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Stability Analysis of Esfarayen Garati Dam using Finite Element Method

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***Abstract* – In this study, stability and behavior of the dam to static forces during construction and first impounding is analyzed and conclusions are being made using finite element method and computer programs. The analysis purposes are as following:**

1) **The analysis of hydraulic fracturing in clay core and interactions of internal zones, and consequently, the study of arching phenomenon inside the core.**
2) **Upstream and downstream slope stability analysis by determining landslide safety factors using calculated stress field in body and foundation of the dam.**
3) **Evaluation of pore pressure at the end of dam construction, and this analysis can be considered a basis for calculating the period of dam construction operations. In addition, by comparing Ru ratio resulted from stress-strain analysis, limit equilibrium assumptions are controlled.**
4) **Determination of the dam settlement during construction period for compensating horizontal profile drawdown that gives required information required for calculation of additional embankment.**
5) **Determination of settlement after construction and during operation of the dam. This value would be used for determination of camber.**
6) **Seepage analysis and study of drainage currents through construction materials and hydraulic equilibrium of dam and the volume of water drained from foundation and body of the dam according to the results of Lugeon test and steady state analysis for 6 months in filled and 6 months in semi-filled dam reservoir.**

The method used for computer analysis of strains during construction and first impounding is the effective stress method with respect to water-soil interactions (coupled mechanical-fluid model). For this purpose, Sigma/W stress analyzer component of GeoStudio 2007 software is employed.

***Keywords* – Stability Analysis, Esfarayen Garati Dam, Finite Element Method**

I. Introduction

Garati Dam is built on Kal-e Velayat River and is located upward Garati village 25 Km far from Esfarayen city in North Khorasan province. This river joins EsfarayenBidwaz River at downward Garati village and enters EsfarayenKal-e Shour River. The axis of the river lays at 57°34' longitude and 36°54' latitude. Image (1) displays a satellite image of the Garati Dam position.

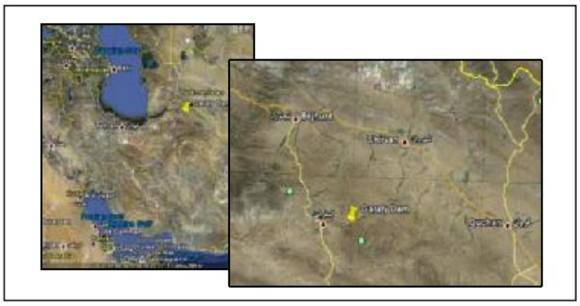

Image 1: Garati Dam position in satellite images

Plot geometry: The critical cross section, which was analyzed, consists of internal zoning including core, filters, drainage pipes, and benches. Figure (1) shows the geometric model of the dam cross section, which is used for stress-restrain analysis.

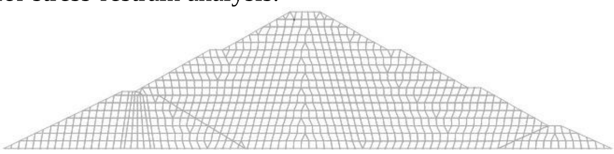

Fig.1. Geometry of critical cross section of the dam

Behavioral model of construction materials: In strain-deformation modeling of construction materials of different parts, Mohr–Coulomb model is employed. Full explanations are given about this well-known behavioral model in most of the books written about behavioral model and soil mechanics. The characteristics of this model are described, the main properties used in Mohr–Coulomb model include:
1) Cohesion 2) Internal friction angel 3) young modulus 4) Poisson's ratio 5) Dilation Angle
Loading: Static analyses using finite element method are done in the following two loading cases:
1) Through dam construction period to the end of construction
2) The first impounding of the dam reservoir.

It is worth mentioning that in most of the dam construction projects in water industry worldwide, behavior of the dam deformation under stress is often analyzed according to the two states which was mentioned earlier, and for other static loadings such as permanent seepage and rapid drawdown, a classical analysis within limit equilibrium range is sufficient, and this point is heeded here.

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II. MATERIALS AND METHODS

Construction loading of Garati Dam: Construction of Garati dam is done in multiple stages, so that cofferdam is constructed in 7 layers and the main dam in 18 layers (the average of the layers' thickness in cofferdam and in the main dam is 3 meters). It is simulated in Sigma/W software environment. It is worth pointing out that in accordance with expected sequences in practice; first, the analysis and construction procedure of upstream and downstream coffers, and then the dam's main body are simulated. Since the analysis is performed in coupled two phases of fluid and soil, and considering timely events resulted from the interactions between these two phases such as consolidation, the minimum schedule for the dam construction is determined by both controlling increase in pore pressure and stability during construction.

