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Internal erosion under spillway rested on an embankment dam

Mohammad Sedghi-Asl[1*], Mansour Parvizi[2], Mohsen Armin[3], R. Flores-Berrones[4]

1. Assistant Professor, Soil Science Department, Faculty of Agriculture, Yasouj University, Yasouj, Iran

2. Assistant Professor, Civil Engineering Deparement, Faculty of Engineering, Yasouj University, Yasouj, Iran

3. Assistant Professor, Watershed Management Department, Faculty of Natural Resources, Yasouj University, Yasouj, Iran

4. Research Engineer, Mexican Institute of Water Technology, Paseo Cuauhnahuac 8532, Jiutepec, Mor. 62550, Mexico

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* *Corresponding Author Email: msedghi@yu.ac.ir, Fax: +98-741-2224840*

Abstract
In this paper we investigate the mechanism of internal erosion caused in the right abutment of the Shahghasem dam's spillway. Shahghasem dam is an earthen dam located in Yasouj, in southwest of Iran. A significant hole and pipe have been observed in the corner of the right abutment from upstream view. The foundation is Marlstone, which has low cohesion and susceptible for internal erosion and piping in some conditions. Going through details of the design maps has shown that Lane's criteria for selecting safe dimensions of the seepage control measures have not been considered properly. A series of the supportive walls are designed to attach to the right part of the spillway in order to increase the length of seepage. The pipe route of the erosion should also be grouted with high quality concrete.

Keywords: *internal erosion, Marlstone, piping, spillway, Shahghasem dam.*

1. Introduction

Internal erosion of soil induced by seepage flow is the main cause of major hydraulic works failures (dikes, earth dams, etc). The issue is defined by the risk of flooding of areas located downstream. When internal erosion is suspected to occur or is already detected in situ, the amount of warning time before the failure takes place is difficult to predict. The development of effective emergency action plans which will lead to preventing heavy loss of life and property damage is strongly desirable [1].

The literature has been reported that one of the main causes of levee, earth dam, and earth-rock dam failures or incidents is the phenomenon known as "piping". In fact, piping and internal erosion are responsible for about 50% of failures in these types of earthen embankments [2]. To keep away from piping in major dams, Casagrande (1968) recommended the following measures: 1. ensure good and proper selection of the construction materials; 2. control homogeneity of these materials during construction stages; 3. construct transition zones between coarse and fine materials; and 4) place properly designed upstream and downstream filters [3].

The erosion starts at any point where the seepage water discharges and works toward the reservoir, gradually enlarging the seepage channel. Depending on the stage of this process, the occurred damage might be classified as a simple “incident”, an accident, or a complete failure [4]. The most significant and often least obvious impact of wildlife intrusions on embankment dams is hydraulic alteration. Hydraulic alteration can manifest itself in different ways, including flow net distortion, internal erosion and piping, and physical barriers to the natural flow of waterways.

Earth dam failure usually happens as a result of internal erosion rather than piping incidents. In fact, reported failures in earth structures due to real piping are rare. Because many of the internal erosion failures result in a tunnel or pipe-shaped erosion feature through the earth structures, they are often referred to as piping failures by engineers, but by this definition these cases are not true piping events [4].

Seepage under hydraulic structures is very important in designing such structures and if it is not considered, the whole structure may fail due to both effects of uplift pressure and piping phenomenon [5-6].

Terzaghi (1939), Lane (1934), and Sherard et al. (1963) present a model of piping in which particles are progressively dislodged from the soil matrix through tractive forces produced by intergranular seeping water [7-9]. The mobilizing tractive forces are balanced by the shear resistance of grains, weight of the soil particles and filtration. The erosive forces are greatest where flow concentrates at an exit point and once soil particles are removed by erosion, the magnitude of the erosive forces increases due to the increased concentration of flow [8, 9]. This view of piping is the classic backwards-erosion style of piping. ‘‘Backwards erosion’’ is generally produced where a roof of competent soil or some other structures allow the formation of a bridged opening. The tractive force causing this type of erosion is directly proportional to the velocity of intergranular flow (Richards and Reddy 2007) [10]. In a different definition, internal erosion gathers four types of erosion: concentrated leak erosion, backwards erosion, contact erosion, and suffusion [11].

