The spillway converges through the upper section from 16.5 feet at the crest to 9 feet approximately 100 feet downstream. The spillway invert slope changes throughout this section, going from relatively flat to a maximum of 2:1 near the bottom of the spillway…*". The joint between the invert and the channel slope is discussed by the authors showing that: "*…the [adjacent] blocks are butted up along the joint without any apparent grouting or additional support or structure to prevent a potentially continuous plane for water to flow into the subgrade during operation*". The spillway ended in an energy dissipating basin shared with the service spillway pipe.

Bruton Dam (UK). The Environment Agency of UK presented in the annual report of 2008 (Environment Agency 2009) the construction of a new WSB spillway at Bruton Dam. The former spillway included a protection of cellular concrete blocks (*Petraflex*) which was not considered capable to withstand the expected velocities of 11 m/s. The new WSB spillway was designed for a conservative total discharge of 500 m^3/s (Pether et al. 2009; Pether 2010) given that the PMF discharge was estimated to be between 250-300 m^3/s. The crest of the spillway was designed with a different protection system (*Dycel* blocks) instead of traditional reinforced concrete slabs. The slope of the spillway channel was 0.25 (4H:1V) and the WSBs were installed over a drainage layer and a geotextile. The blocks included a lifting point on its upper surface to facilitate transport to the construction site using mobile cranes. The WSB channel ended in a reinforced concrete toe beam founded by means of sheet piles (FEMA 2014).

Odgen Dam (UK). There is little published information regarding Odgen Dam spillway. The purpose of this project was to increase discharge capacity of the spillway to be able to pass the PMF flood without overtopping the dam (http://pascoe-ltd.co.uk/project/ogden-ir-wedge-block/). The main works at Ogden consisted of the construction of a WSB spillway on the downstream shoulder towards the center of the dam. Construction was completed in 2013 and the design followed the CIRIA guidelines. According to the information published by *Pascoe, P&S Consulting Engineeers, Ltd.*, the spillway is the largest of its type in the UK. The inlet structure is divided into four spans by means of three piers used to support the beams of the bridge at the crest of the dam. The spillway channel is trapezoidal but, as the available pictures show, the lateral slopes consisted of interlocked concrete blocks. The final rows of the channel seems to be constructed using reinforced concrete to make a rigid stepped invert. The toe structure of the channel was a piled reinforce concrete beam, similar to the Bruton Dam spillway. A stilling basin was built downstream of the toe structure for energy dissipation (Figure 20).

Figure 20. Odgen Dam. Left, downstream view. Right, WSBs before the installation (courtesy of P. Thurlwell, from *Pascoe, P&S Consulting Engineeers, Ltd.*)

4. DESIGN CRITERIA FOR WSB SPILLWAYS

In this chapter, a brief summary and discussion of the different design criteria used at the WSB spillways will be done. This is a challenging goal, given that there is only one published reference (Hewlett et al. 1997) of specific design guidelines at the moment. The additional design criteria used so far is based on the experience of particular case studies with successful performance in the few years that they have been in operation. This also adds some uncertainty, since there is a lack of experience regarding long-term performance. The following text is organized into the following subsections:

- General guidelines
- Inlet and crest details
- Spillway channel
- WSB sizing and construction material
- Toe details and energy dissipation

4.1. General guidelines

> "Although the principle of stepped block protection is simple, the design of a stepped block spillway requires careful attention to detail, bearing in mind that any spillway is only as effective as its weakest point. The design can only be partly standardized; every spillway requires competent engineering design input which addresses the specific problems of the particular site"
>
> *(Pravdivets and Bramley, 1989)*

This quote summarizes the key point to be highlighted before any application of this system to projects. After studying the current knowledgebase, it can be concluded that the hydraulic performance of the WSBs in ideal conditions is sufficient. However, additional performance aspects such as the drainage capacity, the toe stability, the internal stability of the subsoil and the energy dissipation downstream of the WSB channel, among others, are areas that may trigger a failure.

