Study on the behaviour of cut-off-walls in homogeneous and heterogeneous dam foundations

Mehdi Karimnia, Phd Stu., mehd_kar@cic.aut.ac.ir
Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran
and
Amir Shahkarami, Professor, amirshah@aut.ac.ir
Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran

ABSTRACT
Regarding to important role of cut-off-wall behaviour in seepage reduction and dam stability, in this paper we have studied interaction between dam body, cut-off-wall and foundation, considering the effects of interface elements. We tried to examine the behaviour of walls in homogeneous and heterogeneous dam foundations.
We studied on the behaviour of karkheh dam cut-off-wall in heterogeneous foundation and compared the results with the same model but with a homogeneous foundation.
Obtained results show that the cut-off-wall in homogeneous foundation is subjected to a nearly hydrostatic water pressure. In this case relation between elasticity modulus of foundation and cut-off-wall is very important to assign the appropriate behaviour of the cut-off-wall. If these two modulus to be close enough to each other, induced stresses and strains in the wall will be moderate and acceptable.
In the case of heterogeneous foundation, the results are different. In this condition cut-off-wall is subjected to stress and strain localization near to mudstone layers and maximum pore pressure near to conglomerate layer. Although, hydraulic fracturing will not happen in cut-off-wall because of high effective stresses.
Keywords: *interaction, cut-off-wall, homogeneous, heterogeneous foundation, stress localization, hydraulic fracturing.*

1- General project characteristics

Regarding to reservoir capacity (7.78 billion m3) and embankment volume (about 27 million m3), Karkheh storage dam is the largest dam in Iran which is located on the north west of andimeshk in khoozestan province. It is constructed on karkheh river that is the third river regarding to discharge.

Karkheh dam is an earth dam with clay core. The height is 127 m and the crest length is about 3030 m. Dam foundation is consist of conglomerate and mudstone layers with different physical and mechanical characteristics. Conglomerate layers are separated by mudstone layers with 6m average thickness and very low permeability.

Bakhtiary conglomerate is the upper part of the aghagari formation in the dam site. There are six mudstone layers which are laid in this conglomerate layer and divided it to two different parts that are named upper and lower bakhtiary conglomerate layers.

Dam body in the middle part and in the small part of the left and right sides is located on lower bakhtiary conglomerate, thickness of this part in the river bed is about 100 to 105m based on information obtained from exploration logs.
This conglomerate layer is weakly cemented and consist of very tiny sand and silt. Also there are mudstone layers and sandstone lenses in this conglomerate. Mudstone layers in the small area of the dam and reservoir are like very spread lenses which can be supposed nearly continues and horizontal layers in the dam area. Mudstone layers are named from top to bottom +3,+2,-1,-2,-3 respectively.
Left and right sides of the dam foundation in the upper levels are formed by the upper bakhtiary conglomerate.(figure no. 1)
General characteristics of karkheh dam cut-off-wall :
Karkheh dam plastic concrete cut-off-wall is a 42m average depth wall With maximum depth of 70m and length of 2850m. The wall penetrates 3 to 8m into the clay core and 1.5 to 2m into the mudstone layer. Its thickness varies from 0.60 to 1m in different parts.
To achieve an appropriate impermeability and flexibility, 1 to 5 percent bentonite is used to mix design of plastic concrete. Plastic concrete modulus of elasticity must limit to a certain value (because of the required flexibility) and this parameter is strongly related to mix proportion and mixing method, therefore plastic concrete mix design is very important to find appropriate design that satisfies required impermeability and mechanical properties of plastic concrete.