‘‘Internal erosion’’ is similar to backwards erosion piping in that the tractive forces remove soil particles. However, internal erosion is due to the flow along pre-existing openings, such as cracks in cohesive material or voids along a soil-structure contact. By this definition, internal erosion is not due to the dynamics of inter-granular flow and the hydraulics of the problem are quite different than those of the backwards erosion [8]. Rather than being initiated by Darcian flow at an exit point, internal erosion is initiated by erosive forces of water along a pre-existing planar opening, or a weak contact between compaction layers [10].

Formulating his creeping theory, Bligh (1910) assumed the creeping length to be the sum of horizontal and vertical distances traversed by a fluid particle from the upstream bed level [12]. Bligh presented the creeping factor as:

$$C = \frac{L}{\Delta h} \tag{1}$$

where

Δh = the difference between upstream and downstream water levels

L = the flow creeping length.

Based on Bligh’s theory, the hydraulic gradient is assumed to be constant in any location through the structure and equal to $\Delta h/L$. Also, it was recommended that the creeping factor be equal or more than an optimum value so that the structure could resist against any internal erosion (Lane, 1935) [8].

This method provides a highly conservative value for the safety factor. Boiling and piping phenomena occur in cohesionless material soils, especially clean-fine sand. Due to lack of cohesion and low effective stress between the particles, sand grains are easily floated and migrated along with seepage flow. Lane (1935), after studying more than 200 dams worldwide, proposed his weighting-creep theory which postulates a higher head drop in the vertical direction than horizontal (see Leliavsky, 1965) [13]. To meet this, weighting factors of 0.33 and unity were assigned to the horizontal and vertical directions, respectively. Also, the creeping line is considered horizontal if it makes an angle less than 45 degrees with horizontal; otherwise, it is considered vertical. The Lane method yields lower values for uplift pressure than Bligh's. Table 1 shows the creeping factor for various foundation materials. This paper aims to investigate the reasons for piping the right abutment of Shahghasem spillway and finally provide remedial actions to safely control this phenomenon.

In a systematic research, Sedghi-Asl et al. (2012) conducted a lot of experiments to minimize both seepage flow and uplift pressure using application of sheet pile and blanket. Comparing the results of laboratory experiments and empirical methods provided by Lane and Bligh indicates that when the blanket length and cut-off depth are both small (high seepage rate), the latter methods predict much lower values for uplift pressure. According to Sedghi-Asl et al., (2012), the Bligh method can be employed to design hydraulic structures founded on coastal sandy soils [6].

Recently, Tanaka et al. (2012) investigated seepage failure of bottom soil within a double-sheet-pile wall for a case study. They studied seepage and boiling by means of finite element method (FEM) and stability analysis and then calculated safety factor against seepage failure [14].

Chen et al. (2013) performed a set of experiments to investigate seawall piping under water level fluctuations. They reported that the piping occurrence probability in the rounded gravel-filled seawall was larger than that in the crushed gravel-filled seawall [15]. A set of experiments have been conducted by Fleshman and Rice (2014) to assess and address the mechanics of initiating the piping erosion process in sandy soils. The experiments were carried out on several soils, differing in gradation, grain size, grain shape, and specific gravity [16]. Sharif et al. (2015) carried out a set of experiments to investigate piping phenomena using image processing technique for tracking erosion piping from both side-looking and bottom-up views. They suggested some exponential equations to estimate the depth of erosion, side area of the piping zone, and volume of eroded grains [17]. Elkholy et al. (2015) developed an exponential equation to estimate the depth of erosion as a function of time and the coefficient of soil erodibility and then verified that with experimental data [18].

Recently, field observation of the spillway of Shahghasem dam demonstrated local erosion occurred in the right abutment. Therefore this paper aims to look at the measures which may be involved in occurring internal erosion under right side of the spillway. Finally the remedial measures will be presented to safely work on the dam.

