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Computational Analysis of the Experimental Physical Model: Karstic Layer in Dam Foundation

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Abstract: Karstic rocks (soluble rocks) exist in different areas of the world having useful/harmful structural and environmental impacts. One of the useful aspect is availability of rich water resources in some regions. An important defect of this kind of rocks is their low strength against water flows. These rocks usually dissolve in acidic water and as a result abundant caverns are created inside them. The gypsum and salt present in these rocks dissolve even in non-acidic water. Presence of these rocks in different foundations and reservoirs especially in dams could be potentially dangerous and cause enormous problems.

If dams are located above soluble rocks like limestone, dolomite or gypsum they are endangered by karstification. Karstification is a dynamic process resulting in voids within the rocks due to dissolution. This dissolution leads to the formation of a pipe system within the sub-surface

In the physical modeling, effects of cut-off wall height within gypsum layer were examined and monitored. Then with GeoStudio and Flac software, results of physical modeling are analyzed.

In each experiment, cut-off wall height was changed. The result of the experiments indicated that as the gypsum Karst is very weak against water, cut-off wall must continue completely within the gypsum layer, as a complete positive cut-off wall.

Keywords: Solubility, Gypsum, Dam, Cut-off wall, Karst.

INTRODUCTION

Nowadays, dams that are designed and built are for better use of water flowing in rivers and surfaces. They are very important structures for storing water collected in a short wet season or supplied by a remote humid area. In these structures (dams and its basin), leakage and water loss from the dam foundation, reservoirs and abutments are the most crucial problems. Increasing leakage can lead to break down. If dams are located above soluble rocks like limestone, dolomite or gypsum they are endangered by karstification. Karstification is a dynamic process resulting in voids within rocks due to dissolution. This dissolution leads to the formation of a pipe system within the sub-surface (Willmann, 2001).

Due to complexity of Karst areas, these terrains have been considered problematic as sites for the construction of dams. But owing to the increasing demand for water, and the fact that about 15% of the earth's dry ice-free land is underlain by soluble rocks (Ford and Williams, 1989), a large number of dams have been constructed successfully worldwide (Romanov et al., 2003).

There are different methods for preventing the karstification processes in Karstic dam foundation, including grout curtain and cut-off wall (Milanovic, 2000). These methods will cause decrease of groundwater flow or stoppage.

In this research, the effects of cut-off wall height in soluble layer (crushed gypsum layer) on downstream foundation leakage will be investigated. This research composed of 4 tests and as mentioned above, the height of cut-off wall in gypsum layer after each test will change. In each test, leakage from downstream foundation changed during the test.

Effect of Cut-off Wall Height on Extent of Foundation Leakage

Four tests were carried out and the height of cut-off wall in gypsum layer after each test is changed. In each test, leakage from downstream of foundation is measured.

Experimental Model of Dam Foundation

Experimental apparatus (model) and its specifications are shown in Fig.1. In this physical model of dam foundation, water with pressure, about 70 psi, from water

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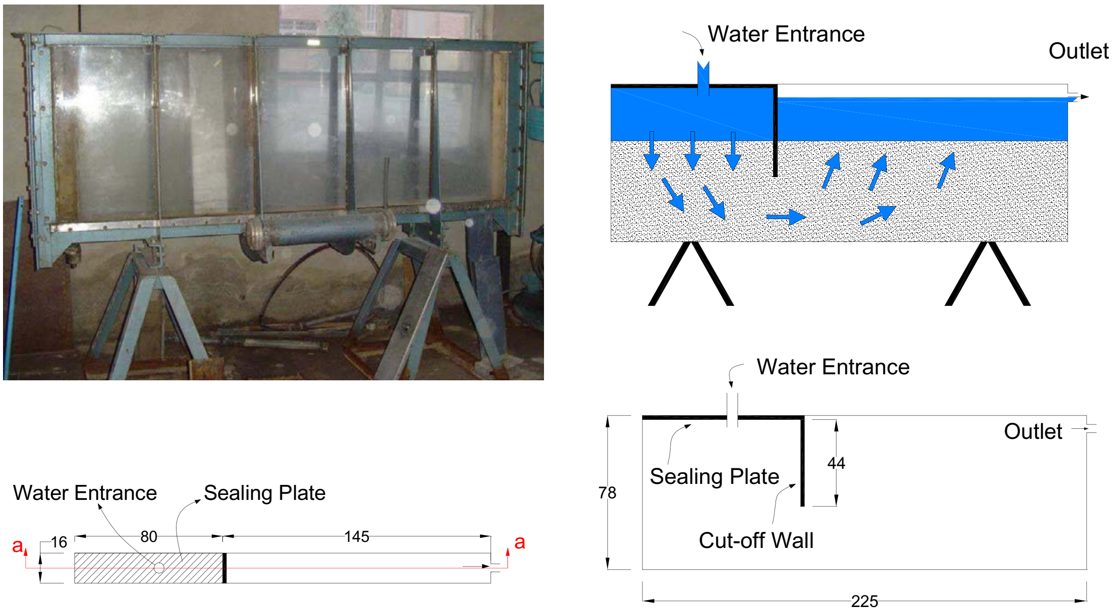

