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Weep Hole and Cut-off Effect in Decreasing of Uplift Pressure (Case Study: Yusefkand Mahabad Diversion Dam)

Salim Azizi[1], Farzin Salmasi[2*], Akram Abbaspour[2] and Hadi Arvanaghi[2]

[1] *M. Sc. Student, Islamic Azad University, Ahar Branch, Iran*
[2] *Department of Water Engineering, Faculty of Agriculture, Tabriz University, Tabriz, Iran*

*Corresponding author's Email: Salmasi@tabrizu.ac.ir

ORIGINAL ARTICLE

ABSTRACT:
In order to have economic designs to reduce uplift pressure in hydraulic structures like diversion dams and concrete gravity dams, so many methods have been proposed that the most important include construction of horizontal aprons/cutoff walls in upstream and downstream of the dam and weep holes in the downstream or proper place between the two cutoffs. The effect of weep holes and cutoff on uplift pressure is the main goal of this study. This study focuses on Yusufkand Mahabad diversion dam in IRAN, by simulation it in Seep/W software. Effect of weep holes location and different depth of the dam cutoff walls on uplift pressure and on exit hydraulic gradient is investigated. Results show that upstream cutoff with 8 meter depth decreases uplift force about 63% and decreases exit gradient 79% respect to without cutoff case. Installing weep hole in downstream stilling basin decreases uplift force 8% and decreases exit gradient 74% more than without weep hole. Based on this research, design of diversion dams can be carry out by minimizing concrete costs and hence become economical design.
Keywords: Diversion dam, uplift pressure, exit hydraulic gradient, cutoff wall, weep hole.

1. INTRODUCTION

Empirically, it has been found that a so-called piping channel or slit comes into existence, extending from the downstream corner of the structure to a length of less than half the bottom length of the dam. At the same time, some material is deposited in front of the structure, in what is called a "sand boil."(Selmeijer and Koenders, 1991). The phenomenon of piping first was studied around the turn of the nineteenth century. Bligh developed an empirical calculation rule in 1910, on the basis of a number of cases of collapse of steel-founded brick dams on diverse earth foundations in India. A safe value for the permitted hydraulic head over the structure can be calculated with the calculation rule, as a product of the total horizontal and vertical seepage length under the structure and a factor which is dependent on the foundation. Bligh's calculation rule is also known as the 'line of creep' method.

In 1935 Lane developed another empirical calculation rule, by which horizontal and vertical parts of the seepage line were calculated in a weighted manner; in the calculation of the seepage length only one-third of horizontal parts were included. According to Lane (1935) this modification of Bligh's rule was necessary to ensure proper calculation of the large flow resistance of vertical parts of the seepage line. He called his method the 'weighted line of creep' method (Anonymous, 2002). The problem of ground-water seepage through a dam and its alluvial foundation with an impervious cutoff is usually solved in practice by neglecting the effect of the dam, considering constant pressure heads at the base of the dam, and hand drawing the flow net for assumed permeability ratios. This simplification of the problem mainly facilitates hand drawing of the flow net and hand calculations and may give results on ground water potential distribution and total flow through the foundation in a very short time.

Cheuk et al. (2008) describe a model-scale investigation into the mechanisms by which uplift resistance mobilized in silica sand, and illustrates how the observed mechanisms are captured in prediction models. Selmeijer and Koenders (1991) presented a mathematical model is to describe the phenomenon of soil erosion under a dam (commonly called "piping"). The analysis presented deals with the groundwater flow problem when a narrow channel is present under a dam. The resulting boundary value problem for the Darcyan seepage flow is solved.

In the study of Kalkaniand and Michali (1984) flow through the permeable foundation of an earth dam with an impervious core and an impervious cut off was studied. Different permeability ratios k_x/k_z of the foundation and depths of the cut off in the foundation were considered. It is shown that calculation of flow through the dam and the foundation may be simplified for cases of k_x/k_z = 10 and 100, and a range of cut off depth from 35%-100% in the foundation. Such simplifications in the study of groundwater seepage through the dam and its foundation will give no more than 10% excess flow for the cases

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described previously. The simplified calculations can be performed as well by hand.