Table 1. Proposed creeping factor by Lane (1935) for various foundation materials (Leliavsky 1965)

Material of foundation	Safe weighted creep ratio (Lane's value)	Bligh's value for comparison
Very fine sand or silt	8.5	18
Fine sand	7.0	15
Medium sand	6.0	-
Coarse sand	5.0	12
Fine gravel	4.0	-
Medium gravel	3.5	-
Gravel and sand	-	9
Coarse gravel, including cobbles	3	-
Boulders with some cobbles and gravel	2.5	-
Boulders, gravel and sand	-	4 to 6
Soft clay	3.0	-
Medium clay	1.8	-
Hard clay	1.8	-
Very hard clay or hardpan	1.8	-

2. Site and dam characteristics

Shahghasem dam, located in Shahghasem valley, south of Yasouj, southwest of Iran, consists of an earth-embankment, 250 meters long and 47.2 meters high, over Marlstone as it is shown in Figure 1a. This dam has a lateral spillway near the right abutment.

The construction of the Shahghasem dam was concluded in 1995, but the dam was not filled due to drought period for 5 years. Recently, field observation of the Shahghasem spillway demonstrated that local erosion has occurred in the right abutment (Fig. 1). Based on the geology of the dam site, in this part the predominant foundation material is marl which contains limestone with fine and homogenous grain size (Fig. 2). The main point is that the cohesion of such material is low, and therefore this material is erodible. It is observed that all the materials are Pabdeh Gurpi formation which is an impermeable formation with very low cohesion. Marlstone is the typical rock of the Pabdeh Gurpi formation.

Fig. 1. a) Ogee spillway of Shahghasem dam

Fig. 1. b) Piping hole and seeping flow between abutment and concrete body at downstream

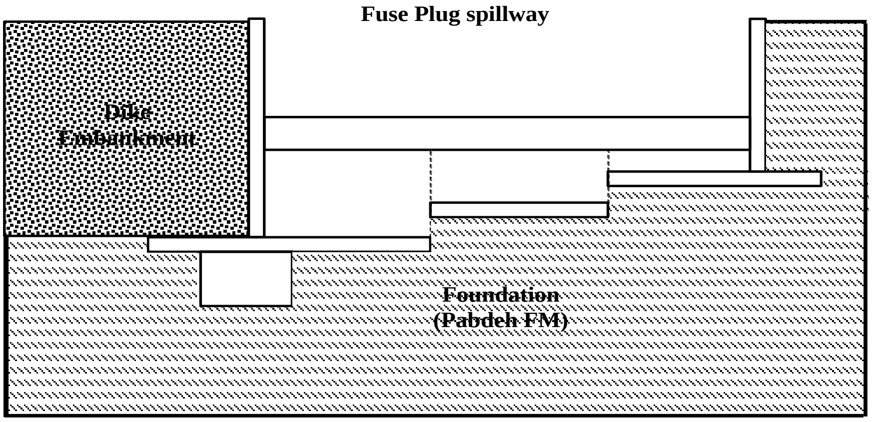
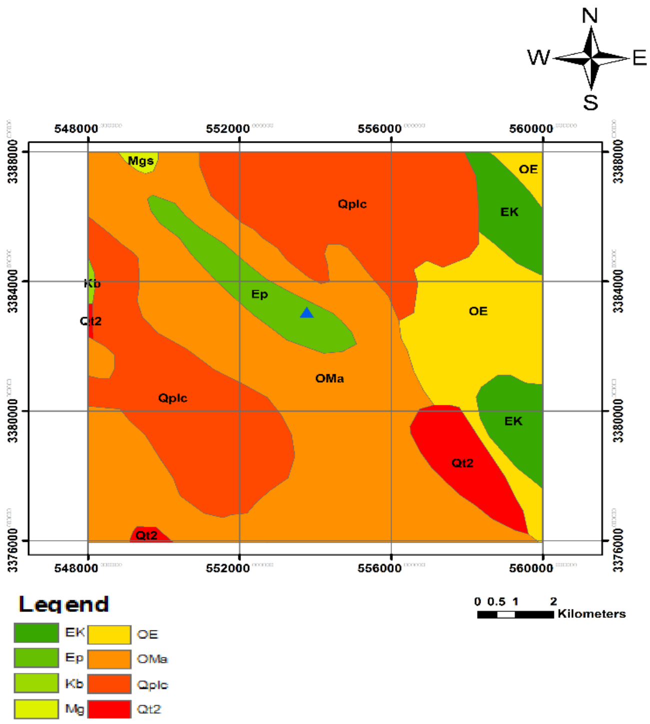