WSB spillways have typically been installed over the downstream slope of embankment dams. The material of the downstream shoulder can be either impervious (Brushes Clough, Bruton, Odgen) or highly permeable (Wadi Sahalnawt, Barriga). There are successful cases in both types of material. Although CIRIA Guidelines establish the convenience of installation over impervious downstream shells, experience has shown that rockfill shells are also suitable as a subsoil of the WSB channel. To do so, there must be an absence of uplift pressures from the dam body as well as the both internal and slope stability. In such case, the high permeability of the rockfill helps to drain the flow from the spillway seepage, which is considered positive for the stability of the WSBs. Nevertheless, placement of the spillway channel in potentially erodible natural soils, which have not passed construction quality controls, can

be washed out by the drainage flows. Precisely, as abovementioned, this issue was the main cause of the only failure registered in this type of spillways (Jeylevski Dam).

The WSB spillways over embankment or rockfill dams usually maintain the same longitudinal slope. It should be noted that there is not experience of tests or case studies of spillways installed over slopes greater than 0.5 (2H:1V). So, additional studies should be done to confirm the overall stability for typical rockfill slopes, up to 0.7 and even higher. It is also generally accepted that the longitudinal axis of the spillway in plan has to be straight from the crest to the toe in order to minimize shockwaves.

Another important issue is to identify the design conditions that can limit the use of this type of system. So far, the published guidelines recommend a limit for unit discharges in a spillway. Thus, the CIRIA guideline indicates on its scope a conservative design limit of up to 2.0 m^2/s although it may accept less conservativism (higher unit discharges) if a project has the participation of experienced engineers. Similarly, FEMA established a limit of 3.9 m^2/s for overtopping protections. However, this limit may also be conservative in some cases as the experience of research tests and case studies did not show evidence that higher values could cause a failure of the system. Hence, more research is needed to establish the thresholds of the critical variables (unit flow, flow depth, velocity) and their limits to establish appropriately conservative limits or detailed guidelines.

4.2. Inlet and crest details

The inlet structure is typically located at the dam crest. At the selected place, the upper part of the dam body is excavated to create the space needed for the spillway inlet. Such structures should be an extension of the impervious element of the dam to avoid additional seepage flow during operation. The structure is usually composed of a reinforced concrete slab (Figure 21) with a hydraulically efficient crest shape but there are exceptions such the articulated protection used in Bruton Dam (Dycel blocks). The main goals are to improve inflow conditions at the spillway entrance and orient flows parallel to the axis of the spillway channel. The cross-section of the invert can be entirely parabolic (Hewlett et al. 1997) or simpler such as a horizontal slab with vertical transitions at upstream or downstream ends (Figure 19, right). The joint between the inlet structure and the first row of WSBs at the spillway channel is typically designed by overlapping the reinforced concrete slab over the WSBs.
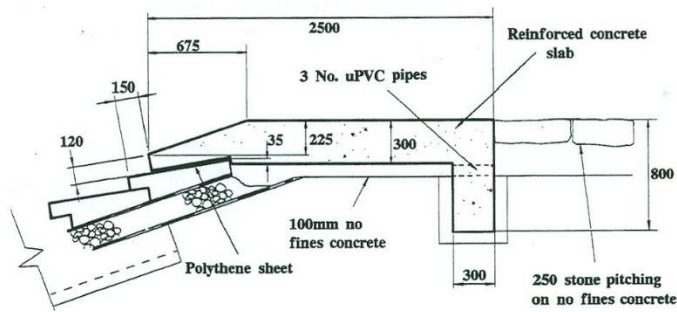

Figure 21. Crest details. Left, sketch of the cross section at Brushes Clough Dam (courtesy of R. Baker). Right, picture of downstream end of the concrete slab at the spillway crest of Barriga Dam.

When required, accessibility from the dam to the spillway crest should be provided by means of bridges or fords (Figure 22)

Figure 22. Bus crossing ford at the crest of Klinbeldin spillway (courtesy of R. Baker)