Fig.1. Physical model of dam foundation (dimensions are in term of centimeter). **(a)** Apparatus of model of dam foundation. **(b)** General View of dam foundation during the test. **(c)** Top of Apparatus view. **(d)** Section a-a.

entrance location (Figs. 1 b, c and d) enters the foundation in the upstream of cut-off wall. To assess the effect of cut-off wall height, height of cut-off wall is changed after every test.

When water flow comes to the surface of gypsum layer with smallest amount of head loss, then the gypsum layer should lay adjacent to all possible lines of water flow; consequently gypsum layer must cover all the model. Also, water must penetrate through the gypsum layer to arrive at the downstream. Therefore, cut-off wall must intersect gypsum layer so that the water cannot pass through the space between top of gypsum layer and bottom of cut-off wall. Layering of the model is shown in Fig. 2.

Physical and Chemical Characteristics of Used Gypsum

Table 1 gives all the characteristics of crushed gypsum and crystallized gypsum that was used.

In order to test solubility and karstification of the gypsum, it was necessary to stop the migration of gypsum grain through the pores of the lower sand. In that respect, gradation of the sand should satisfy the filter criteria for the crushed gypsum grains.

Figure 3 demonstrates filter range zone for the gypsum. According to this figure it can be concluded that the sand used in experiments works as a filter and does not allow passage of gypsum and gypsum grains through sand grains, hence erosion will not take place.

Therefore, the loss of gypsum in the cell is due to the solution phenomenon.

Preparation of Equipment (apparatus) for Starting Tests

In this model upstream (location of water entrance,

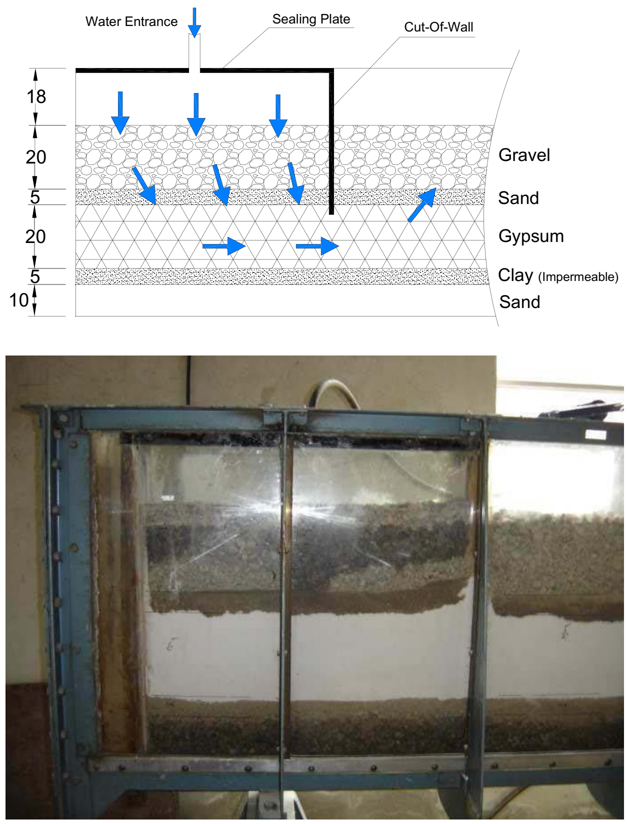

Fig.2. Soil classification in model of dam foundation **(a)** schematic. **(b)** actual (Dimensions are in term of centimeter)