Fig. 2. a) Cross section of spillway and its foundation



LEGEND OF MAP

Geo _Unit	**Description**
Oma	Cream to brown - weathering, feature - forming, well - jointed limestone with intercalations of shale (ASMARI FM)
Mgs	Anhydrite, salt, grey and red marl alternating with anhydrite, argillaceous limestone and limestone (GACHSARAN FM)
Qplc	Fluvial conglomerate, Piedmont conglomerate and sandstone.
Ep	Blue and purple shale and marl interbedded with the argillaceous limestone (Pabdeh FM)
Ek	Grey and brown, medium - bedded to massive fossiliferous limestone (KAZHDUMI FM)
Kb	Undivided Bangestan Group, mainly limestone and shale, Albian to Companian, comprising the following formations: Kazhdumi, Sarvak, Surgah and Ilam
OE	Undivided Asmari and Jahrum Formation, regardless to the disconformity separates them
Qt2	Low level piedment fan and vally terrace deposits
▲	Location of spillway

Fig. 2. b) Geological map of dam location with scale of 1:100000

Looking at design reports and as-built maps indicated that there was no sufficient watertight barrier between the concrete structure and the abutment or the embankment and also downstream filter to plug eroded particles. With respect to time, expanding of the hole was significant. The main point during flood periods is that the seeping flow was clear water. There was no remedial or safety measure to control this phenomena. Up to now, remedial measures have not been performed yet. Figure 3 shows the plan and the front views of fuse plug spillway.

In Figure 1b, it can be observed that there is a longitudinal hole along with side wall of spillway which is going to expand more and more. Field observation has indicated that maximum flow rate seeped along hole is about 8 liters per second. This value may be dangerous for stability of the spillway.