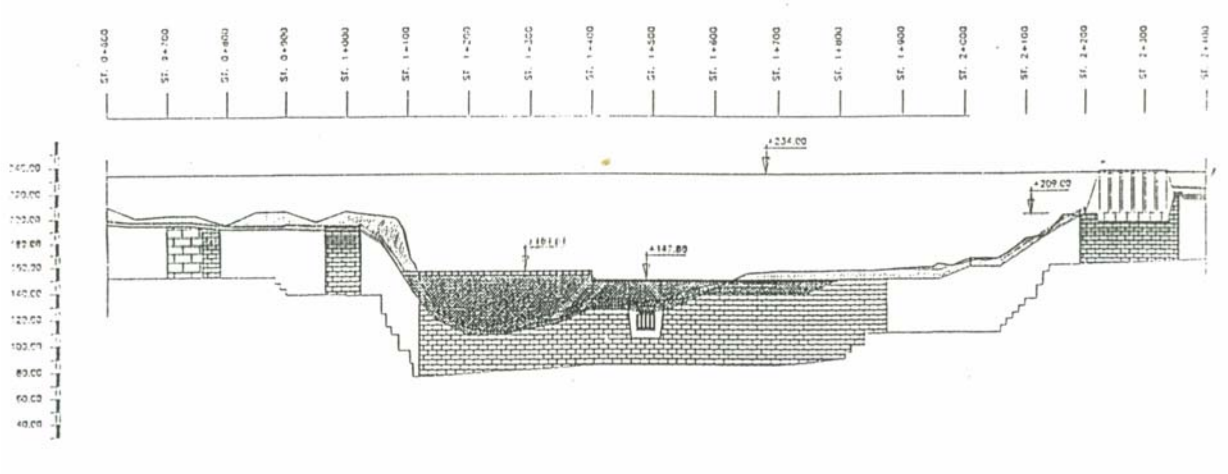

Figure 1: *Longitudinal section of Karkheh reservoir dam*

Respect to mentioned information and regarding to project importance and too much required concrete, many mix designs have been tested and finaly, optimum design has been selected after technical and economical study.

2- Mechanical characteristics of dam body and foundation layers

To achieve mechanical properties of dam embankment, mudstone and conglomerate layers, direct shear and triaxial tests have been used.
CD and CU triaxial tests have been done under different lateral stresses on many samples then elasto-plastic behavior of the conglomerate has been resulted. Also triaxial tests for embankment and Direct shear tests in strain control condition for different mudstone layers have been done. The results show low strength of these layers, but the results are not valid for high depths because lateral stress can not be used in this test.

Obtained results from different kinds of tests, such as mechanical properties of different parts of the dam body and foundation layers are mentioned in the following table (table no. 1). All parameters are the same for two mentioned models, but homogeneous foundation properties are same as conglomerate layer.

Table 1: *Cohesion, internal friction and density for different parts of the dam*

ZONE & DESCRIBTIONS			Density wet (t/m^3)	Density sat (t/m^3)	Friction degree	Cohesion (t/m^2)
CLAY CORE ZONE 1	Bottom of core Zone (1A)	U.U.	2.01	2.07	6.5	8
		C.U.	2.01	2.07	13	5
		C.D.	2.01	2.07	24	2
	Top of core Zone (1B)	U.U.	1.85	1.95	6	7
		C.U.	1.85	1.95	20	3
		C.D.	1.85	1.95	22	2
RIP-RAP & SHELL & FILTER	Zone (2)	Depth from 0 to 10m zone (2A)	2.05	2.2	45	0
		Depth from 10 to 20m zone (2B)	2.05	2.2	41	0
		Depth from 20 to 40m zone (2C)	2.05	2.2	39.5	0
		Depth from 50 to 60m zone (2D)	2.05	2.2	38.5	0
		Depth greather than 60m zone (2Б)	2.05	2.2	38	0
	Zone (3)	Depth from 0 to 10m zone (2A)	2	2.2	46	0
		Depth from 10 to 20m zone (2B)	2	2.1	40	0
		Depth from 20 to 40m zone (2C)	2	2.1	38	0
		Depth from 50 to 60m zone (2D)	2	2.1	37.5	0
		Depth greather than 60m zone (2E)	2	2.1	37	0
ALLUVIUM	Zone (4)	All	2	2.2	38	0
CONGLOMERA	Zone (5)	All	2.2	2.3	39.4	8.5
MUDSTONE	Zone (6)	No −2	1.95	2.1	22	7
	Zone (7)	No −1	1.95	2.1	22	7
	Zone (8)	No +2	1.95	2.1	21	5
	Zone (9)	No +3	1.95	2.1	22	7
	Zone (10)	No +4	1.95	2.1	22	7
DUMPING MAT	Zone (11)		1.8	2	33	0

3- Study of pore water pressure induced by dam impounding

To obtain water pressures which affect dam and cut-off-wall, we used FLAC software which is capable to do that.