Loading at first time impounding:

After analyzing stress-strain in construction period, loading of the dam impounding is performed in three stages at a one-year intervals. Considering the dam's reservoir level lines, these stages include:

Stage I: From minimum water level to the level 1226 within three months

Stage II: From level 1226 to 1242 within three months

Stage III: From level 1242 to 1251 within 6 months.

The one-year period for the dam to reach its full impoundment is chosen with respect to water resources programming as well as enforcement of critical condition regulations. It should be noted that the effect of buoyancy force for coarse aggregates in upstream shell settlement is applied in this analysis.

Geotechnical parameters used in this analysis

Geotechnical parameters of materials of different parts of the dam body, which were used in static analysis, are achieved through the following methods:

1) Clay core: In Mohr-coulomb model parameter analysis, the core's solid part (cohesion, friction, young modulus, and Poisson's ratio) is resulted from Consolidated UndrainedTriaxial Compression Test using pore pressure measurement. In addition, other parameters (porosity, permeability, coefficient of consolidation and so on) are obtained from consolidation test results.

2) Rockfill shell: To obtain geotechnical parameters of the rockfill shell materials, at first, the elasticity module of the construction materials are obtained using index and resistance parameters achieved from laboratory as well as Marshall Test results, then using Sigma/W software and 'try and error' method, the stress-restrain curve parameters in the same stress range proposed by Marshall Module are derived. Mentioned parameters are chosen so that it necessitates the most critical conditions regarding critical loading setup. These results are also compared and coordinated with similar cases in dam building projects worldwide.

3) Filter and drainage: considering gradation, compression, and texture of construction materials that would be used as filter materials, and using parameters of other similar dams, the parameters of behavioral model was chosen. It is worth to point out that choosing the most critical conditions is heeded here as well. In Table (1), summary of geotechnical characteristics of the body of Garati dam are shown.

Table 1: Summary of geotechnical characteristics of the body of Garati

Material number	Type of Material	γ_{Sat} KN/M^3	γ_{wet} KN/M^3	E´ Kpa	v´	C´ Kpa	φ´ degree	n porosity	K Cm/s
1	Clay core	20	21	10000	0.35	29	24	0.3	$1.67*10^{-8}$
2	Rockfill shell Type I	21	22	50000	0.3	0.0	44	0.35	80
3	Rockfill shell Type II	21	22	40000	0.3	0.0	41	0.35	80
4	Filter and Drainage	20	21	30000	0.25	0.0	35	0.3	$1*10^{-3}$

Studying hydraulic fracturing possibility in clay core after the first impounding

Studies show that the most critical condition for hydraulic fracturing event takes place at the time of the first impounding. To check for probability of this event, the values for vertical stress, horizontal stress, principal maximum stress, principal minimum stress, and surcharge in neighboring elements toward upside of the core in the first impounding are compared with pore pressure, and the results are shown in Figure (2). The results show that the hydraulic fracturing in the first impounding would not happen with acceptable confidence. As noted before, shell parameters are selected so that to create the critical conditions needed for maximum arching, and the difference between vertical (direct) stress and the surcharge does confirm this fact.

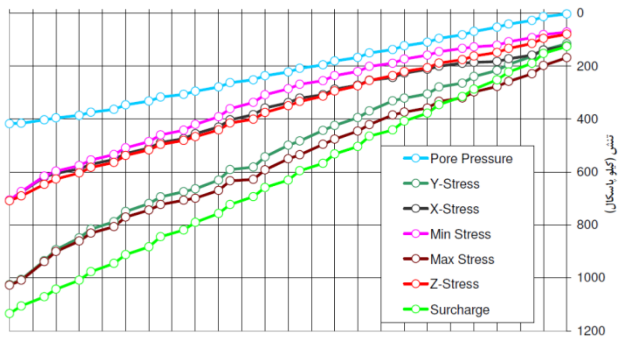

Fig.2. Total stress, pore pressure, and surcharge at upper front of the core at the end of the first impounding

Evaluation of pore pressure during construction period and after completion

With respect to the type of Garati cofferdam, which is an earth dam with a clay core, the period of dam

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construction is modeled as analysis of coupled effective stress in seven layers with almost equal thickness. Several timely analyses show that considering properties of available materials, if construction time of the cofferdam takes six months, the maximum pore pressure ratio (Ru) at the end of the core construction would remain inside the safe boundaries (Less than 0.5 on average) in limit equilibrium. Figure (3) shows the status of pore pressure distribution at the end of construction of this section of structure.