Zoorasna and Hamidi (2008) studied Karkheh storage dam in Iran as the case study and six different connecting systems were modelled. Total flow, maximum hydraulic gradient, shear stress, shear strains and percent of plastic points were determined in connection zone. Results showed that the characteristics of cut off-core connecting system affects total flow discharge and maximum hydraulic gradient in connection zone. Using of a concrete slab at the base level of core with or without penetrating cut off into the core results in an extreme reduction of the hydraulic gradients at the vicinity of the intersection zone. This can help in reducing erosion and leakage from connection zone. Based on geological information of the Fengman dam, the seepage flow of the dam is analyzed by Yu et al. (2009). There are many different affecting factors on seepage problem, for example: the effect of the parameter of concrete, cut-off wall, the permeability coefficient of cut-off wall, drainage hole and grout curtains etc. It is observed that the grout curtain, which was performed during the dam construction, is not effective and the leakage occurs under the main grout curtain. For that reason, a cut-off wall is recommended.

In this study, Yusufkand Mahabad diversion dam (under operation) information's was obtained from regional water organization west Azerbaijan (in IRAN) including several cross-sections of the dam, soil thickness strata under the dam with its hydraulic conductivity, upstream and downstream water levels. The purpose of this study is to determine a way to reduce the uplift pressure and exit hydraulic gradient too. Seep/w software is applied for uplift pressure simulation. The water level difference inserts a ground water flow in the subsoil, below dam foundation. The flow may be sufficiently powerful to cause erosion. This effect is commonly known as "piping," and clearly, civil engineers would like to be able to design against it. Fig.1 shows the diversion dam body with its spillway.

Figure 1. View of the Yusufkand Mahabad diversion dam and its ogee spillway

Mahabad river that dam has been constructed on it, is formed by interconnection of two branches of Kuter and Bitas. Kuter river watershed area is 53,700 hectares and Bitas river watershed area is 27,900 hectares. Total watershed area included about 2 percent of the total area of West Azerbaijan province.

Seep/w is a finite element software product for analyzing groundwater seepage and excess pore-water pressure dissipation problems within porous materials such as soil and rock. Its formulation allows considering analyses ranging from simple, saturated steady-state problems to sophisticated, saturated-unsaturated time-dependent problems (Geo Slope, 2004).

In seepage problems, Laplace's equation combines Darcy's law and the continuity equation into a single second order partial differential equation. The two-dimensional Laplace equation for steady state flow is:

$$\frac{\partial}{\partial x}(-k_x\frac{\partial H}{\partial x})+\frac{\partial}{\partial y}(-k_y\frac{\partial H}{\partial y})=0 \qquad (1)$$

Where H=total head, k_X=hydraulic conductivity in x direction and k_y=hydraulic conductivity in y direction. For unsteady or transient flow condition, Eq. 1 changes to Eq. 2.

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial H}{\partial y}\right)+Q=\frac{\partial\theta}{\partial t} \qquad (2)$$

Where Q=flow rate or discharge, θ=the water volume content and t= time.

If k is assumed to be independent of x and y, that is if the region is assumed to be homogeneous as well as isotropic, then Eq. ,1 transforms to Eq. 3.

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=0 \qquad (3)$$

MATERIAL AND METHODS

Dam simulation in Seep/w software

Fig. 2. Shows cross section of Yusufkand diversion dam. In primary simulation, a cut off is used in upstream with a depth of 8 meters in order to study its effect on the reduction of uplift pressure. In the next step, its effect on the reduction of uplift pressure is investigated by simulating weep hole in the bottom of stilling basin (at downstream of dam) and change of weep hole position in the stilling basin floor. Finally, with fixing the position of the weep hole, different cut offs depth were tested and the values of uplift pressure, seepage under foundation and exit gradient is investigated.