4.3. Spillway channel

The spillway channel consists of a section of overlapping rows of WSBs forming a stepped chute. The chute should be geometrically uniform to avoid the occurrence of unanticipated hydraulic behaviors. Irregularities, protrusions, poor construction, large displacements or loss of any WSB unit may cause high pressure fluctuations, unacceptable uplifts and shear forces which can lead to serious damages in the spillway (Hewlett et al. 1997). The profile of the flow along the channel keeps the typical pattern of the stepped spillways where three zones can be distinguished (Figure 23): Zone A, blackwater from the upstream weir until the inception point (IP in Figure 23) between the turbulent boundary layer and the free surface; Zone B, where air entrainment begins and the turbulent flow continues accelerating, and Zone C, where aeration is fully developed and uniform flow is approximately reached.
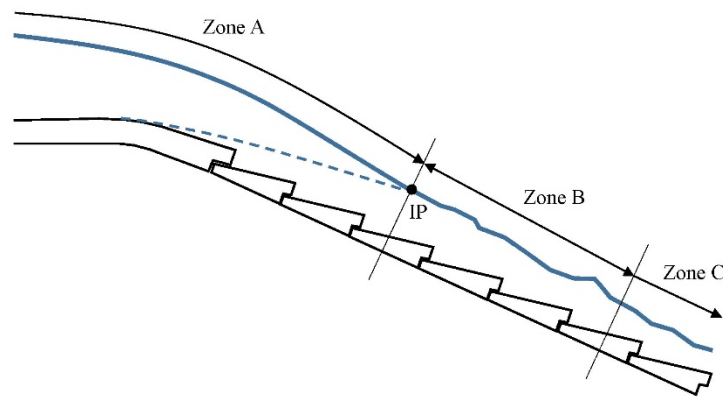

Figure 23. Typical flow patterns over a WSB stepped profile.

Within Zones B and C, the pressure fluctuations are higher than Zone A; however, self-aeration has a positive effect in attenuating pressure fluctuations (Hewlett et al. 1997). In addition, at Zone B, the flow velocities are still sufficiently low to develop the negative pressures at the riser of the WSB (*wedge effect*) and the flow depths are larger, so the expected subgrade flow or interblock seepage at the joints is also higher than Zone C. Therefore, in absence of uplift pressures caused by malfunction of the drainage layer, critical conditions for the WSBs could be also expected at Zone B, given that pressure fluctuations are present and aeration is not completely developed.

The cross section of the channel is usually trapezoidal and in rare exceptions rectangular. Trapezoidal section present economical and constructive advantages given that lateral slopes preserve stability of the soil material of the dam body underneath the channel. Typical lateral slopes are between 0.33 (3H:1V) and 0.50 (2H:1V) but the final decision should be founded on a geotechnical analysis. The sides of the channel are usually constructed with WSB as well but other constructive systems, like stone pitching (Figure 24, left) or articulated concrete blocks (Odgen Dam), have been employed also. Special attention should be noted at the design of the joints between the slopes and the invert to avoid the disruption of the flow or the appearance of preferential seepage paths. Different alternatives have been used with a good performance so far, like precast concrete or reinforced concrete edge beams.
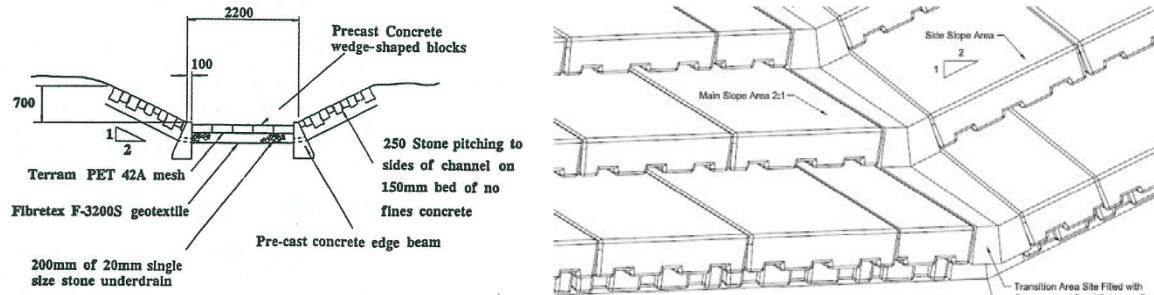

Figure 24. Examples of joints between invert and side slope of WSB spillway channels. Left, Brushes Clough Dam (courtesy of R. Baker). Right, Barriga Dam

Such edge beams can have a constant (Figure 24, left) or variable (Figure 24, right) cross section. The later tries to replicate the stepped profile of both the invert and side slope of the channel, especially interesting when the whole surface of the channel is formed by WSBs.