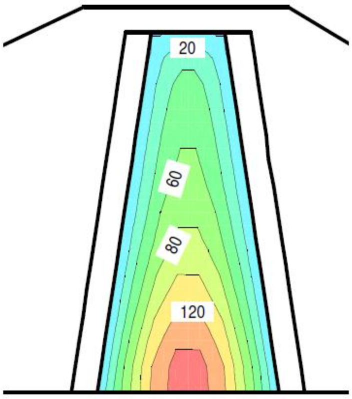

Fig.3. Pore pressure distribution in clay core of the cofferdam at the end of construction period

After building upstream and downstream cofferdams, body construction of the main dam in 18 layers with equal thickness began. Several studies and analyses in various time intervals were done and the results show that in case the construction of the main dam takes three years, the maximum pore pressure ratio (Ru) at the end of the core construction would remain inside the safe boundaries (Less than 0.5 on average) considered in limit equilibrium.

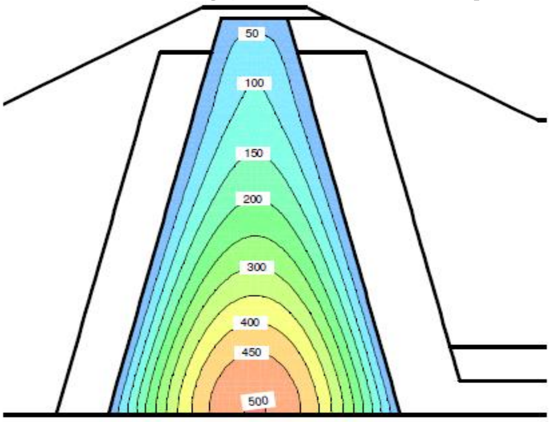

Fig.4. Pore pressure distribution in clay core of the dam at the end of construction period

Stress distribution

Total stress contour curves for minimum and maximum horizontal and vertical stresses at the end of construction and at the first impounding are shown in Figures (5) to (12). As it can be seen, vertical (direct) stress values are shown for borderlines between the core and horizontal shell, and the reason is the difference in elasticity module of the materials in these two regions.

