# Upgrading Historical Masonry Dam with Envoronmental Friendly Technologies : A Case Study

**Mohammad Safi[1], Seyed Saeed Beheshti[2]**
1- Assistant Professor, Shahid Beheshti University, Tehran, Iran
2- Lecturer, Shahid Beheshti University, Tehran, Iran

Email : m_safi@sbu.ac.ir

## Abstract

Masonry gravity dams are normally considered in the category of small dams. The relatively small allowable stress of masonry material and also the difficulties in seepage control under high water pressure have limited the use of such dams. However most of the existing historical dams are made of masonry. Most of these dams are not only in operation and provide services to the downstream of the dam but also have been changed into heritage sites and historical attractions. The protection of these structures becomes more critical in seismic prone area where the dam and its reservoir are subjected to earthquake risk. Golestan historical masonry dam, located in north east of Iran close to Mashhad city and 1050 km north east of the capital is a tourist area. The dam was heightened about 5 meters in 1947 and has a maximum height of 21.5 meters form foundation level and total crest length of 132 meters. The dam is currently under operation for local irrigation but it has major leakage problem in case of high water levels. This paper presents the complementary activities for stabilizing and water tightening of the dam with new materials and technologies compatible with the historical features of the dam and also the environmental and ecotourism features of the area. The innovative design includes the crack repairs with three dimensional under surface reinforcement, underground cutoff wall and dam body grouting and surface waterproofing which was executed using smooth method statement and live monitoring procedure.

**Keywords: Masonry gravity dam, Upgrading, Environmental friendly, Seismic Retrofit.**

## 1. INTRODUCTION

Iran is one of the seismic prone areas in the world and with many historical masonry structures vulnerable to earthquake. For such structures, design goal options are to provide a retrofit that has a minimal effect on the integrity of the historic fabric. It should minimize changes to the appearance of the structure and protects specific architectural or historic features and finally direct damage toward areas of lesser significance. Thus the design process should follow a logical sequence:

1. Develop a global design strategy that will provide continuity to the structure, and design a system that ties the structure together. It is important that the basis of the retrofit design be one of allowing the structure to function as an integrated system.
2. Predict the location and pattern of cracks that may occur during major earthquakes, and address the potential stability and probable failure modes.
3. Design retrofit measures that can assure the stabilization of each cracked section and limit permanent damage to acceptable levels.

The seismic performance of gravity dams is generally checked for two level of earthquake so that local damages are minimized during minor or moderate earthquakes (DBE) and structural damages are minimized during major earthquakes (MCE) [1,2]. Two fundamental design approaches can be taken to improve the earthquake performance of masonry structures [2]. Strength-based design relies on improving the strength of the masonry material and changing the overall structural configuration. It assumes the elastic behavior of the structure and focuses on traditional means for delaying cracking. Stability-based design is concerned with the overall performance of the structure and with assuring structural stability during the post-elastic, post-yielding phase. Stability-based design features can reduce the potential for severe structural damage and collapse after yielding has occurred.The conventional engineering approach to seismic retrofitting is strength based; that is, structural elements are provided that have sufficient strength to resist the forces generated by the elastic response of the structure during a design-level earthquake that is the maximum earthquake level the structure can endure and still exhibit an elastic, or reversible, response. It is understood that the forces generated during major seismic events can exceed those generated during the design-level event.

## 2. PERFORMANCE ASSESSMENT OF OLD MASONRY DAMS

The relatively small allowable stress of masonry material and also the difficulties in seepage control under high water pressure have limited the use of such dams. However most of the existing historical dams are made of masonry. Most of these dams are not only in operation and provide services to the downstream of the dam but also have been changed into heritage sites and historical attractions. The protection of these structures becomes more critical in seismic prone area where the dam and its reservoir are subjected to earthquake risk. The number of instances when severe earthquake motions have acted on masonry structures is quite large but for the masonry dam much less damages have been reported. The only references to masonry dams in Iran relates to the Kashan earthquake (200 kilometers south of the capital) in 1844 (M = 6.4). The two masonry dams situated in the epicentral area sustained no major damage.