For mudstone layer(-1) we supposed continues and discontinuse conditions and obtained water pressure distribution in core and cut-off-wall.

Results of analyses show that water pressure which affects cut-off-wall, is time-dependent. If foundation around the cut-off-wall is much permeable, water pressure distribution on the wall will be nearly hydrostatic soon after dam impounding, but if there are impervious layers in foundation too, water pressure distribution on the wall will be time-dependent.

Respect to high permeability of shell material, only dam core, foundation and cut-off-wall are considered in the model. Two different conditions, continues and discontinues, for mudstone(-1) layer, are supposed. Result of water pressure distribution on the cut-off-wall can be seen in the following figures (figures no. 2 to 5), because of high permeability of conglomerate layer and low energy dissipation, water pressure distribution in homogeneous foundation is nearly hydrostatic.

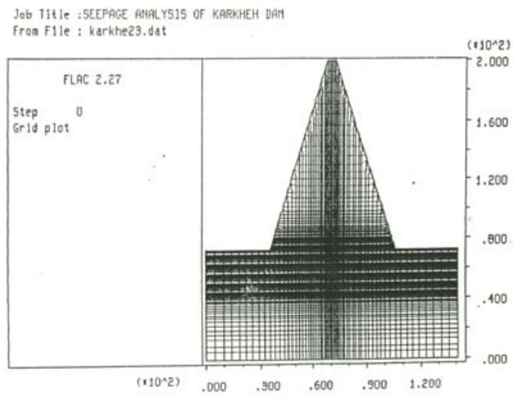

Figure 2: *Seepage analysis model*

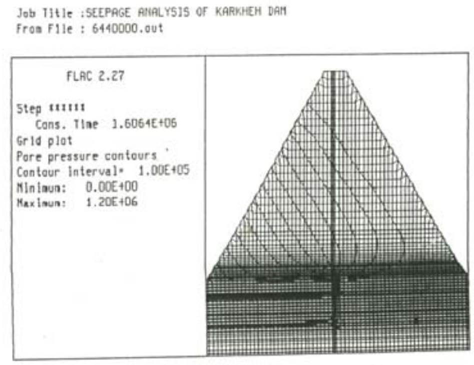

Figure 3: *Pore water pressure (impounding)*

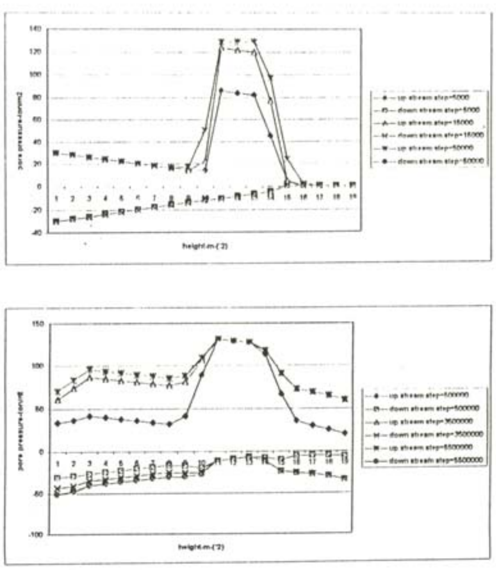

Figure 4: *Water pressure distribution on Cut-off-wall (continues mudstone -1)*

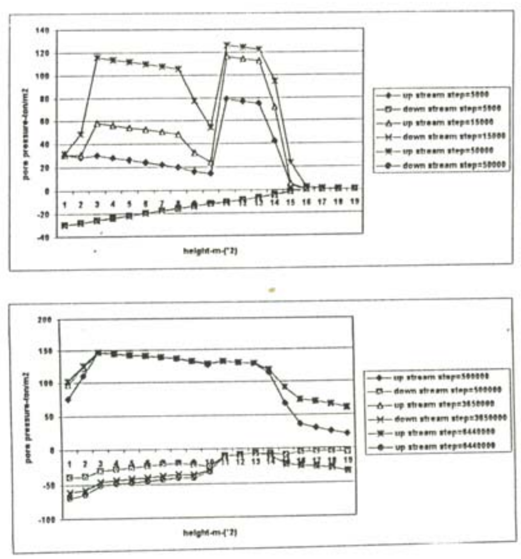

Figure 5: *Water pressure distribution on cut-off-wall (discontinues mudstone -1)*

