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A parametric study on friction-loss in water conveyance tunnels considering misalignment of precast concrete segments

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ABSTRACT

In many tunneling projects, it is common that the lining concrete segments misaligned during Tunnel Boring Machine (TBM) operation or after excavation process. Misalignment of concrete segment, especially in water conveyance tunnels, can affect fluid transfer capacity and causes local head-loss. Present study is composed of a series of Three Dimensional (3D) numerical simulations which explores the effects of the steps occurrence the tunnels created by segment off-sets in subcritical free surface flow. Results show that recirculating flows occur after the steps. This strong vortical motion after the steps causes considerable head-losses especially for higher steps which should not be neglected in the estimation of total head-loss. The results of simulations also show that the effects of the wall roughness and segment length on the head-loss could be ignored for practical estimations. Moreover, it is found that for a specified high expansion ratio, local head-loss coefficient of the bottom step is less than coefficient of the side step. Exploring presence of a sequence of misaligned concrete segments shows that the head-loss coefficient of sequenced steps is less than summation of independent coefficients of the same steps.

1. Introduction

As water resources and demands are unevenly distributed through the world, water transfer systems such as water conveyance tunnels are designed to secure continues human access to water (Ballestero, 2004; Gupta and van der Zaag, 2008). Water conveyance tunnel constructions often take years to complete, and during that time equipment is moved to and huge volumes of excavated soils and rock (muck) must be moved. Due to this fact, scientists and engineering focused on alternative drilling and blasting methods. These attempts leads to an automated/mechanized drilling technology known as TBM which facilitates excavation and construction of long tunnels at the optimal time (Dalgıç, 2003; Farrokh and Rostami, 2009).

During excavation and progress of TBM, precast concrete segmental lining is usually installed to protect the tunnel wall. During the lining installation, it is probable that some concrete segments may not match perfectly together and some segment misalignment occur (Farrow et al., 1994). For such segment misalignment various reasons such as high rate seepage flow, weak earth-quake events, improper installation and other reasons can be mentioned (Georg and Davorin, 2004). In this conditions, dowel and bolt systems can be applied to reduce the misalignment between lining segments and rings (King, 2006; Mayer et al., 2009). On the hand, it is also common to use the lining segments without any bolts or dowels (using joints such as tongue and groove or knuckle and hinged). Furthermore, details of tunnel construction like horizontal or vertical curve in tunnel path and segment geometry can affect the application of dowels or bolts (Arnau and Molins, 2012). Specifically, in universal or tapered ring segments, it is usual to use the sockets such as dowel and bolts; while hexagonal segments does not include socket systems. In tunnels constructed with hexagonal segments which dowels or bolts cannot be used, large segment misalignments have been observed (Maidl et al., 2012). Even in tunnels with universal or tapered ring segments, it is possible that the dowels and bolts fail due to bad geological conditions and sub-surface problems and also large steps occur. In Fig. 1 some examples of tunnel lining misalignment are shown. As shown in this figure, misalignments can occur in different parts of tunnel lining such as invert, side, and top segments.

From hydraulic studies point of view, lining misalignments protrude an obstacle in flow path similar to a step. Steps in water transfer tunnels would cause distortion in streamlines and formation of recirculating flows in upstream and downstream sides of the obstacle in the reverse direction of the main flow, causing energy dissipation. Several

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Nomenclature

b	subscript for bottom steps
B	tunnel width
g	acceleration of gravity
h	flow depth
H	tunnel height
H_L	local head-loss
H_i	total head in section i
H_s	step height
H_T	total head-loss
H_1	total hydraulic head upstream of the step
H_2	total hydraulic head downstream of the step
i	subscript for section number
k	local head loss coefficient
$k_{sequence}$	local head loss coefficient of sequential steps
k_{single}	local head loss coefficient of single step
k_w	local head loss coefficient of a step with width of w
L	distance between sections 1 and 2
L_r	reattachment length
L_s	step length
m	number of available data in section i
n	manning roughness coefficient
N	number of sequential steps
s	subscript for side steps
S	tunnel longitudinal slope
V	flow velocity
V_i	mean velocity in section i
v_{ij}	velocity in j point in section i
W_s	step width
x	longitudinal direction
y	transverse direction
y_i	mean water depth in section i
y_{ij}	water depth in j point in section i
z	vertical direction
α	aspect ration