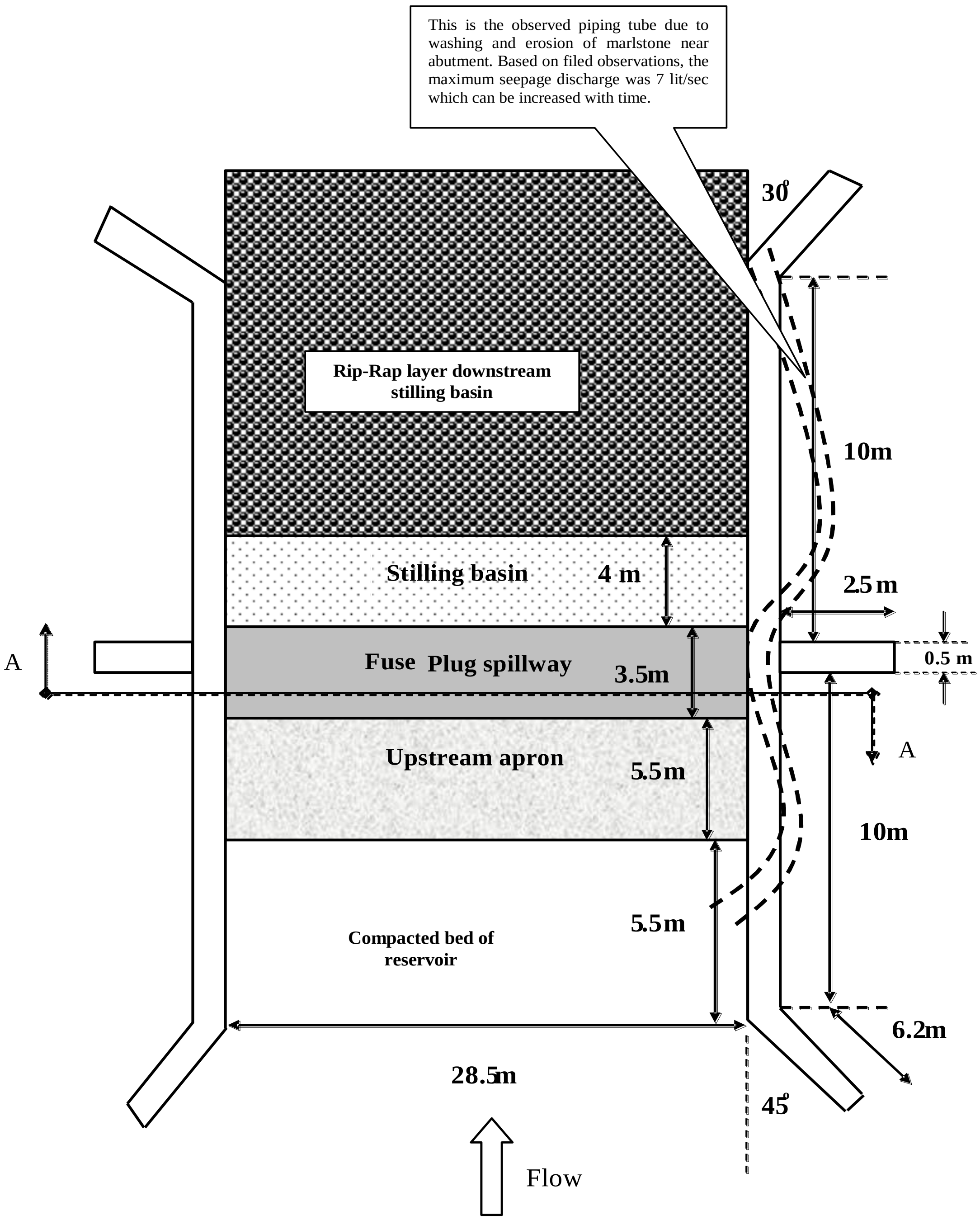


Fig. 3. a) Plan view of fuse plug spillway of Shahghasem dam (the dashed tube is piping hole)

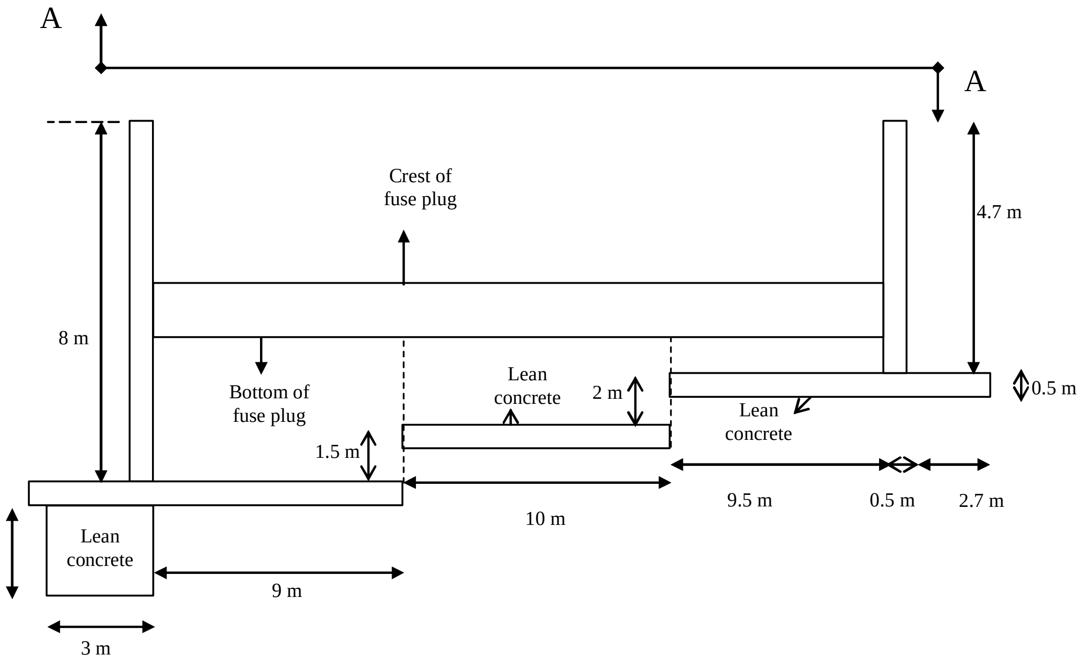


Fig. 3. b) Front view of fuse plug spillway of Shahghasem dam (not to scale)