Table 1. Characteristics of used crushed gypsum and crystallized gypsum

Crystallized Gypsum	Density (gm/cm^3)	2.32
	Molecular mass	172
	Water	0.209
	SO_3	0.466
	CaO	0.325
Crushed Gypsum	Molecular mass	146
	Density (gm/cm^3)	0.97
	Elementary Setting Time (min)	6-8
	Secondary Setting Time (min)	18-22
	Crystallization water	5-6 %
	Compressive Strength(kg/cm^2)	80
	Bending Strength(kg/cm^2)	38
	Purity	95%

upstream of dam), was sealed by a steal plate to avoid leakage. Confined flow was facilitated to upstream by a ½ inch-tube. Water pressure was approximately equal to 70 psi which is equivalent to 49 m water head.

The experiments comprised of 4 tests. In these tests, cut-off wall height in gypsum layer was changed. Thickness of gypsum layer was 20 centimeters in all tests. Different cut-off wall heights in gypsum layer were 5, 10, 15 and 20 centimeters respectively. All the tests are illustrated in Fig.4.

In the last test, cut-off wall is inserted completely in the gypsum layer; and even a small portion of the wall (3 centimeters) was placed under gypsum layer within clay. In order for the water to be able to pass only through gypsum and not to penetrate through the edges of gypsum layer, the contacts between fiberglass and gypsum is filled by compacted clay.

Physical Test Result

Figure 5 shows the layering after test no. 1. As shown in the figure, in the downstream of cut-off wall and beneath the cut-off wall, because of high hydraulic gradient, the layering is disordered completely.

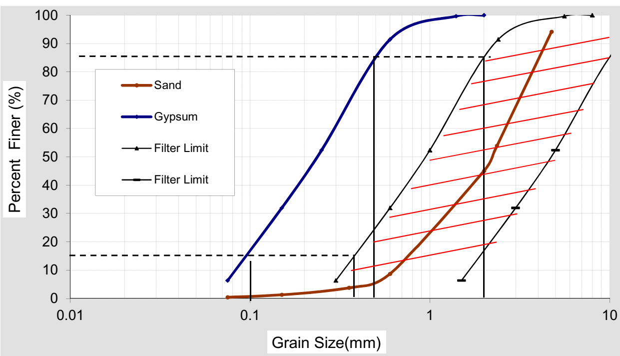

Fig.3. The grain-size distribution curve for sand and gypsum (the hatched zone is the filter range for the gypsum)

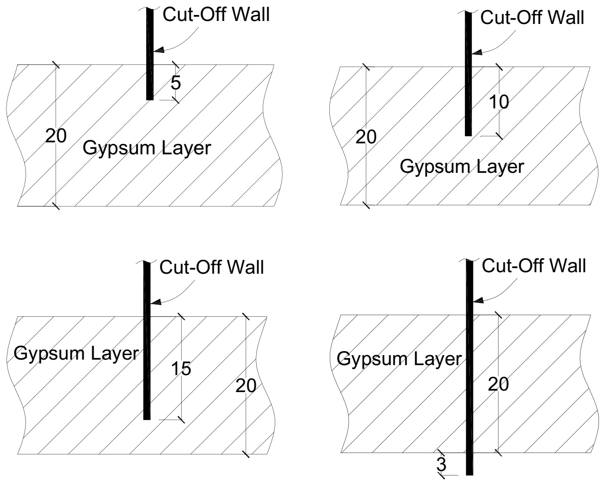

Fig.4. Different steps of test nos. 1-4. Cut-off wall height within gypsum layer is (a) 5 m (b) 10 cm, (c) 15 cm. (d) Cut-off wall is situated completely within gypsum layer.

Discharge variations in the beginning and at the end of the tests are shown in Fig. 6. Beginning time is that time when water arrives downstream and exits from the outlet tube and the outlet discharge is called primary discharge. The ending time is that time when confined water under the sealing plate at upstream, is converted to unconfined water and the outlet discharge is called secondary discharge.