There are different formulations (Essery and Horner 1971; Matos 1999; Pinheiro and Fael 2000; Sánchez-Juny et al. 2008; Chanson 1994; Chanson 1996a; Chanson 1996b; Chanson and Toombes 2002; Chanson 2006; Yasuda et al. 2001; Fratino 2004; Chamani and Rajaratnam 1999; Chamani 2000; Boes and Hager 2003; Mateos Iguacel 1997) to estimate the relevant hydraulic variables for the spillway design like flow depths, unstable flow regimes, aeration, bulking, the position of the inception point, etc. but it will not be the subject of this document. For more information, it is recommended to consult state-of-the-art materials such as by Dr. Chanson or the bibliography of the PhD Thesis of Dr. Antonio M. Relvas which includes a thorough synopsis on this topic.

The WSBs of the spillway channel usually lays over a granular material for drainage purposes (Figure 24, left). This material is usually highly permeable and can be composed of one or more layers, extended over the subsoil or the material of the downstream shell of the embankment dam. In addition to the drainage function, the material has to be internally stable and fulfill the filter conditions with respect the adjacent materials considering the expected subgrade flows. The sense of the flow may change depending on the type of dam material: upwards in case of embankment dams or downwards (or also upwards depending on the particular conditions) in rockfill dams. Besides, the granular material has to be sized to avoid the wash out of the particles through the drainage slots of the WSB and to allow an easy placement of the block in order to achieve a proper alignment with the adjacent blocks during construction. The gaps of the side joints between adjacent blocks should be minimized during installation (see effect of gaps on the uplift pressures in Figure 25), but not as much to reduce significantly the flexibility of the entire system. In addition to reduce seepage flow, the configuration of this joints between successive rows should be staggered. This may need the use of half blocks or special angle blocks at the joint between the invert and the channel slope.
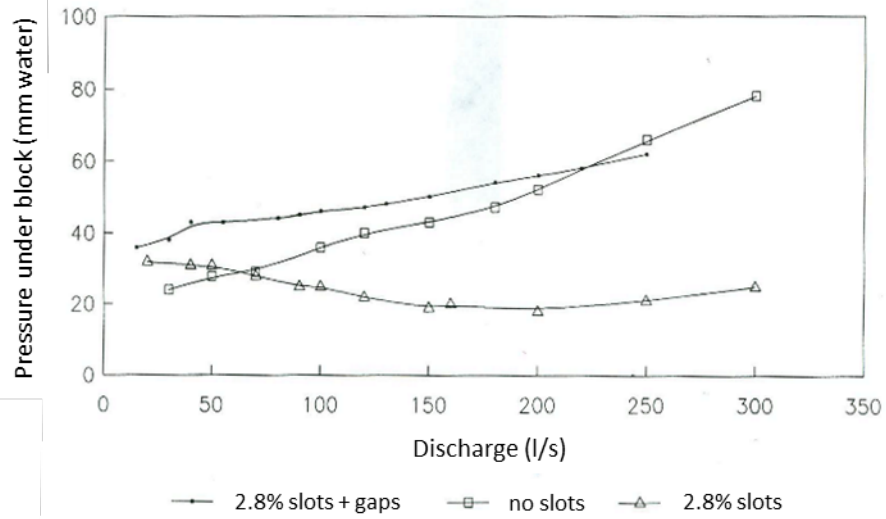
Figure 25. Effect of the gaps at side joints on pressures under WSB (courtesy of R. Baker)

Different criteria are available to design the drainage layers such as the seepage capacity of the granular material (Martins 1990) and filter conditions between adjacent layers (Hewlett et al. 1997). However, nowadays the decision of the thickness of the drainage layers is based only on experience and construction criteria. So, CIRIA recommends 20 cm or 4 times the d_{85} size of the specific material which composes each layer. Different criteria have been proposed by various entities. Nevertheless, the thickness of the drainage layers does affect the seepage capacity and, therefore, the degree of saturation inside the layer which is a key aspect of the stability of the blocks. Furthermore, uncertainties about the balance among inflows, outflows and seepage flows at each section of the drainage layer of the spillway are high. Such balance should depend on, among others, the spillway flow, seepage at the joints and drainage slots, the negative pressures at the riser, the permeability of both the drainage and dam body materials, the drainage capacity at the toe and, sometimes, the hydraulic conditions at the toe structure. Therefore, the subject seems to be complex and its relevance for the stability analysis of the WSBs can be high. This topic is being investigated nowadays by UPM and CIMNE.