Boundary conditions

Total number of used elements in simulation were selected about 2485 elements, water level in upstream is 6 meter, water level in downstream is set to zero (the most critical case in simulation occurs when water level differences between upstream and downstream be maximum), left side boundary of structure is set to 8 meters from dam crest, and it's value in right side is set to 10 meters from end of stilling basin. All nodes in the dam floor and stilling basin invert were selected as "no flow boundaries". In order to apply boundary conditions at weep hole location, water head was selected to be equal to water head at floor of stilling basin, 12.5 meter, that represents zero pressure at that point (stilling basin level from datum is z=12.5 m). According to Fig. 2, the horizontal length of dam is 9 m, stilling basin length is 20 m and end sill length is 4.5 meter. So, in providing charts, uplift pressure is calculated in 33.5m length of dam.

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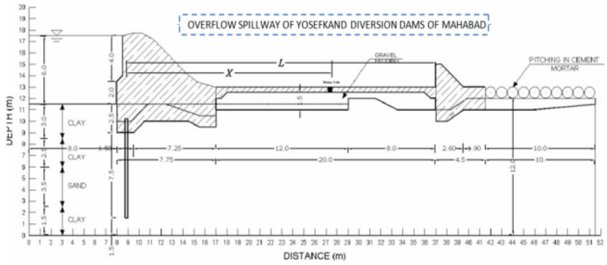

Figure 2. Cross section of Yusufkand diversion dam

According to geological studies, the permeability of soil layers of foundation are given in Table (1). The first layer under dam foundation is Beaten (compressed soil) and last layer under foundation is clay.

Table 1. Permeability of foundation's layers

Material properties	Clay	Fine sand	Clay	Beaten soil
K_{sat} (cm/s)	$1*10^{-6}$	$1.4*10^{-5}$	$1.2*10^{-5}$	$1*10^{-4}$
Layer thickness (m)	1.5	3.5	5.5	1.5

Geometric models and dam's simulated cases

Simulation of dam's foundation was done by quadrilateral elements (meshing process) Fig. (3) shows Yusufkand diversion dam with constructed elements in Seep/w.

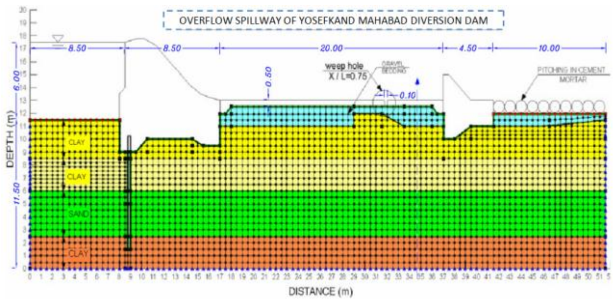

Figure 3. Simulated model of Yusufkand dam by Seep/w software

In Table (2) different dam modelling scenarios is presented. In cases 1 to 3 only effect of the cut off has been studied. In cases 4 to 7 effect of weep holes and in cases 8 to 10, effects of weep holes and cut offs on uplift pressure is investigated. In Table (2), *L* is stilling basin length and *x* is distance from beginning of stilling basin.

Table 2. Different scenarios in position of the weep hole and cutoffs

Case	Upstream cutoff	Weep hole	Weep hole location (x/L)	Depth of upstream cutoff (m)
1	No	No	-	-
2	Yes	No	-	4
3	Yes	No	-	8
4	Yes	Yes	0.25	8
5	Yes	Yes	0.5	8
6	Yes	Yes	0.75	8
7	Yes	Yes	1.0	8
8	Yes	Yes	0.75	4
9	Yes	Yes	0.75	2
10	No	Yes	0.75	-

RESULTS

Based on simulation results, flow net under the dam is shown in Fig. 4 for sixth case. Weep hole location in Fig. 4 is at location x/L=0.75. Flow line direction near the weep hole, demonstrates the effect of weep hole in reduction of uplift pressure. This can be seen in equpotential lines concentration near the weep hole too.

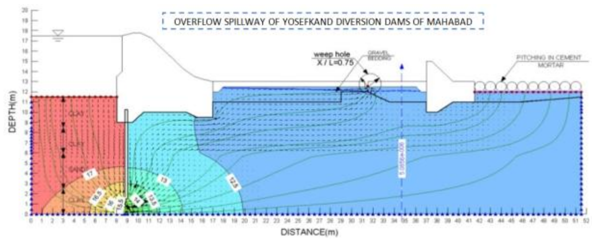

Figure 4. Flow net below the dam for the sixth case in Table 2

Fig. 5 shows distribution of uplift pressure for case 6 (table 2).The total amount of uplift pressure is *-478.235 KN/m* which according to table (3) is declined to 62% and we have 9.5% increase compared with fourth case. It can be seen that uplift pressure is decreased in weep hole location. So in the case (5) there is depression in uplift pressure. Negative pressure in the Fig. 5 at distance between weep hole and end sill, states that piezometric height under pool is below the stilling basin floor and the pressure head in weep hole is zero.