As was seen above, from test 1 to test 4, the slope of discharge curves decreases. Besides, the duration in which confined water at upstream is converted to unconfined water, increases. This shows that with increase in cut-off wall height, leakage discharge from foundation (gypsum layer) decreases. These tests also show that leakage discharge increases with time. In general, in the karstic layer, leakage discharge from this layer increases because of dissolution and development of fractures and cracks. Because of low permeability of clay, it cannot enter the clay layer under the gypsum layer.

Fig.5. Layering after the test.

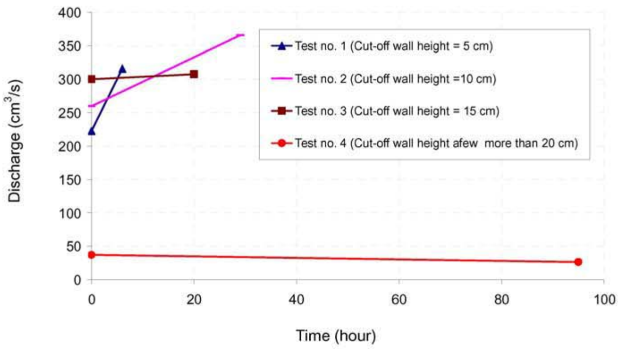

Fig.6. Discharge variations in four tests.

In test 4, water was forced to flow just under the gypsum layer, because the cut-off wall has blocked the gypsum layer. Therefore, leakage discharge would not change greatly because clay and sand are not dissolved by water flow. Also, low permeability of clay and hardening of gypsum caused the reduction of leakage discharge with time. Figure 7 depicts percentage of leakage discharge variation.

If the cut-off wall height increases within gypsum layer, sensitivity of leakage discharge variation decreases (Fig.6).

In natural conditions, it is necessary that the whole of karstic layer, especially gypsum, be sealed with cut-off wall or grout curtain. Partial sealing of the layer can be unsafe and risky.

Computational Analysis

Two different analyses have been made in this laboratory work. In analysis no.1, the beginning of discharge and the ending of discharge for any test (25%, 50% and 75%) were modeled and simulated and permeability of gypsum layer was measured.

Model Structure

This model composed of 2 layers of sand and gypsum. The specifications of these layers are listed in Table 2.

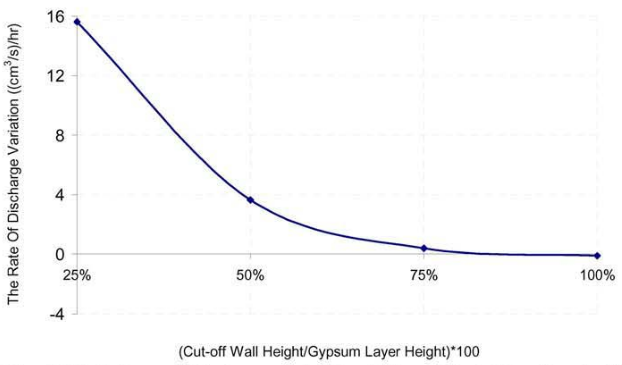

Fig. 7 Variation of discharge rate for different heights of cut-off wall

Table 2. Specification of materials

	Height (cm)	Permeability (m/s)
Sand	5	0,01
Gypsum	20	Variant

When water from upstream enters the sand and gypsum layer, it can only pass from the bottom of cut-off wall. In Fig. 8 and Fig. 9 model structure is shown.

Analysis of this model is done in two scenarios. In scenario 1 for different discharge, permeability of gypsum is measured and also the maximum velocity in the gypsum layer is evaluated.

In scenario 2, for the constant upstream head of 53 m the permeability of gypsum, ($4.6E^{-3}$ m/s), variation of velocity in the bottom of cut-off wall for different cut-off wall height are assessed.

Scenario 1

For example, in Table 3, with a 53 m pressure head in upstream and 222 cm^3/s (beginning the test of 25% cut-off wall) downstream discharge, the permeability and the maximum velocity is evaluated with GeoStudio software, also, with the 53 m pressure head in upstream and 316cm^3/s (ending the test of 25% cut-off wall) downstream discharge, analysis was repeated. In Table 3, the results of these analyses are listed. Highlighted columns are the result of the software analysis.