3. Material properties of foundation

According to geological maps of the dam, foundation materials are Marlstones which is consisted of rock fragments and clayey with silty fine grains. Generally speaking, this material is termed as Marlstone, but its behavior is more similar to soils compared to rocks. In other word, these types of rock have low cohesion. To achieve more details of the foundation materials, four samples were taken from upstream, middle, and downstream of the right abutment of spillway satisfying ASTM standard. A number of experiments, including gradation (ASTM C136), direct shear test (ASTM C3080) and finally falling head test were performed.

The specimen preparation procedure was adopted from that used by Mesri and Cepeda-Diaz (1986) [19]. Specimens were carefully brought to laboratory for performing direct shear tests. Loss or gain of moisture by the sample was avoided at all stages of preparation by keeping the sample in plastic bags and also carrying out operations in humidified atmosphere. Specimens were placed in a shear box which had two stacked rings to hold the sample; the contact between the two rings is at approximately the mid-height of the sample. Several specimens were tested at varying confining stresses to determine the shear strength parameters, the soil cohesion, and the angle of internal friction.

The main point during sampling and doing experiments was separation of the rock samples and grains due to wetting of the grains and saturation of the taken samples. Table 2 shows the results of falling head test to determine permeability of the materials experimentally.

Table 2. Results of falling head test to determine material permeability

number	Place of sampling	Depth	Type of sampling	Dry unit weight (gr/cm^3)	Water content		Permeability of materials (cm/sec)
					before	after	
1	upstream	10 cm	Remolding based on the laboratory compaction test	1.88	15.1	19.9	$2.25 * 10^{-6}$
2	downstream	10 cm		1.89	18.6	23.1	$2.17 * 10^{-6}$

As it is observed, the permeability is not so permeable to occurrence of the piping hole. To have a better conclusion, it is necessary to see the results of the other tests as well. Figure 4 shows the results of direct shear test for abutment materials at upstream and downstream side of spillway. The Mohr–Coulomb failure criterion represents the linear envelope that is obtained from a plot of the shear strength of a material versus the applied normal stress. This relation is expressed as:

$$\tau = C + \sigma.\tan\varphi \qquad (2)$$

where τ is the shear strength, σ is the normal stress, C is the intercept of the failure envelope with the τ axis, and φ is the slope of the failure envelope. The quantity C is often called the cohesion and the angle φ is called the angle of internal friction.

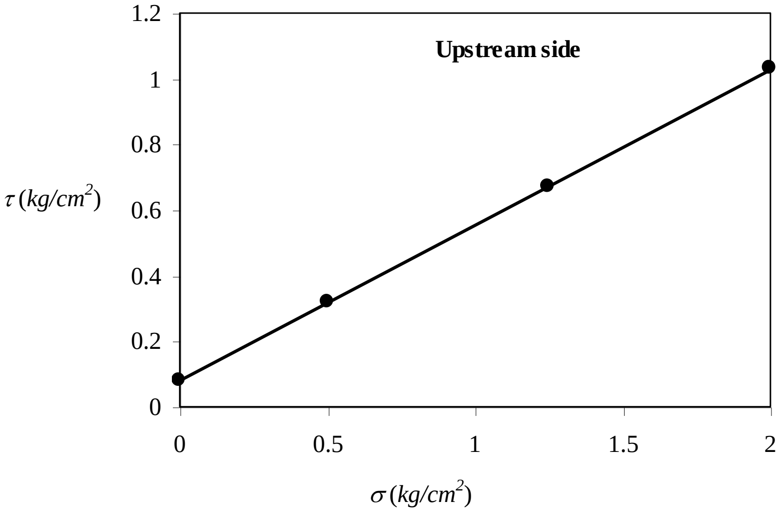


Fig. 4. a) Relationship between normal stress and shear stress of the upstream soil of abutment

