Increasing the efficiency of under road culverts in protecting the desert roads against torrents & flash water

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INCREASING THE EFFICIENCY OF UNDER ROAD CULVERTS IN PROTECTING THE DESERT ROADS AGAINST TORRENTS & FLASH WATER

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Abstract: *Owing to the huge damage caused by flash water and torrents in the desert roads, the attempts to prevent such damage have received a great attention. Culverts are the popular engineering tool usually used for converting the accumulated runoff water from one side of the desert roads to the other side. This engineering tool prevents overtopping which stops the safe traffic stream over the roads. Since the culvert entrance geometry is one of the prime factors affecting its accurate performance. The present study is a trial for increasing the discharging efficiency of such culverts to give more safety for the desert roads. Investigating the influence of using inclined headwall at the culvert entrance on discharge efficiency, its inclination angle in the same direction of the flow and in the opposite direction will be tested as well. A needed survey for references related to the current study topic, covers a suitable time period were included in a tabulated form, with the needed technical comments. The theoretical approach also was introduced. A comparative study was done for the results obtained by most popular researchers and the calculated discharging efficiency reached by each of them, and given in a tabulated form.*

Key words: *Culverts, Discharge coefficient, Headwall, Desert road culverts.*

1. Introduction

Assiut governorate is one of the most developed governorates in Upper Egypt. In the last two decades, many great engineering infrastructure projects were carried out for serving several Industrial areas constructed in the desert extension to the East and West of the River Nile in all Upper Egypt governorates. Such new industrial communities and new cities need great logistical activities, transportation, and perfect desert highway networks which represent the heart of such needed logistical activities. Many desert highways were constructed in the Eastern and Western deserts to join all the Upper Egypt governorates, and their new industrial communities. Since the Eastern Egyptian desert is located in an arid region (13mm average annual rainfall), the region does experience occasionally intense rainfall events (often 60 mm/hour) over fairly short periods. The rainfall events are, as in the most arid areas, the result of severe local convective thunderstorms created by unstable weather conditions and the aerographic effect of these regions (Zeller 1990 [1], Greenbaum 1998 [2]). These storms generate flash floods that run rapidly along the network of dry wades drain the mountains and cause severe damage to people property and specially highways. Along the last twenty years, more than once flash water and torrents attacked the Eastern main desert highways (Zeinab and, Sallam 2004 [3]) in El-Minia, and Assiut governorates. This flash water causes a huge damage to road body and stops the traffic stream among many of the Upper Egypt governorates affecting negatively the commercial and daily human activities.

The present study focuses on more efficient protection for such desert roads against the expected attack of the flash flooding or torrents by improving and increasing the performance efficiency of the under desert roads culverts. Since culverts are the most popular constructional tool used for converting any accumulated flash water from one road side to the other without any water overtopping for the road. The geometry of the culvert entrance is of a great importance in improving, and increasing its performance efficiency so, our work here is for testing the influence of equipping an inclined headwalls in the entrance of such culverts.

Effect of the equipped headwall angles to the direction of the flow was tested as well. The chosen approach was carefully done after studying the previous researches carried out related to our topic and highlighted some parameters still need more investigations for achieving the main needed goal required for introducing the most efficient culverts in discharging flash flooding through roads without any damage.
From studying the previous available researches concerning the under desert roads culverts performance, it was noticed that many of the affecting parameters concerning increasing such culverts discharging efficiency were investigated. At the same time no study was carried out to know the influence of using the headwalls in the entrance, and their inclination to the direction of the flow .That is why the topic of our study was chosen.
Six angles of headwall inclination to the direction of the flow can be tested with eight discharges for each angle of headwall inclination. The obtained results were recorded, discussed through tables, and charts from which main conclusions were drawn down.

2. Culverts

A culvert is a structure under the roadway conveys the surface water through a roadway embankment or away from the highway for drainage [4]. In spite of, culverts are minor structures but they have a great importance in protecting desert roads against flash floods and torrents. For economy and hydraulic efficiency, engineers should design culverts to operate with submerged inlet during the flood flows. Determination of culvert performance is not a simple problem because of the effect of different factors such as geometry of the inlet and exit, culvert alignment, barrel shape, materials, culvert slope and length. However, once the operation type is established the analysis may proceed according to the well defined principles. Therefore the discharge through culverts is controlled by one of three means [5].