4.4. WSB sizing and construction material

The size of the WSBs has been studied considering hydraulic parameters (Hewlett et al. 1997) and there are guidelines to decide the average thickness depending on the maximum unit discharge and the channel slope. There are another issues, as durability, economy, debris impacts, installation, handling, manufacturing, vandalism and others, which should be considered to decide the final size of the blocks. The decision has to consider also the possible settlements at the downstream shell and the difficulty of adaptation of the spillway channel to them as the blocks are larger. Special caution should be paid to the stability of half blocks which are less stable according to specific tests performed at the Salford University.

The hydraulic conditions of the tests performed to obtain the design curves at MCEI and Salford University were conservative given that the failure of each WSB was defined without considering the effect of the adjacent ones (Hewlett et al. 1997). So, many of the tests accomplished in stepped channels with rows of WSBs, replicating the installation at the spillway, could not reach the failure with the maximum available discharge at the facilities, with exception of blocks working under hydraulic jumps. This fact makes the WSBs protection system to be hydraulically reliable. However, the weakness of the system is that the failure of one block, understood as lifting off from the original place, may cause the failure of the entire spillway. In Barriga Dam, the WSBs in the same row were cabled together using the transversal orifice of the block (Morán and Toledo 2014; Morán and Toledo 2015).

The shape of the WSBs has been deeply studied and some general rules are widely applied at this time. The main are as follows:

- The height of the riser between two consecutive blocks, expressed by the ratio L/Δ (Figure 1) should be from 5 to 6.5. This ratio is accepted as a key factor to generate the wedge effect and, therefore, the stability of the block since this set up reaches the maximum positive pressure at the upper surface of the WSB.
- The aspect ratio recommended for mass concrete to avoid fracturing in handling and installation processes, expressed by L/t_a, is from 3 to 4. The minimum constructive thickness is approximately 10 cm. Vandalism and durability concerns in extreme climates can vary this criterion.
- The ratio B/L is recommended to be from 0.8 to 2 with the aim of keeping a certain flexibility of the spillway to accommodate to embankment settlements.
- The drainage openings of the WSBs downstream the riser consist of either drainage slots or vertical orifices. However, vertical orifices are more likely to be clogged during exploitation. The recommended ratio of the total opening surface to plan surface of the spillway is from 2.5% to 5%.

The construction material of WSBs has consisted of different types of concrete, either precast or in site. The first units developed in Russia were manufactured with reinforced concrete, which could be possible by the large size of the units. This material made the blocks more resistant against impacts. However, the use of smaller units and the industrial manufacturing led to the extensive use of precast mass concrete. The challenge at this time is to get an economical material which achieve durability with a high impact resistance. Nowadays there is ongoing research to get this by adding different types of fibers or additives.

4.5. Toe details and energy dissipation

An appropriate design of the toe or terminal structure is essential for correct operation of the spillway. This is primarily because the toe structure supports the downstream row of the WSBs of the spillway channel, which in turn are the support of the rest of the rows of the spillway. Additional functions of the toe structure include:

- Energy dissipation at the downstream toe, avoiding damage to the dam and spillway
- To prevent the turbulence generated by energy dissipation can affect the downstream rows of WSBs of the spillway
- To guarantee the free exit of seepage flows conveyed by the drainage layer, to avoid unacceptable uplift pressures under the WSBs.

Hydraulic Jumps. As it was mentioned in section 2.3, it is known that WSBs are not stable under hydraulic jump conditions so, when a hydraulic jump could affect the downstream rows of the spillway channel, special measures should be considered. If a stilling basin is to be designed, the downstream part of the spillway channel could be constructed with a reinforced concrete stepped slab which was installed at Brushes Clough and Odgen Dam (Figure 16, Figure 26). Alternatively, it is also possible to increase the size of the WSBs at the downstream end of the spillway channel according to the design figures experimentally obtained by CIRIA. A heavier blocks can withstand higher pressure fluctuations at this point.
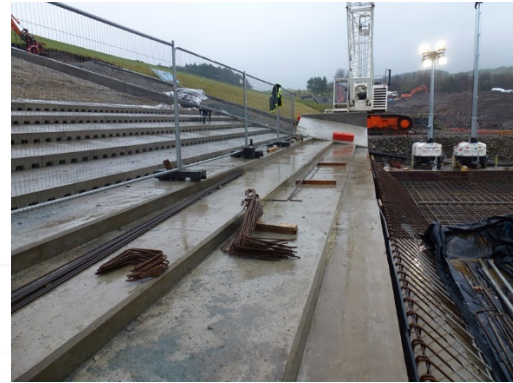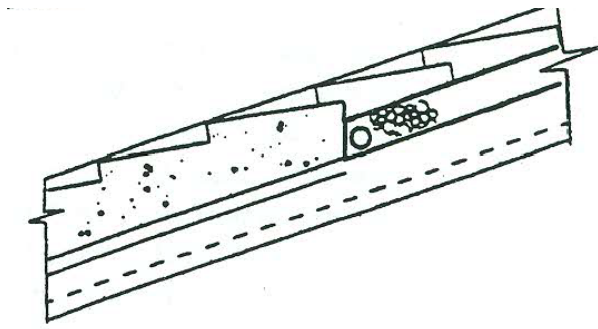
Figure 26. Details of the joint between the downstream row of WSBs and the reinforced concrete stepped slab. Left, sketch of Brushes Clough Spillway. Right, photograph of Odgen Dam (courtesy of R. Baker and P. Thurlwell from *Pascoe, P&S Consulting Engineeers, Ltd.*)