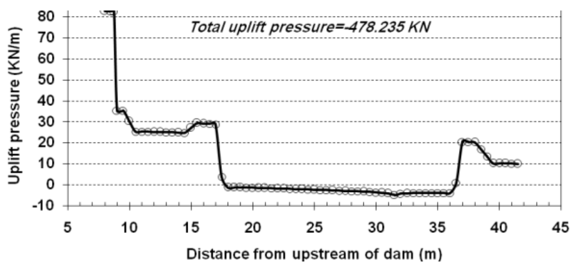

Figure 5. Uplift pressure in bottom of stilling basin for the sixth case

Fig. 6 shows diagram for the hydraulic gradient in case 6. Maximum gradient in the downstream is 0.021 m/m and according to Table (3) has reduced by 66% compared to the third case and has increased by 14% compared to the fifth case. Hydraulic gradient at the weep hole is 0.15 that has reduced to 58% compared to forth case.

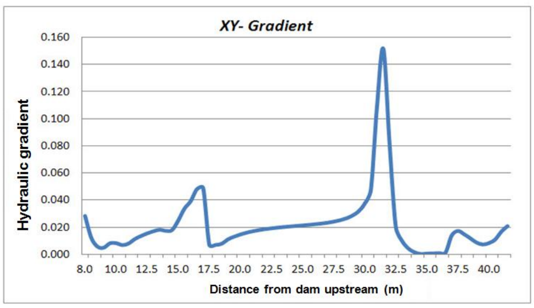

Figure 6. Hydraulic gradient below stilling basin for the sixth case

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Results of the first to 10th cases are shown in Table (3). For example, in the seventh column related to the fourth case, number 66% ↓(1) means decrease of 66% uplift pressure compared to case 1 or in seventh column related to the eighth case, number 14% ↑(6) means increase of 14% uplift pressure compared to case 6.

Table 3. Results for first to 10th case in Seep/w software

Case	q ($m^3/s/m$)	Total uplift pressure U(KN/m)	hydraulic gradient at end sill	hydraulic gradient at weep hole	hydraulic gradient at cutoff end	Percent decline or increase in uplift pressure ↑↓
1	7.0488 ×10-5	-1238.37	0.3	-	-	-
2	2.923×10^{-5}	-690.73	0.125	-	1.7	44% ↓(1)
3	1.478×10^{-5}	-453.68	0.063	-	1.5	63% ↓(1)
4	4.0889×10^{-6}	-419.42	0.016	0.36	1.62	66% ↓(1)
5	4.352×10^{-6}	-463.88	0.018	0.17	1.6	9.5% ↓(4)
6	5.085×10^{-6}	-478.23	0.021	0.15	1.57	12.5% ↓(4)
7	1.523×10^{-5}	-486.29	0.029	0.14	1.53	13.5% ↓(4)
8	1.107×10^{-5}	-558.28	0.046	0.49	2.04	14% ↑(6)
9	2.674×10^{-5}	-865.19	0.11	1.18	2.15	44% ↑(6)
10	3.065×10^{-5}	-980.29	0.13	1.35	-	51% ↑(6)

Effect of upstream cut off depth on uplift pressure, hydraulic gradient and seepage rate

Fig. 7. Shows effect of upstream cut off on uplift pressure distribution for cases 1-3 in table 2. According to Fig. 7, it can be found that uplift pressure will decrease with increasing in upstream cut off depth. Comparison is among three cases: 1) without excitant of upstream cut off, 2) upstream cut off with 4 m in depth and 3) upstream cut off with 8 m depth. From Fig. 7, if the upstream cut off depth become more, uplift pressure that is instable factor of dam stability, will become smaller.