The first mean is the geometry of the inlet while the culvert is running partially full on mild slopes, or running full in steep slopes. At this case the culvert is running under inlet control only.

The second mean is the combined effect of the entrance, length, slope, shape, and roughness of the culvert barrel while the condition of running may be full or partially full.

The third mean is the elevation of the tail water at the outlet. When the water depth is higher than the culvert spring it will be running full. Inlet control is affected by the inlet geometry and the existence of the headwall and its inclination. Outlet control is affected by all the geometrical and hydraulic parameters of the culvert such as the inlet configurations, barrel shape and slope, roughness and water elevation in U.S and D.S.
Generally, culverts can be classified according to more than one criteria such as construction materials, barrel cross section, alignment, position and purpose of construction.
Materials most commonly used in construction of culverts are reinforced concrete, corrugated metals, timber, cast iron, verified clay and sometimes stone masonry. Using a specific material is depending on the design factors and the economical considerations. The concrete sections can be cast in place or pre-cast unites.
The cross section of a culvert may be circular, oval, elliptical, arched, box rectangular or square. The rectangular section for culverts is used when it is desired to reduce the height of the culvert to keep the roadway level as it is. For small discharges single barrel can be used. Otherwise excessive flood requires more than one opening and it is called multiple culverts.
Culvert alignment should be the same of the natural stream that crosses the roadway. So the culvert may be skew or perpendicular to the centerline of the roadway. Proper design requires a good alignment to reduce construction costs. A good designer should design the culvert with a grade keeps suitable velocity because less velocities cause sediment in the culvert barrel and high velocities cause scour. Flow type through the culvert barrel shouldn't be changed within the length of the culvert so changes in slope within the length of the culvert should be avoided as possible.
Hydrological studies for highway culverts are essential to estimate discharge amount which must be handled safely and economically. There are many methods of estimating the designed discharge of culverts. For example the rational method, direct observation method, judge method, .etc. may be used.

The amount of the flood water (runoff) which considered as a product in the hydrologic cycle is affected by two major groups of factors: Climatic factors such as rainfall and evaporation. Rainfall density, duration, frequency and distribution time have the major effect. On the other hand, physiographic factors depending on the catchment's area of the rainfall. These factors are: soil type and its water holding capacity, surface infiltration conditions, geological conditions, land use or cover, ground water table, and topographic conditions. Once these factors are known the design discharge could be estimated by any method of calculating the peak discharge of road culverts [18].

3. Previous studies

Many experimental studies and field observations were carried out for illustrating culvert performance. Among of them, those of Chow 1959 [6], Henderson 1966 [7], Norman et al. 1985 [8], Moawad 1995 [9] and Chaudhry 1993 [10]**.** They pointed out that, several factors affect on the flow through culverts whether they running full or partially full. These factors are x-sectional shape and dimensions, length, roughness, inlet and outlet geometry, edge configurations, slope, U.S. and D.S. water depths. Culvert may flow with inlet control or outlet control depending on such factors. Henderson 1966 [7] concluded that culvert in mild slopes does not run full unless the ratio between U.S. water depth (H) and the pipe diameter (D) is more than 1.2 in case of circular x-section. Chaudhry1993 [10] indicated that this ratio is much more than 1.2 and reaches 1.5 because of the sharpness of the edge and the contraction flow at the inlet.

3.1. Inlet control

Laster 2003 [11] stated that, inlet flow control condition occurs when the culvert barrel can convoy more than the inlet will accept. Inlet control condition affected with inlet geometry and configuration, U.S. water depth, barrel shape and slope. FHWA (Federal Highway Administration) had published in the HDS (Hydraulic Design Series) No. 5 [8] that culverts flowing under inlet control condition have one of the following cases:

First case is when the barrel is not full and the U.S. water depth is less than the barrel spring. As shown in Fig. (1-a). Culvert in this case acts like a weir and the relation between discharge and U.S. water height can be written as:

$$Q = C_d B H^{1.5} \tag{1}$$

Second case is when the barrel is not full but the U.S. water height is higher than the barrel spring. As shown in Fig.(1-b). Culvert in this case acts like an orifice and relation between discharge and U.S. water height can be written as:

$$Q = C_d A \sqrt{2gh} \tag{2}$$

Third case which shown in Fig. (1-c), from which it is clear that, on steep slopes culvert may runs full and the relation between discharge and head loss can be written as [12]:

$$H_l = \frac{fLQ^2}{2gDA^2} + H_{ex} + H_{in} \tag{3}$$

3.2. Outlet control

Outlet control flow condition occurs when the culvert barrel is not capable to convoy as much as flows which the inlet opening can accept (Laster, 2003 [11]). The control section is located at the exit. Geometric and hydraulic characteristics affect the flow and play role in the performance of the culvert. Culvert barrel is always running full as shown in Fig. (1-d), and the outlet is submerged. The relation between discharge and head loss can be written as Darcy Weisbach equation No. 3. [12].

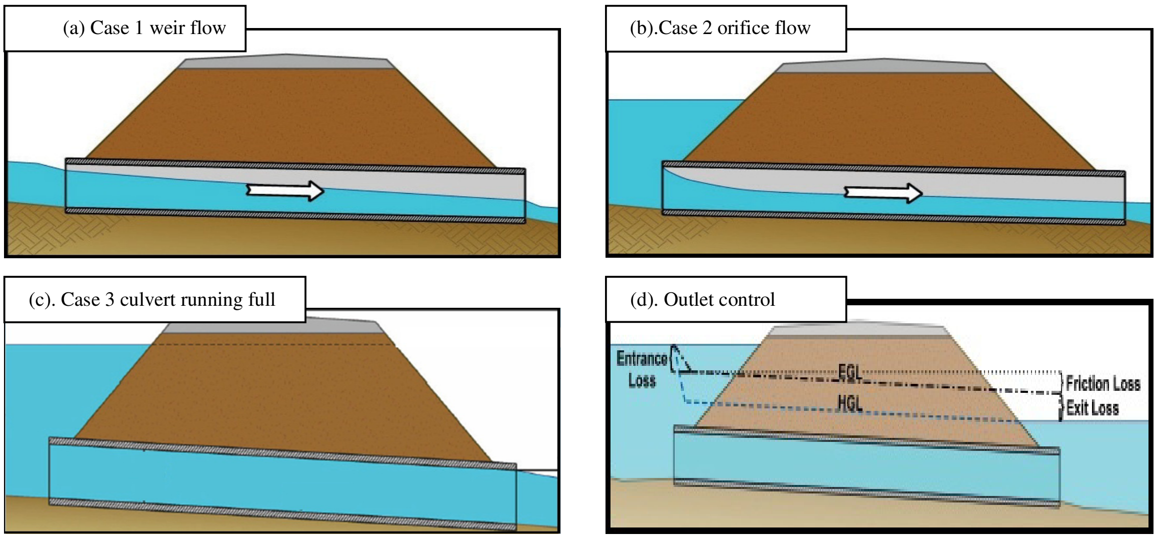


Fig. 1 cases of control flow

3.3. Culvert headwall

Headwall is a retaining wall normally constructed at both ends (U.S. or D.S.) of a culvert barrels. Headwall functions are to Control erosion and scour resulting from excessive velocities and turbulence, Stabilize the side slopes filling at the culvert entrance, anchor the culvert body (one barrel or more) to prevent movement, reduce seepage through road embankments, enhance the hydraulic efficiency of culvert [8]. A culvert fulfills both the structural and hydraulic requirements for the stream crossing and may constructed from a variety of materials but headwalls usually constructed from reinforced concrete, plain concrete or masonry. They may be cast in place or pre-cast units depending on site and economical considerations. In all ways headwall must be constructed perpendicular to the centerline of the barrel with a good fixation to it is required.

For best hydraulic performance, a rounded or beveled edge between the headwall and the barrel should be done [16]. If high headwater depths are likely, a short apron is often desirable to prevent bottom scour at the toe of the wall.