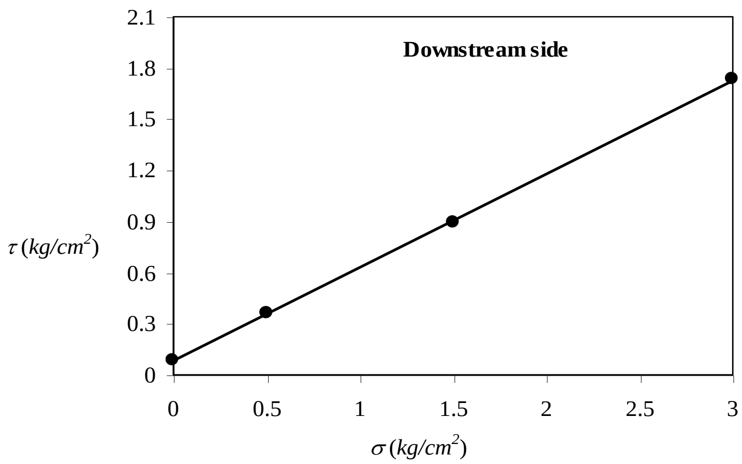


Fig. 4. b) Relationship between normal stress and shear stress of the downstream soil of abutment

By regression of the data of two soil samples of the upstream and downstream sides of abutment following relationships which are called Mohr-Coulomb equation are yielded:

$$\tau = 0.08 + \sigma.\tan 29 \qquad (3)$$

$$\tau = 0.1 + \sigma.\tan 25 \qquad (4)$$

According to geological maps, the foundation material is Marlstone, but this kind of stone is quite loose and soluble in water. As it is seen that the cohesion of the two samples are low and internal friction angle is medium. Therefore the materials of abutment are categorized sensitive to erosion, because there is not enough cohesion between grains. Although the internal friction angle is not law but the low cohesion of two samples comparing to clayey soils have not been considered by design engineers. By saturating of the soil samples into water, all the grain were dispersed and then solved gradually in water. For more details figure 5 shows graduation curve of the foundation materials.

The mean diameter of the dispersed rock a grain is 0.02 which is quite law and based on the Unified methods is corresponded to silty soil. Also the gradation curve is not perfectly well-graded.