To evaluate the expected earthquake performance of a masonry gravity dam, it is first necessary to establish the intensity and frequency characteristics of the earthquake motions to which the dam might be subjected. The earthquake forces acting in the structure could be expressed as the product of the earthquake acceleration and the mass of the corresponding part of the structure. More recently the elastic properties as well as the mass of the dam materials have been incorporated into the mathematical models, and as a result the vibration properties of dams have been recognized to have a controlling influence on earthquake response behavior [2,3].

For gravity dams subjected to static loads, uplift increases the tendency for cracking along the upstream face of the dam and reduces compressive normal stresses within the dam structure and along the dam foundation contact, which correspondingly reduces sliding stability. To include the effects of uplift in a static analysis using the finite element method, an analysis can be performed in the usual manner, neglecting pore pressures and calculating total stresses. Pore pressures, based on appropriate considerations regarding the presence and effectiveness of drainage systems within the dam and its foundation, can then are summed with total stresses to calculate effective stresses. It is usually assumed that oscillations occur quickly enough to prevent significant penetration of water into the cracks [4]. Consequently, pore pressures are usually treated as though they are constant during both static and dynamic loading conditions.

Generally, two-dimensional analyses for static loading conditions are conservative [1]. In case of high seismic loading two dimensional analyses will almost always indicate the development of high tensile stresses, whereas three dimensional analyses may indicate much lower stresses. When evaluating the performance of a masonry dam for a DBE, it is appropriate to apply factors of safety to material strengths and require that there be no excessive damage, no irreparable damage, no life-threatening uncontrolled release of the reservoir water, and no interruption to systems or components needed to maintain safe operation. When evaluating the performance of a masonry dam for MCE, criteria based on factors of safety applied to material strengths are not applicable since extensive damage, including extensive irreparable damage [2]. Normally, if cracking through the thickness of the dam is not indicated and if substantial intact material remains at cracked locations, the sliding stability will be acceptable. Following sections present two real world example of seismic performance evaluation and retrofit of historical masonry dams.

## 3. GOLESTAN HISTORICAL MASONRY DAM

Golestan historical masonry dam, located in north east of Iran close to Mashhad city and 1050 km north east of the capital is a tourist area. Figure 1 shows the downstream view of the dam which was constructed about 520 years ago. The dam was heightened about 5 meters in 1947 and has a maximum height of 21.5 meters form foundation level and total crest length of 132 meters. The width at the foundation and crest levels is 29.6 and 10.5 meters respectively. A water intake is located close to the right abutment for daily water consumption. A small spill way is also located at the left abutment. The dam is currently under operation for local irrigation but it has major leakage problem in case of high water levels.

### 3.1 EXPERIMENTAL STUDIES

The old dam body material had been built with limestone and lime based mortar. But the new masonry part has different properties and has been constructed using masonry with Portland cement mortar. Lugeon tests showed coefficients of permeability about 10-5m/s at lower levels of the dam. Young's modulus was ranging from 2000 MPa to 2500 MPa. The dynamic uniaxial modulus of elasticity values were ranging from 2500 MPa to 3125 MPa. The foundation material had average cohesions of 0.15 and 0.55 kg/m in saturated and unsaturated conditions respectively. The average internal friction angles of 26 and 31 degrees were also determined for the two conditions respectively. Test results have been summarized in table 1.

**Figure 1- Downstream view of the Golestan historical dam**

**Table 1- Material properties of Golestan masonry dam obtained from test results**

| Density t/m3 | Poisson Ratio | Dynamic Elasticity Modulus MPa | Long Term Elasticity Modulus MPa | Maximum Compressive or Bearing Capacity MPa | Title |
|---|---|---|---|---|---|
| 1.95 | 0.20 | 3125 | 2500 | 6.9 | Heightened Part |
| 1.68 | 0.15 | 2500 | 2000 | 6.0 | Initial Dam Body |

Grout tests were also performed and resulted to the maximum allowable grout pressure of 1.9 bars. The average grouting volume per hole was also estimated. The variations of the values were considerably different for different zones in the dam body. Figure 2 shows the consumption of the grout material. The stress strain behavior of the masonry material for Golestan dam in deteriorated and grouted conditions has been presented in figure 3. For this case grouting has improved the strength up to 40 percents and also increased the ultimate strain by 3percents.