3.4. Culvert efficiency improvements

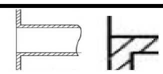
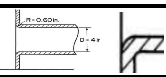
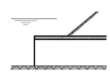
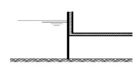
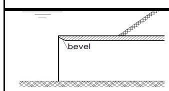
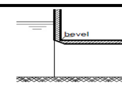
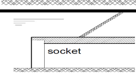
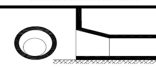
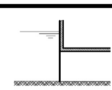
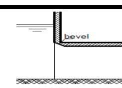
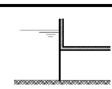
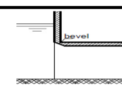
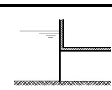
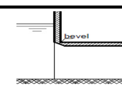
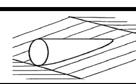
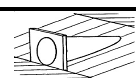
Since the economical considerations are the prime factor in constructing such essential structures, the same barrel cross section shall be used with some other barrel shapes to gain the maximum discharging efficiency for the same x-sectional barrel area through some geometrical modification. Regarding to this fact, the entrance geometry and configurations should be modified. The culvert performance efficiency can be represented by the value of the discharge coefficient when the culvert operates with inlet control. It also can be represented by the coefficient of entrance head loss when the culvert operates with outlet control [13]. A larger coefficient of discharge or smaller head loss gives a higher efficiency. Many attempts were made to improve the hydraulic efficiency of culverts by modifying the entrance configurations.

After reviewing the available previous studies and discussing their main results, a comparative study was carried out to differentiate between the main obtained results by each study for highlighting the most efficient method that used to improve the performance of such culverts. Table (1) and (2) were constructed for tabulating all the used data and measured parameters. In addition to the recommended technical points concluded from each study. At the same time, the constructed tables include a special column for the calculated percentage of increased efficiency of the culvert performance.

From such constructed tables for both inlet control and outlet control conditions, it is clear that no one of such studies used the headwall with different inclination angles to the stream flow as a tool for enhancing the inlet geometrical configurations for improving the working efficiency. Also no one tested the influence of the headwall inclination to the stream flow in the same direction of the flow and in the opposite direction.

In table (1) the performance was represented by the coefficient of discharge. The efficiency of the culvert was calculated according to the increase of the discharge coefficient. The studies examined different lengths and different cross sections for culvert barrels.

Table 1: Comparative study of some of previous works (Inlet control).

Reference	x-sec. & length (Inch)	Definition sketch Before	Definition sketch after	Calculated increase of efficiency %	Notes
Lorenz, 1953 **[13]**	D=4 L=420			-	Square edge
				10	Rounded edge R=0.6
French, 1964 **[14]**	D=5.5 L=363			-	Projected square
				17.3	Square +Vertical Headwall *
				55	beveled + Vertical Headwall*
				-	Projected beveled
				2.5	beveled + Vertical Headwall*
				59.8	Socket +projected
				74.8	Socket + Vertical Headwall + wingwall*
French 1969 **[15]**	8×4, 12×6			-	Square + Vertical Headwall *
				34.2	Bevel edge + Vertical headwall*
	4×4			-	Square + Vertical Headwall *
				28.7	Bevel edge + Vertical headwall*
	6×12			-	Square + Vertical Headwall *
				29.7	Bevel edge + Vertical headwall*
Smith 1995 **[16]**	12.1cm L=1.85m			-	Projected
				16.7	Vertical Headwall *

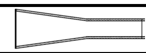
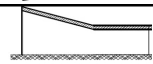
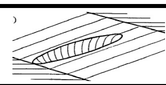
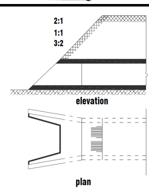
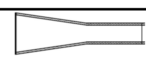
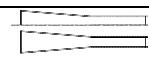
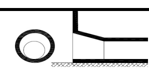
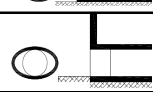
t taper inlet. ** using vertical headwall.*

From the above comparative table (1), the following main technical points can be obtained:-

1. Using the headwall without any inclination to the stream of flow at the upstream of the culverts improves the hydraulic performance, and maintains the same discharge with low water height at the upstream side of the culvert. Which was explored by French1964 [14], 1969 [15], and Smith 1995 [16].
2. For the circular pipe culverts, the best inlet shape is the taper inlet with angle of slope 15.5^{o} (Slope 4:1). This taper gives the maximum discharge coefficient, C_d=0.93 for the inlet control (French 1964 [14]).
3. The worst shape of the inlet for the circular culverts is the projected sharp edged without headwall. Besides, the worst shape for box culverts is the conventional sharp edged without any modifications.
4. Using the beveled or the rounded edge barrels improves the hydraulic performance of culverts.