Fig. 1. Examples of concrete segment misalignments in different parts of tunnel lining.

researchers studied various aspects of recirculating flows in the pipe and open-channel flows. In these studies, pressure change, hydraulic resistance coefficients, flow pattern (location of reattachment point), vortex structure, and turbulence characteristics were investigated in forward and backward facing steps by experimental and numerical methods (Ando and Shakouchi, 2004; Biswas et al., 2004; Hall et al., 2003; Kostas et al., 2002; Tihon et al., 2001). According to these studies, definitive agreement was reported between experimental measurements and numerical simulations (Ranjan and Pantano, 2013; Thangam and Knight, 1990). Several numerical schemes and turbulence closures were used for simulating wave-like stationary patterns, stagnant zones and complex vortex structures around steps (Cho and Goldstein, 1994; Lan et al., 2009; Li and Zhang, 1998; Wen et al., 1997). From these studies, it can be inferred that the reattachment length (the distance from backward facing step to the point that flow attaches to the wall again which known as reattachment point) which could be essentially important in local head-loss near the step, depends on the expansion ratio (the ratio of step height to flow depth) and the ratio of inertial to viscous forces within a fluid known as Reynolds number (Thangam and Knight, 1990). The low amount of the expansion ratio caused by segment misalignment (due to the low thickness of segmental lining compared to the tunnel diameter) and high Reynolds number distinguish flow analyses in the segments offsets of water conveyance tunnels from common steps in channels. The frequent presence of lining segment misalignment in water conveyance tunnels and significant difference between the lining segments off-sets and common studies in hydraulics about the step ident the necessity of a study deals directly with tunnel lining segment misalignment. In this regard, Najafi and Nabipour (2012) applied Two Dimensional (2D) numerical model to simulate segment off-sets during the TBM operations in tunnels. They showed that existence of steps in the tunnel reduces the flow discharge considerably and decreasing the approaching angle of the step would improve the flow condition. However, the impact of offset between adjacent segments on the head-loss has not been quantified and discussed in this study.

In another series of studies on flow over the steps, flow condition over the obstacles is described (Bravo and Zheng, 2000; Hanna et al., 1996; Leu et al., 2008). Hanna et al. (1996) investigated the impact of Froude number (ratio of flow velocity to wave celerity) and shape of an obstacle on free surface profile using numerical method. Bravo and Zheng (2000) applied a numerical model for flow analyses over a rounded step. They concluded that the rounded step significantly reduce the peak in turbulent characteristics observed in the backward-facing step. From these studies and other similar studies reported in the literature, it can be found that flow around the steps caused by concrete segment misalignment in conveyance tunnel can be simulated through numerical models.

Following previous studies on the lining segment misalignment such as Najafi and Nabipour (2012), present study states the results of Three Dimensional (3D) numerical simulations of flow pattern around the bottom and side steps of the lining in tunnels due to the misalignment of tunnel segments using a two-phase flow model known as Volume of Fluids (VOF). Specifically, this paper deals with the impact of lining segment misalignment protrusion on flow structure and quantification of the head-loss in water conveyance tunnels. Furthermore, the effects of various geometrical parameters such as step length and width, expansion ratio, wall roughness and step sequencing on local head-loss will be addressed. For this purpose, a series of numerical models were constructed which will be explained in the following section.

2. Methodology

In this study, Fluent 6.2 package which is a finite volume based computational fluid dynamics software together with GAMBIT meshing