Toe structures: deflector blocks and flip buckets. The typical values of the Froude number at the toe of WSB stepped spillways are between 2.5 and 4.5 (Hewlett et al. 1997). Such values can correspond to oscillating hydraulic jumps, so special toe or terminal structures have been tested to fit the special conditions of these spillways. Deflector blocks (Figure 27) were tested at Salford University and detailed guidelines for their design were published (Hewlett et al. 1997).
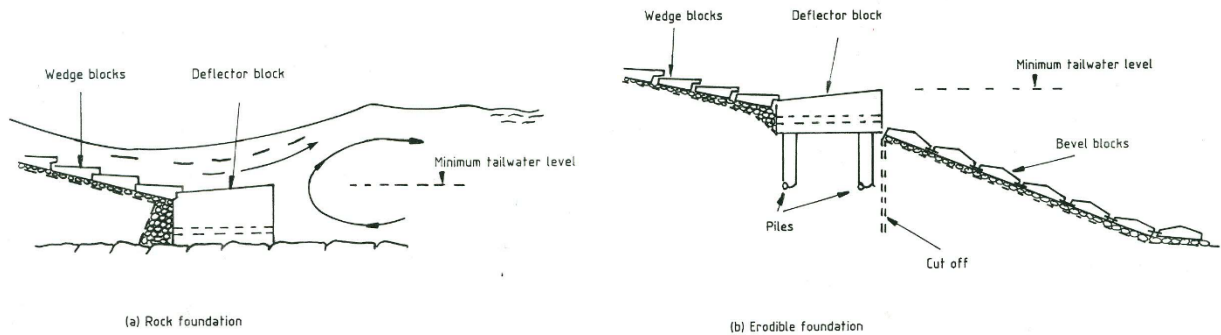

Figure 27. Deflector blocks at rock or erodible foundations (Baker 1991)

In addition to this, flip buckets can be used to dissipate energy (Morán and Toledo 2014; Morán and Toledo 2015). Such toe structures keep the highly turbulent dissipation of energy away from the spillway channel. Practitioners should follow appropriate hydraulic guidelines to develop appropriate designs that will function as intended (Figure 28). For flip buckets, tailwater must be carefully considered to minimize adverse effects to the jet and also permit the drainage outflow. Clearly, the selection of an appropriate toe structure requires consideration of geotechnical issues regarding the foundation and permissible impacts downstream due to scour.

Figure 28. Flip bucket at Barriga Dam. Left, view from downstream. Right, lateral view during operation in 2008.

5. CONCLUSIONS

This historical review has showed only a small portion of the body of research and case studies that exist regarding WSBs as well as an appraisal of the current state of the technology and its applications. The interest about this protection method is still vibrant with ongoing research, international seminars, and recent case studies (Odgen Dam) that confirm this personal opinion. However, the technology is still young and there are uncertainties which could be reduced by both additional research and the wide dissemination of the technical information of real cases to the technical community. Even though this text has referred to WSB spillways, most of the information included herein could also be useful in the design of similar overtopping protection.

Although prudence and caution are important values of dam engineers, no improvements and technology developments could be done without the courage of those who were not satisfied with what knowledge and information they had at the time. The author wishes to dedicate this manuscript to all of these pioneering engineers and researchers, who were perhaps not always understood.

6. ACKNOWLEDGMENTS

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