For outlet control some attempts are summarized in the table (2). In this table the performance was represented by the head loss (H_l). The efficiency was represented according to the decrease of the head loss (H_l). The studies examined different lengths and different cross sections for culvert barrel and gave a head loss equation for each type of entrance modification. The U.S submergence ratio (H/D) at which the culvert running full was introduced.

Table 2: Comparative study of some previous works. (Outlet control)

Reference	x-sec. & Length cm	Definition sketch	H/D	Decrease in head loss%	Notes
Khalil&zein 1995[17]	15×10 L=100		>1.3	-	Conventional inlet
			=1.1	22	Side taper 3:1
			=1.1	29	Side taper&deck3:1
Hesham.k.M 1998[18]	D=15 L=120		>1.13	-	Vertical inlet
			=1.06	12.5	Slope face 2:1
	14*7 L=120		>1.13	-	Vertical inlet
			=1.06	5.7	Slope face 1:1
	10×10 L=120		>1.1	-	Vertical inlet
			=1.03	8.3	Slope face 1:1
Elbahar 1998 [19]	5×5 L=100		>1.23-1.4	-	Box inlet(conventional)[R]
			=1.05-1.26	32.4	Side taper 5:1[R]
			=1.05-1.26	21.6	Slope deck 3:1[R]
			=1.05-1.26	21.4	Slope taper 3:1[R]
Khalid.A.A 2004[20]	D=14.4 L=216		>1.27-1.54	-	Conventional inlet
			=1.33-1.165	34.5	Flared 4:1
			=1.08-1.21	30.3	Elliptical inlet

R rounded edge inlet R=.5cm

From the table (2), the following main technical points can be obtained:-

1. The performance of culverts is affected by the inlet shape and configurations.
2. For the circular pipes culverts, the best inlet shape is the taper inlet Slope 4:1 (angle equal to 15.5^{o}). This taper gives the minimum head loss for the outlet control (Khaled A. A. 2004 [20]).
3. For the box culverts, the best inlet shape is the inlet with side taper 5:1 in the horizontal plane with rounded sides (R=0.5 cm). So, it gives the minimum head loss which means the best performance (Elbahar 1998 [19]).
4. The worst shape of the inlet for the circular culverts is the projected sharp edged without headwall. Besides, the worst shape for box culverts is the conventional sharp edged without any modifications.

From the above comparative tables (1 & 2), It is clear that the inclination of the headwall at the inlet hasn't been studied yet. That is why we decided to study the effect of its inclination on the discharge efficiency of the culvert in this work.

4. Theoretical approach

Flow in culverts could be controlled by inlet or outlet depending on where the control section is. Inlet control depends on the U.S. water depth, entrance shape, and edge conditions. Outlet control depends on all factors as U.S. and D.S. water depths, culvert entrance and shape, length, slope, and roughness. For studying the headwall inclination on the performance of a culvert U.S. the inlet must be submerged.

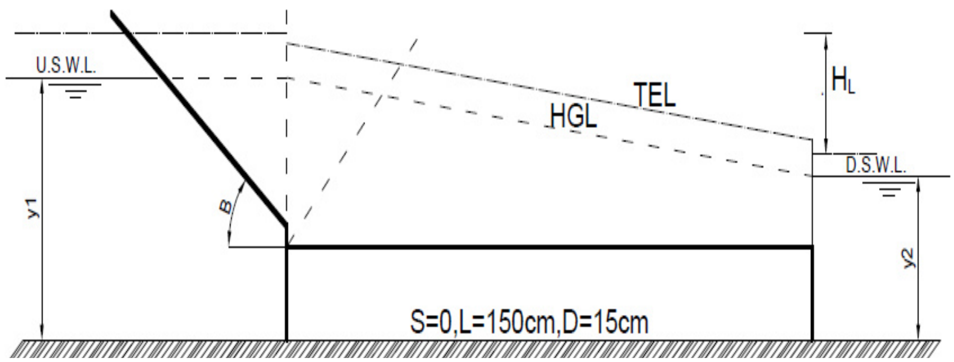


Fig.2 Definition sketch for experimental model flow.