On the basis of these results,the velocity and permeability in any test are increasing. For example for cut-off wall 25%, velocity increased from 0.93 to 1.36 m/s and this repeated for cut-off wall 50% and 75%.

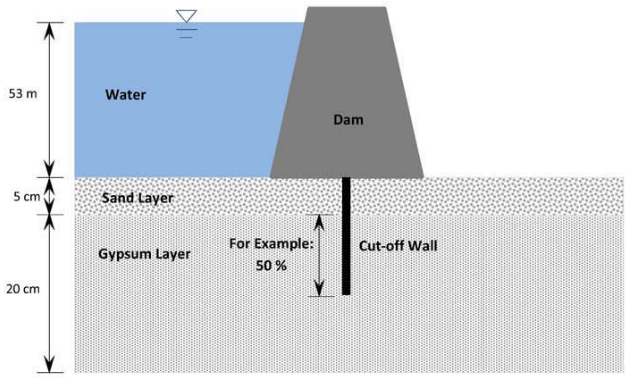

Fig.8. Computer model structure of dam foundation.

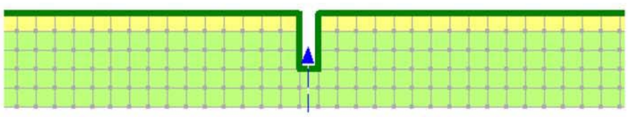

Fig.9. Model structure of dam foundation

Table 3. Gypsum permeability and maximum velocity

(Cut-off wall Height/ Gypsum Layer Height)*100	Beginning of the Test			End of the Test			Duration of the Test (hr)
	Discharge (cm^3/s)	Maximum Velocity (cm/sec)	Permeability (cm/sec)	Discharge (cm^3/s)	Maximum Velocity (cm/sec)	Permeability (cm/sec)	
25%	222	0.93	$4.6E^{-3}$	316	1.36	6,55E-3	6
50%	260	1.61	$7.7E^{-3}$	366	2.29	11E-3	29
75%	300	3.74	$13.8E^{-3}$	308	3.8	14.1E-3	20
100%	37	0	0	27	0	0	96

With the increasing of velocity, after a long time, the laminar flow in the voids is transited to turbulent flow. With establishment of turbulent flow, the ratio of solubility increases suddenly. These variations are very dangerous for the dam foundation or reservoir because of break-d own or leakage.

Scenario 2

In Table 4 the result of this scenario are listed. The highlighted column is the result of the software analysis.

It can be seen that the velocity under cut-off wall is increasing with the increase of cut-off wall height in gypsum layer i.e., whenever the more area of gypsum layer is sealed with cut-off wall, the water velocity in the unsealed area is increased.

Table 4. Velocity under cut-off wall

(Cut-off wall Height/ Gypsum Layer Height)*100	Upstream Head (m)	Permeability (cm/sec)	Velocity under Cut-off wall (cm/sec)
25%	53	4,6 E-3	1,25
50%	53	4,6 E-3	1,7
75%	53	4,6 E-3	2,93

This shows, with partial sealing of gypsum layer, complete water flow from gypsum layer cannot be stopped. Also, with time, velocity in karstic layer increases (result of scenario 1).

Gypsum is very weak against water head and fractures develop quickly. Thus, for preventing leakage in karstic layer in dam foundation, it is recommended that sealing of karstic layer by cut-off wall or grout curtain is necessary.

CONCLUSION

Gypsum dissolution is a great threat to dam foundation and its reservoirs. Because of unpredictable condition of karstic areas and possibility of existence of fractures and fissures in these areas, increasing of hydraulic gradient on fractures will lead to the progress of karstification. Karstification can cause water loss from reservoir and from around or under the dam. Also this phenomenon can lead to inhomogeneous subsidence.

The sealing of part of soluble layer in the dam foundation or reservoir can pose threats in the future. Therefore it is recommended that remediation and sealing methods must be carried out in the entire soluble layers.

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