4- Interaction analysis of cut-off-wall and dam foundation

To model stage construction in earthfill dam, we need to a program that can activate and inactivate elements during the program running, which flac program has got this capability. In each stage mechanical parameters are determined based on new lateral stresses to use in the analysis. Four node plane strain elements are used to model 38m deep cut-off-wall with 1m thickness which penetrates 8m into the core and 4m into the mudstone layer.

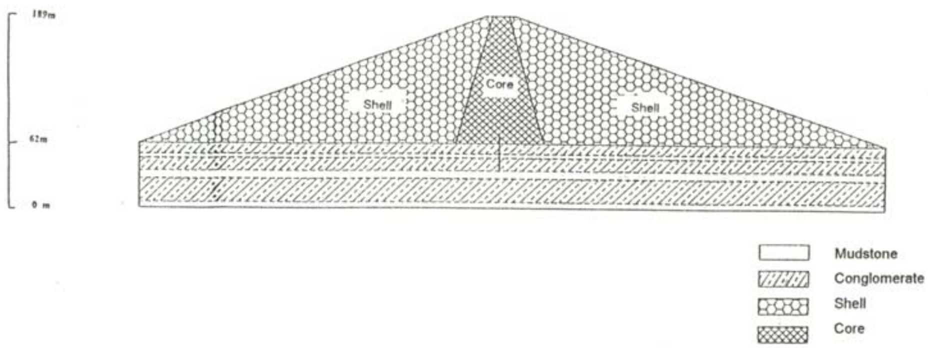

Figure 6: *Dam body and foundation*

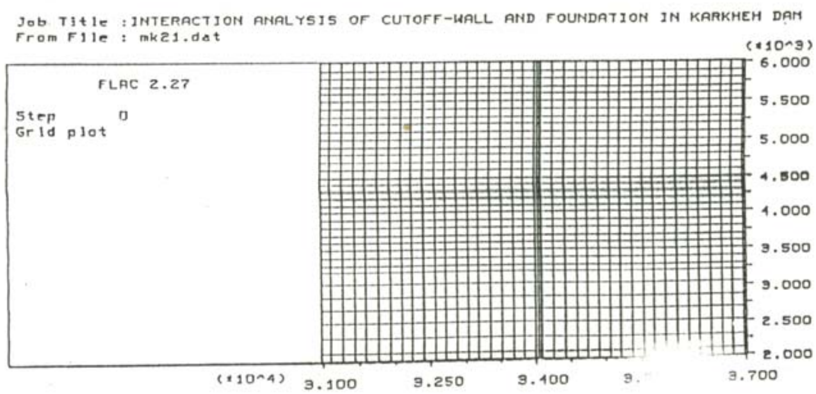

Figure 7: *Mesh, around the cut-off-wall*

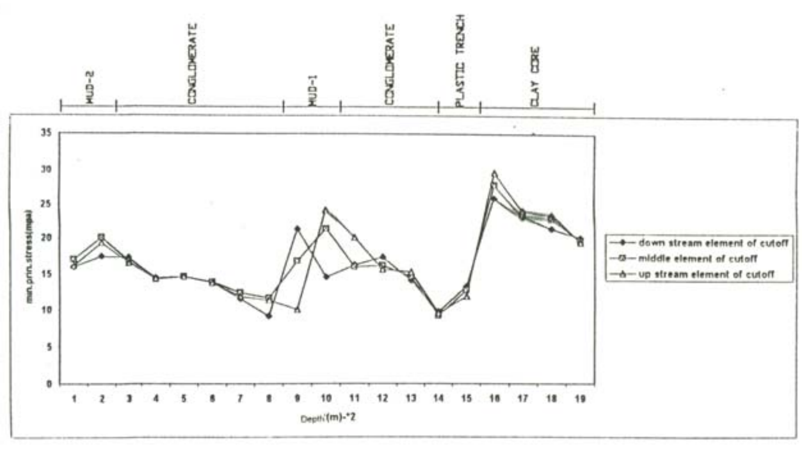

Figure 8: *Major principal stress (dam impounding stage)*

Interface elements are used to model the contact surface of the wall, core and foundation. To model the impounding stage, pore water pressure made by impounding, is obtained from the previous part. Dam section and modelling domain is shown in the following figure. Different analyses in different conditions have been done to assign cut-off-wall behaviour. Therefore, the model response under different geometrical conditions and mechanical properties have been studied and the results are mentioned here.

Major principal stresses on the top of the wall are minimum. These stresses will increase around the conglomerate layer and will be maximum in the mudstone layers. Big difference between mudstone and conglomerate modulus of elasticity causes stress localization in the cut-off-wall around the mudstone. Minor principal stresses, beneath the core, are the highest that the reason is high value of poisson's ratio. These stresses decrease beneath the conglomerate (because of normal stress decrease), and increase in the mudstone layers (because of normal stress increase).
Also deviatoric stresses are maximum around mudstone layers. After dam impounding, Major principal stresses in down stream side elements of the wall decrease and in the upstream side elements increase because of the wall movement toward downstream. High amount of deviatoric stresses in cut-off-wall around the mudstone shows stress localization in this part of the wall.