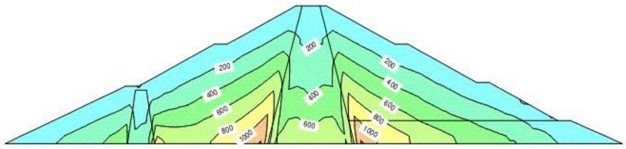

Fig.5. Vertical stress distribution at the end of dam construction

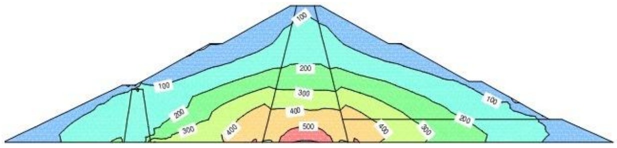

Fig.6. Horizontal stress distribution at the end of dam construction

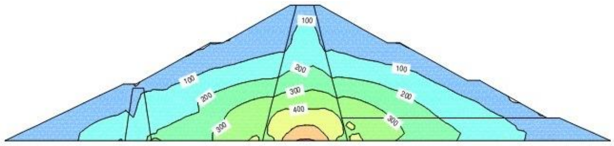

Fig.7. Minimum principal stress distribution at the end of dam construction

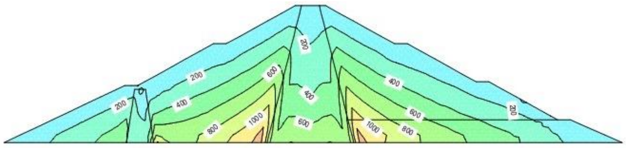

Fig.8. Maximum principal stress distribution at the end of dam construction

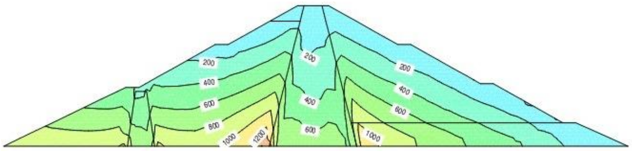

Fig.9. Vertical stress distribution at the end of first impounding

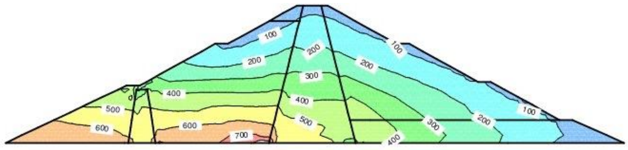

Fig.10. Horizontal stress distribution at the end of first impounding

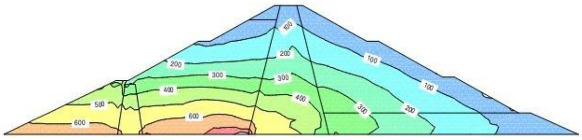

Fig.11. Minimum principal stress distribution at the end of first impounding

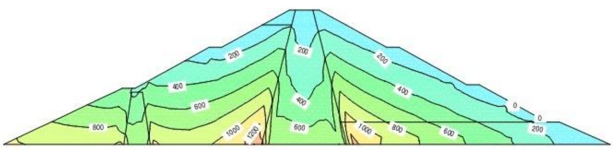

Fig.12. Maximum principal stress distribution at the end of first impounding

Evaluation of the dam body movements

Assuming three years for dam construction, vertical and horizontal displacement distributions at the end of construction period are shown in Figure (13) and Figure (14), respectively. Maximum settlement of the dam at the end of construction is equal to 65 centimeter. After first impounding and regarding impounding conditions, settlement -and horizontal displacement distribution would look like Figure (15) and Figure (16), respectively. Based on subjects already mentioned and upon performed calculations, and considering existing experiences on settlement of rockfill dams at operation period (rockfill material settlement phenomenon), -assuming settlement in construction period is compensated over the crown and on clay core at the end of the construction- camber (settlement) of the dam (related to settlements of operation period) is suggested to be equal to 100 centimeter in maximum cross section.

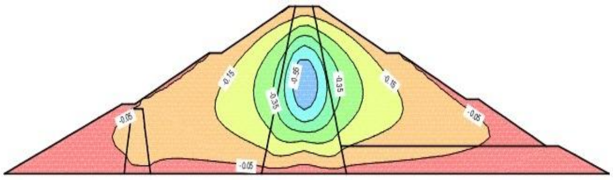

Fig.13. Dam's body settlement at the end of dam construction

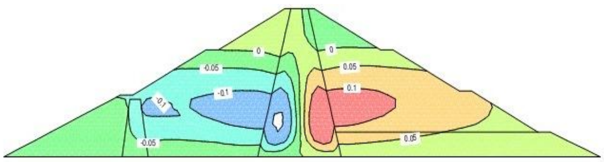

Fig.14. Horizontal displacement at the end of dam construction

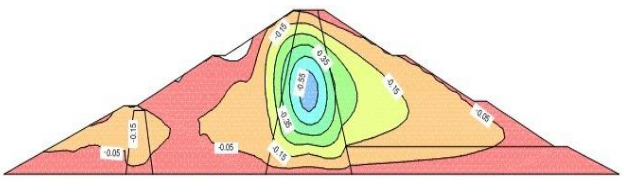

Fig.15. Dam's settlement at the end of the first impounding

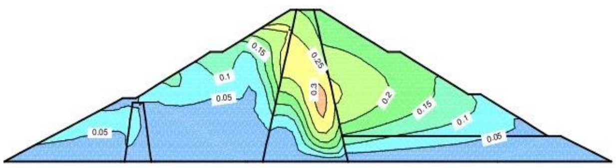

Fig.16. Dam's horizontal displacement at the end of the first impounding

Seepage Analysis

One of the most important parts of both earth and rockfill dams, is the study of discharging flow through construction materials as well as hydraulic balance of the dam and the amount of water discharging from foundation and body of the dam. Since Garati is a reservoir dam, sealing off the dam's body materials and rockfill foundation is crucial. Permeability coefficient of the body materials and rock foundation of the Garati Dam are shown in Table (2). Materials permeability numbers are resulted from Lugeon experiments.

Table 2: Permeability coefficients of the material used in body of the dam

Material properties	Kx (m/s)	Ky (m/s)
Core	$5*10^{-10}$	$1.67*10^{-10}$
Rockfill shell	0.88	0.88
Horizontal drainage blanket	0.22	0.22
Granular filter and vertical drainage	$1*10^{-5}$	$1*10^{-5}$
Rock foundation	$1*10^{-7}$	$1*10^{-7}$

To evaluate the amount of drainage passing through the dam, numerical analysis of the seepage is performed using Seep/W component of GeoStudio 2007 software. Considering high permeability of both shell and drain filter materials compared to core material, the effects of these parts are ignored in analysis to assure their effectiveness. Figure (17) shows considered core mesh idealization in seepage analysis. The analysis is performed in steady state for 6 months in filled and 6 months in semi-filled dam reservoir.