Referring to Fig (5) the following functional form of variables used in dimensional analysis are selected to represent all parameters affecting the problem. The general functional relationship for these variables can be given in the form

$$C_d = \phi(\rho, \mu, g, y_1, y_2, \beta, H_l) \quad (4)$$

Using the dimensional analysis principle based on the aid of the "Buckingham π theorem" considering ρ, μ, g as the repeated variables, it could be proved that

$$C_d = \phi(\frac{y_2}{y_1}, F_e, R_e, \frac{H_l}{y_1}, \beta) \quad (5)$$

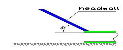
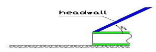
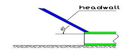
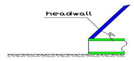
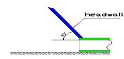
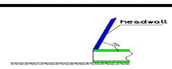
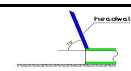
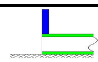
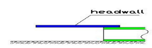
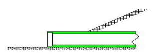
Since the effect of R_e is neglected as the viscosity has a negligible effect on the hydraulic.
Re-arranging the terms gives the equation the following shape.

$$C_d = \phi(\frac{y_2}{y_1}, F_e, \frac{H_l}{y_1}, \beta) \quad (6)$$

5. Experimental work program

A set of wooden inlet headwalls were manufactured in the work shop of the faculty of Eng., Assiut University. They were coated to prevent water effect. Different angles of inclinations of headwalls to the direction of the stream, in the same direction of the flow and in the opposite direction, were prepared to be tested for determining the discharge coefficient for each headwall inclination angle (0, 30, 45, 60, 75 and 90) to recommend the most efficient inclination of the inlet headwall which permits the passage of maximum discharge in minimum time as described in table 3. Experiments were carried out in a channel has a trapezoidal shape of 1:1 side Slopes, 13 m long, 84 cm bottom width, and 54 cm height in the irrigation and hydraulic laboratory of civil engineering department, Assuit University. The discharge ranges from 5 to 40 l/s. The experimental model of culvert was represented as a circular pipe of 15 cm diameter, and 150 cm long impeded in the above mentioned channel.

Table3. Studied headwalls angles of inclination in the direction of the stream and in the opposite direction.

In the direction of the flow				In the opposite direction of the flow			
No of tested model	Name	Inclination angle B	Shape	No of tested model	Name	Inclination angle B	Shape
1	A	30		6	F	30	
2	B	45		7	J	45	
3	C	60		8	K	60	
4	D	75		9	L	75	
5	E	90		10	M	0	
11	N	-		Conventional			

6. Conclusion

From the above presented technical surveying for the previous studies carried out to investigate methods of increasing the efficiency of under roads culverts in protecting such desert roads against flash floods, and torrents, the following main points can be drawn dawn:

1. The carried out studies covered all the parameters may affect the efficiency of the under desert roads culverts hydraulically, and geometrically. But no one investigation had been carried out concerning the use of headwalls with different angles of inclination to the stream flow.
2. Choosing studying the effect of using inlet headwalls in culverts with different angles of inclination to the stream flow,(in the same direction, and in the opposite one), for improving culverts performance and efficiency was to complete the shortage in the reviewed literature.
3. the comparative study carried out for the most popular investigations concerning improving the under desert roads performance and efficiency showed that :

- For the circular culverts, the **best** inlet shape is the taper inlet with slope 4:1while [14],
- For the box culverts, the **best** inlet shape is the inlet side taper with slope 5:1 in the plan, with rounded edges [19].

At the same time the comparative study showed that:

- For the circular culverts, the **worst** shape of the inlet is the projected sharp edged without any headwalls. While [13],[14],[15],[16],
- For the box culverts the conventional sharp edged inlet without any geometrical modifications is the **worst** shape [17],[18],[19].

Notation

A	Barrel area	Fr	Froude number.
B	Barrel	S	Barrel slope
β	Headwall inclination angle	H_{ex}	Exit loss
C_d	Discharge coefficient	H_{in}	Inlet loss
D	Culvert height	H_l	Head loss
f	Friction factor	h	Water height over the orifice
g	Acceleration of gravity	Q	Discharge
L	Culvert length	Y_1	Upstream water depth
R	Hydraulic radius	Y_2	Downstream water depth
R_e	Reynolds's number		

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