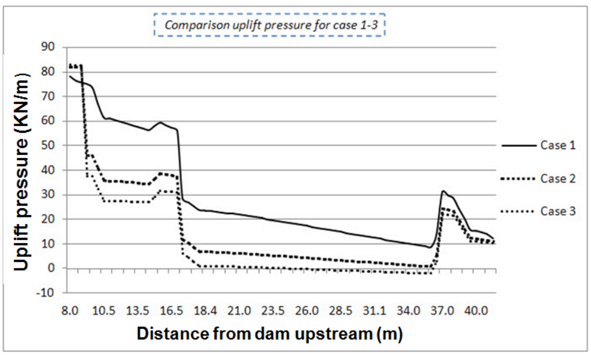

Figure 7. Effect of upstream cut off on uplift pressure for cases 1-3 in table 2

Area under the uplift pressure distribution in Fig. 7, yields total uplift pressure required in dam stability analysis. In Fig. 8 the total uplift pressure is calculated for cases 1 to 3 for comparison. With increase of cut off depth, from zero to 8 meters, the total uplift pressure in unit width of the dam is reduced by 63%.

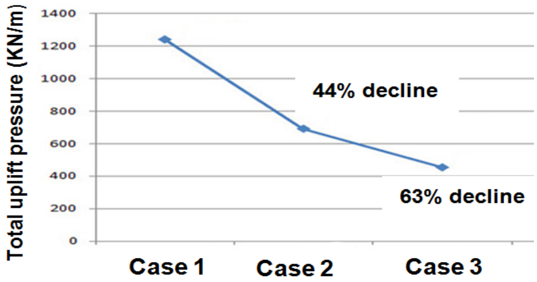

Figure 8. Comparison of total uplift pressure in unit width of the dam for cases 1-3

Fig. (9) shows the hydraulic gradient under foundation. It can be found that by increase of upstream cut off depth (cases 1-3), hydraulic gradient is reduced under foundation. The most reduction is at the beginning of dam foundation, connecting point of the dam to the top of the pond. Fig. (10) shows percent of hydraulic gradient reduction for the 1-3 cases.

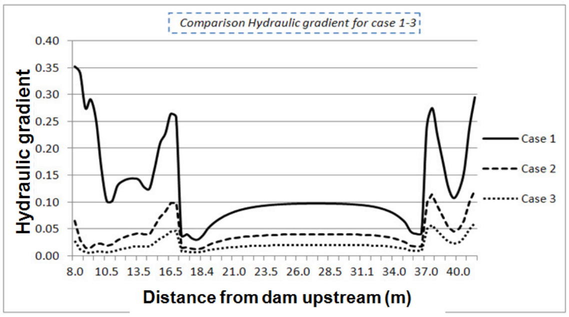

Figure 9. Effect of upstream cut off depth on hydraulic gradient

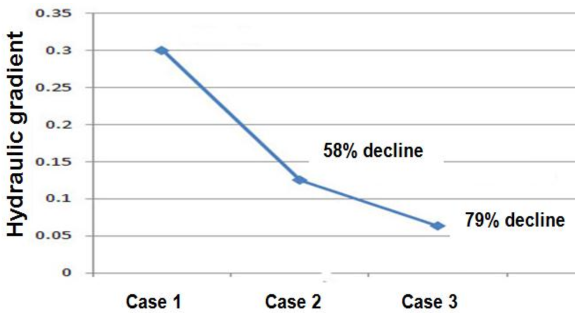

Figure 10. Reduction percent in the exit hydraulic gradient for cases 1 to 3

The weep hole effect on uplift pressure and exit hydraulic gradient

Fig. 11 presents the effect of weep hole location in the uplift pressure distribution. According to Fig. (11), it can be seen that when weep hole is away from the dam upstream, pressure increases. For better view of the effect of weep hole location at hydraulic gradient, comparison among cases 4-7 presented in Fig. (11).