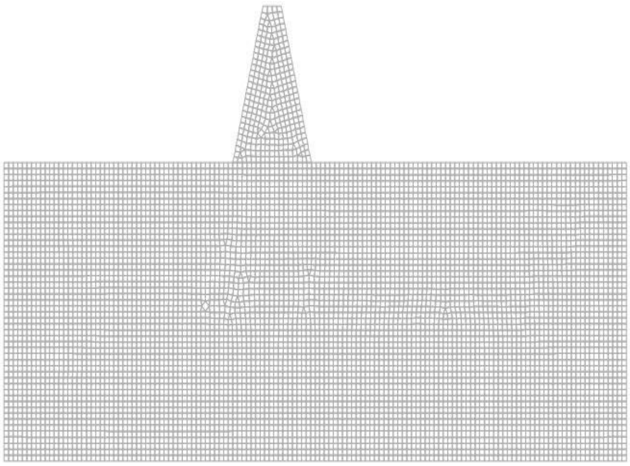

Fig.17. The ideal cross sectional geometry mesh considered for seepage analysis.

Figure (18) shows isogradient and isopotential lines in cross sectional full reservoir. Based on performed analyses, yearly drainage through both body and foundation of the dam would be equal to 4250880 liter, which is acceptable for this project. Maximum seepage gradient of the flow through filter and downstream alluvium are 1.6 and 0.2, respectively, which are acceptable values. Therefore, considering impermeable foundation (relied upon in place experiment), this dam will not face any considerable problem.

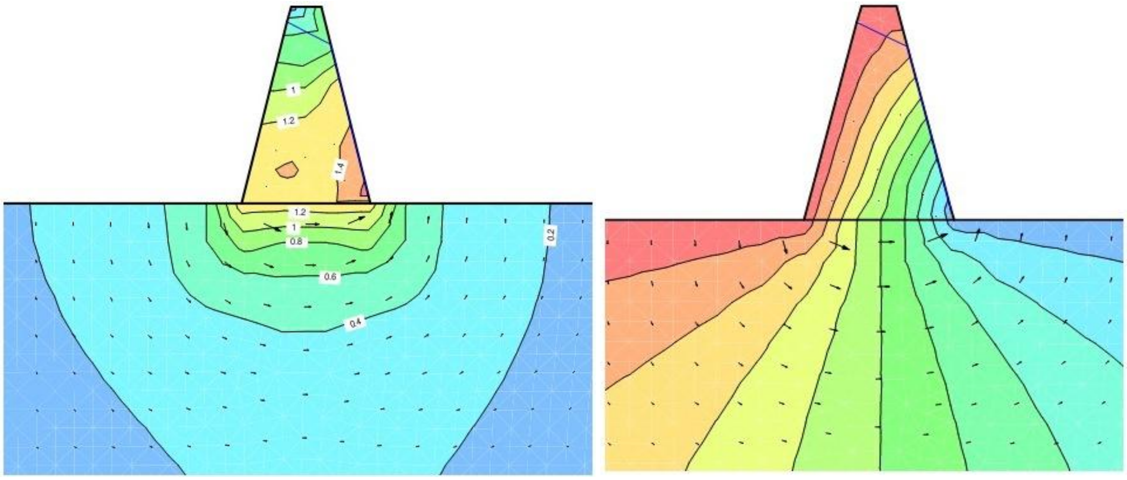

Fig.18. Iso potential and iso gradient lines in steady state, in seepage analytical model (Filled reservoir)

III. Conclusion

In summary, the results of the stress-strain analysis performed during construction and in first impounding can be described as follows:

1) In case upstream cofferdam construction takes 6 months and the main dam takes 3 years, the distribution of pore pressure would be within safe limits.

2) Maximum settlement at the end of construction equals to 65 centimeter, which compared to other dams is an acceptable value.

3) Hydraulic failure event at the end of the first impounding; comparing pore pressure with different total stresses shows that Garati Dam has acceptable safety against this phenomenon.

4) Based on subjects mentioned earlier and upon performed calculations, and considering current experiences on settlement of rockfill dams in operation period (rockfill material settlement phenomenon), assuming settlement of construction in construction period is compensated on the crown and on clay core at the end of the construction, the camber (settlement) of the dam (related to settlements of operation period) is suggested to be equal to 100 centimeter in maximum cross sectional profile.

5) Based on performed analyses, yearly drainage through body and foundation of the dam would be equal to 4250880 liter, which is an acceptable value for this project. Maximum seepage gradient of the flow through filter and downstream alluvium are 1.6 and 0.2, respectively. Therefore, considering in site experiment results and impermeability of foundation, this dam will not face any considerable problem regarding permeability.

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