Maximum Vertical strain is %1.35 beneath the mudstone(-1) layer while maximum lateral strain is %1.2 beneath this layer. These strain values show that if cut-off-wall properties to be selected properly, its strength would be enough.
In impounding stage, maximum pore water pressure value, 1.25Mpa, happens in the contact point of conglomerate and mudstone layers. To study the effects of pore water pressure on probable cracks and possibility of crack opening and hydraulic fracturing in cut-off-wall, values of stresses normal to model plane, which cause to close the cracks, are needed. These stresses were determined next to the conglomerate layer Because pore water pressure is critical in this layer. value of this stress is 2Mpa, so hydraulic fracturing safety factor is 1.6 which shows the wall is safe against hydraulic fracturing (figures no. 6 to 11). In both conditions, stress state in the contact part of cut-off-wall and clay core are nearly the same. In the homogeneous condition, because of hydrostatic water pressure and the same parameters of the foundation around the wall, deviatoric stress in the wall changes moderately. Deviatoric stresses in the homogeneous foundation and cut-off-wall are nearly the same, it shows that elastic properties of the cut-off-wall are selected properly. Maximum deviatoric stress in lower part of the cut-off-wall is 35 kg/cm2. There is not stress localization in the cut-off-wall because of homogeneous foundation, therefore strain values variation in the cut-off-wall elements is moderate and its maximum strain value is limited to %0.6. In the case of homogeneous foundation, maximum water pressure in cut-off-wall is 13 kg/cm2 and happens near conglomerate layer. In homogeneous foundation, the effects of water pressure on making cut-off-wall hydrofracturing is nearly similar to heterogeneous foundation.