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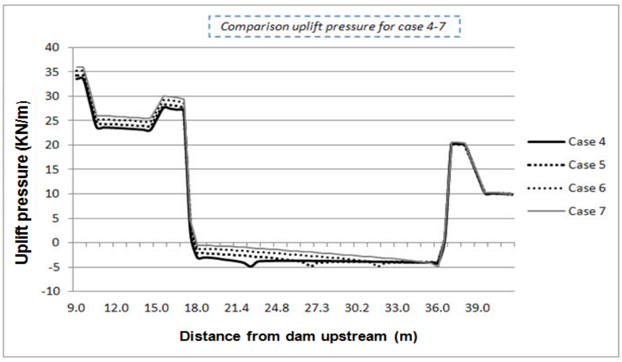

Figure 11. Effect of weep hole location in the uplift pressure distribution

Fig. 12 shows effect of weep hole location on the hydraulic gradient for cases 4-7 (see also table 2). According to Fig. (12) it can be found that when weep hole is away from the dam upstream, hydraulic gradient is decreased.

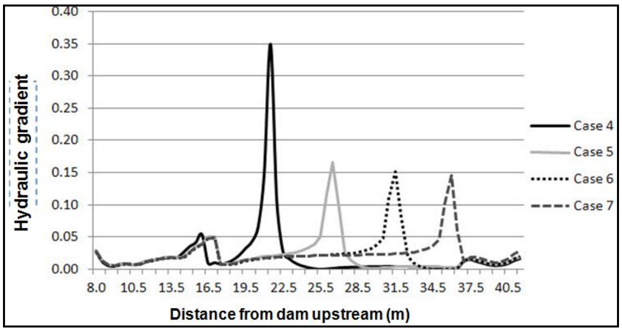

Figure 12. Effect of weep hole location on the hydraulic gradient for cases 4-7

Fig. 13. Comparison of water hole effect on the hydraulic gradient reduction in shallow and water hole

Effect of both weep hole and upstream cut off on uplift pressure and hydraulic gradient

According to Figs. 13-14 by fixing weep holes location and changing the location of the upstream cut off, it can be found that reducing the length of the upstream cut off, make increase of uplift pressure and hydraulic gradient that is resulted from reduction of flow path length and flow rate increase.

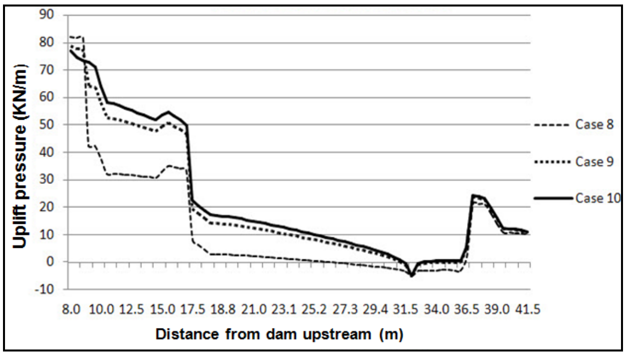

Figure 13. Effect of both weep hole and upstream cut off on uplift pressure

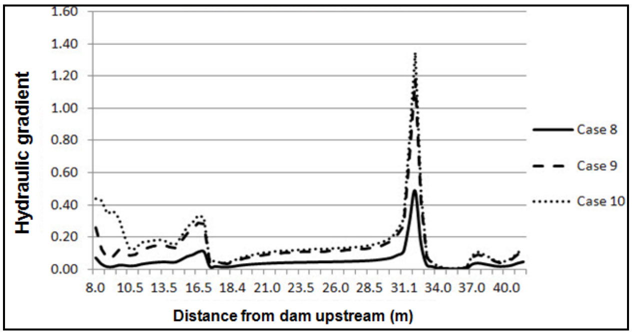

Figure 14. Effect of weep hole locations on the hydraulic gradient

CONCLUSION

–Weep hole reduces uplift pressure and exit hydraulic gradient for a proposed dam and more closer its location to upstream, more significant this reduction.

- In the case of small diversion dams, exit hydraulic gradient is smaller than the critical value and is not considered a major design parameter.
- In the case of diversion dams, constructing of weep holes in invert of stilling basin, implements all of the positive tasks in uplift reduction and this effect will increase by closing of weep hole location to dam upstream.
- Length of dam cut off is designed according to size of permeable layer depth, otherwise, with increase of length of upstream blanket, we can reduce exit gradient and uplift pressure effectively.

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