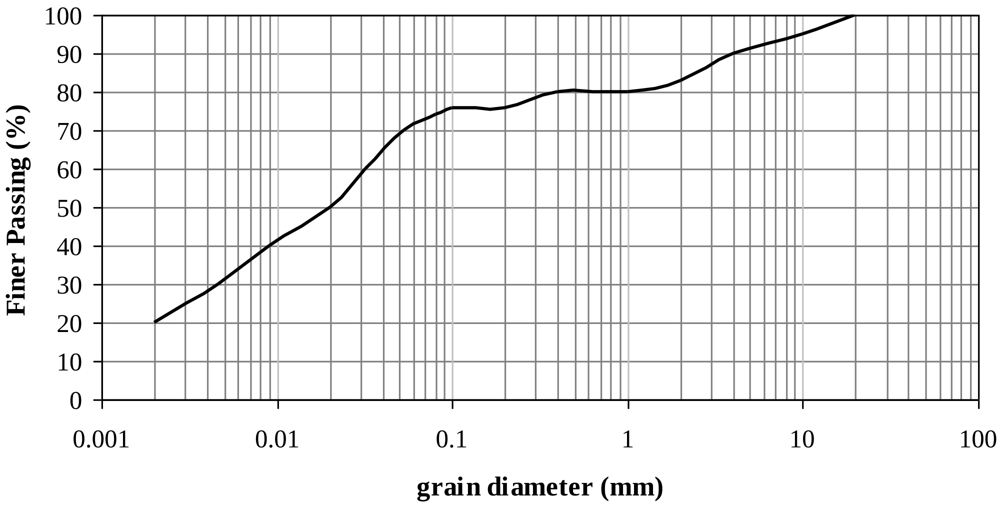


Fig. 5. Gradation curve of the materials of rock foundation

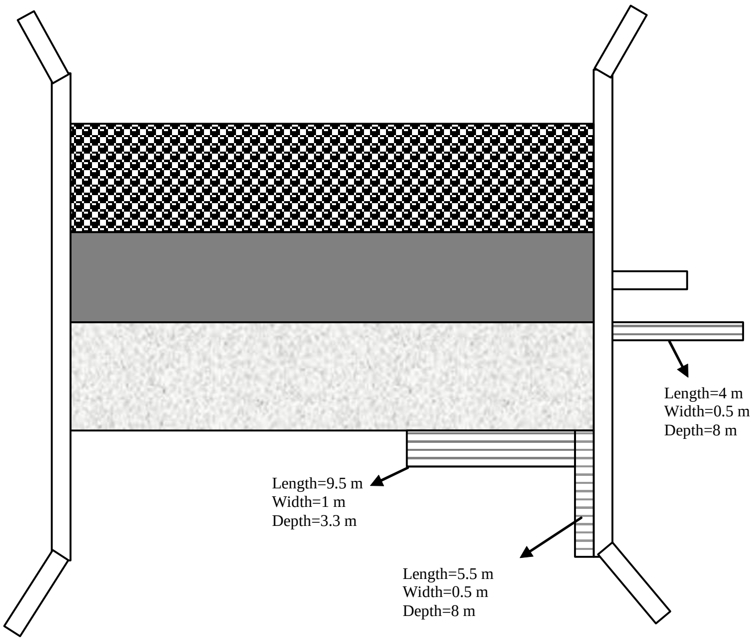
4. Discussion

It is necessary to look at as-built maps for finding the cause of this inappropriate design (Figs. 3a and 3b). It is observed that there are not enough watertight barriers between the concrete structure and the abutment or the embankment. First criterion in hydraulic engineering to safety design a hydraulic structure against piping is Lane and Bligh's creeping factor. By considering this simple formula, it can keep away from these destructive phenomena. Unfortunately in design maps and reports of the dam, there is no sign to consider these criterions. The main parameters in Lane's creeping factor are head difference between upstream and downstream (Δh) and creeping length of seeping water along with spillway (L). Based on the dimensions of the wire and creeping length, Δh and L were determined by using as-built maps as 6 and 15m respectively. The lane's criterion C was computed 2.5 using inverse method which is quite less than recommended by Lane (1934). The recommended value for this type of rock is 4, therefore for such a low cohesion rock the creeping length should increase to 24. From hydraulic and structural view point, concrete wall attached to the main wall of spillway should be considered.

The remedial measures differ from one site to the other since the geological formation and geotechnical properties of the given site are important for considering the proper stability measures. Considering drainage layers and filters with acceptable gradation along with spillway would be an action before constructing of the structures. At this stage, during operation this scenario is not capable. Other scenarios to improve the health of spillway are first filling the cavity hole by grouting concrete and second increasing the length of seeping water around the wall of spillway. In this case study, we used both filling and increasing the length scenarios. Another main cause of piping is that there is no downstream filter to plug eroded particles in as-built maps. Such a sensitive rock with low cohesion should be protected by filter layers along with concrete. This filter does not allow migrating fine grains along with concrete or foundation.

In addition to above-mentioned reasons, there is another cause for occurring piping. This cause is asymmetry foundation of the spillway which affected flow path and its diversion to right side. If the right supportive wall as well as lateral wall normal to spillway has been installed in deeper depth, then the seeping water to reach downstream side should track longer path and consequently its energy decreases.

The best case is an integrated approach to control internal erosion as well as piping. The first part is to attach a concrete wall to the main wall provided that the Lane's criterion is satisfied (Fig. 6). The second remedial action is to fill the hole pipe with concrete and cement.



Legend:

These walls are the added supportive walls with different dimensions to prevent piping and internal erosion. With this remediation, the seepage path will be blocked and the head loss of water seeping and flow will be drastically decreased.

Fig. 6. Final remedial measure to protect spillway against piping in right abutment

Concluding Remarks

Simple laboratory procedures are available to assess piping potential in cohesive materials, but no such methods exist for non-cohesive soil or rocks. In this research, piping type is categorized as internal erosion. According to Lane's creeping factor, practical remedial measures which can be prescribed for this special case is to first: attaching a series of supportive walls to the right wall of spillway as Figure 6 and second: filling the piping hole with high quality cement. It is also observed Marlstone foundation is sensitive to piping and internal erosion since this type of rock has a low cohesion.

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