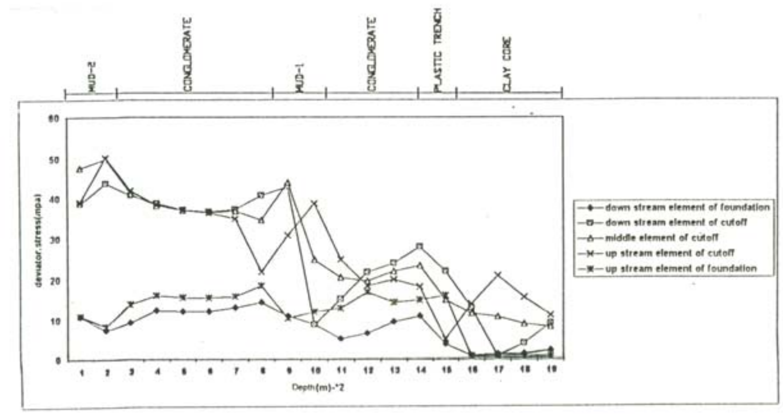

Figure 9: *Deviatoric stress (dam impounding stage)*

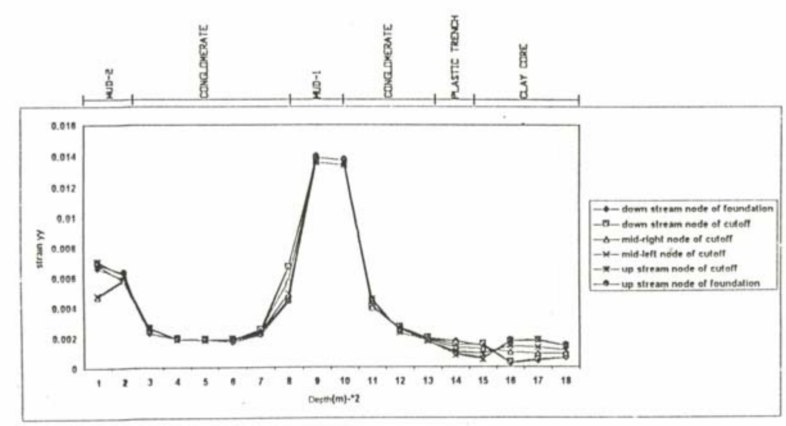

Figure 10: *Major principal strain (dam impounding stage)*

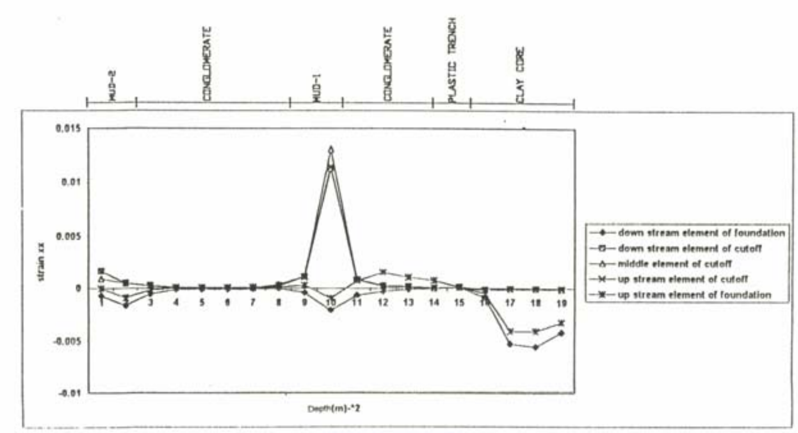

Figure 11: *Minor principal strain (dam impounding stage)*

5- Conclusions:

Regarding to the analysis results in the case of heterogeneous foundation, maximum cut-off-wall deformations happen next to the mudstone(-1) which is a weak layer in a manner that maximum vertical strain and maximum horizontal strain are %1.35 and %1.2 respectively. But in the case of homogeneous foundation, stress localization will not happen along the wall (next to the conglomerate layer) and horizontal and vertical maximum strains are limited to %0.6 and %0.4 respectively.

In both cases, results show that if elasticity modulus of cut-off-wall decreases to less than 2000Mpa, stresses which are normal to the model plane will decrease (these stresses cause to close the cracks). Therefore next to the conglomerate layer where pore water pressure is maximum, probability of hydraulic fracturing will increase. Thus cut-off-wall elasticity modulus must not decrease to less than 3000Mpa. Moreover increasing the modulus of elasticity to more than 7000Mpa, cause stress localization increase near mudstone layer (in heterogeneous foundation) and tension stress increase in the upper part of the wall (in both cases), therefore value of this modulus must be limited to a certain value (in the safe side about 6000Mpa). Also, in both cases, if the upper part of the wall (next to the core) is subjected to tension stresses, some appropriate solutions must be considered to sealing and protecting this part.

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