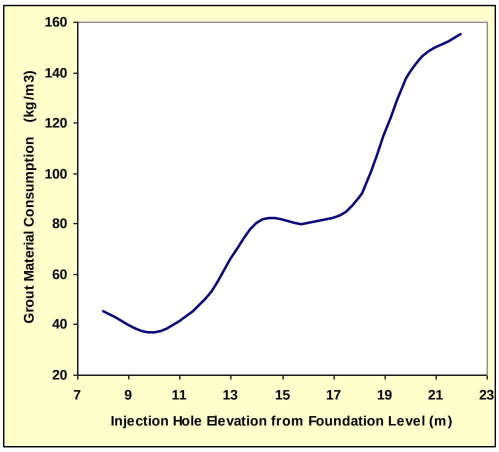

**Figure 2- Consumption of grout material through height at Golestan masonry dam**

### 3.2 SEISMIC SAFETY ASSESSMENT

Based on the safety assessment studies two major problems was distinguished for the Golestan dam. The first problem was the inadequacy of shear strength at the contact surface of the old and new parts of the dam in seismic load condition. Similar problem was assessed at the contact surface of the dam body and foundation. The other major problem of the dam was the uncontrolled seepage. As shown in figure 4, the hydraulic gradient at the lower elevations of the dam body exceeded the allowable values. The pore water pressure inside the voids in the dam body also created stress capacity problems in seismic load condition.

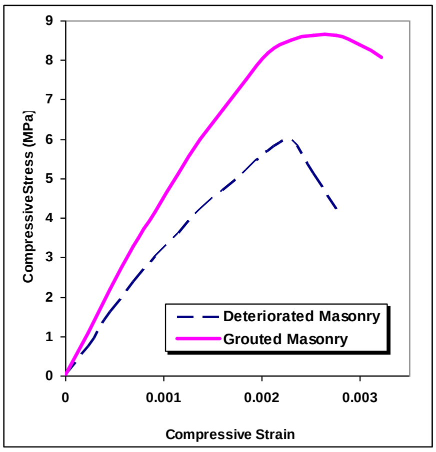

**Figure 3- Stress strain behavior of the shell material in deteriorated and grouted conditions for Golestan masonry dam**

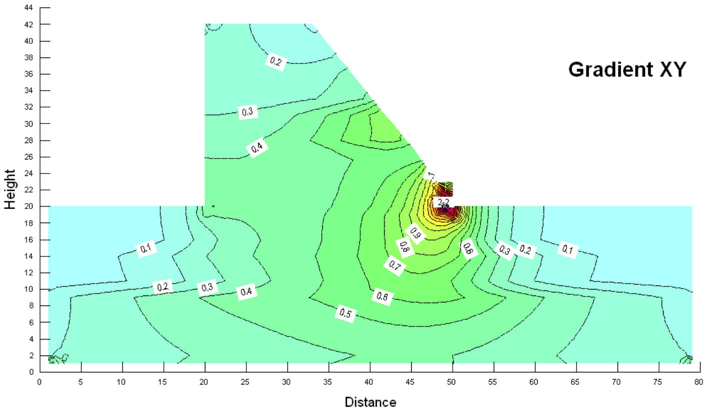

**Figure 4– Distribution of resultant hydraulic gradients obtained from seepage analysis**

Similar to the previous case study dynamic and nonlinear analyses were also performed to assess the realistic behavior of the dam during earthquake. Natural vibration modes from dam foundation reservoir interaction model are listed in table 2.

**Table 2- First 10 natural periods of vibration of Golestan masonry dam**

| Mode Number | Natural Period |
|---|---|
| | Seconds |
| 1 | 0.1923 |
| 2 | 0.1178 |
| 3 | 0.0967 |
| 4 | 0.0873 |
| 5 | 0.0805 |
| 6 | 0.0787 |
| 7 | 0.0783 |
| 8 | 0.0661 |
| 9 | 0.0599 |
| 10 | 0.0594 |

Site specific spectra were obtained based on seismic hazard studies and have been shown in figure 5. Figure 6 shows the maximum shear stress in the masonry obtained from spectrum analyses. The results showed that the maximum shear stress exceeded the allowable values at the interface of the new and old part and also the foundation level. It was determined that shear cracks may occur during earthquake at some point. Thus the crack potential was carefully checked using nonlinear analysis.

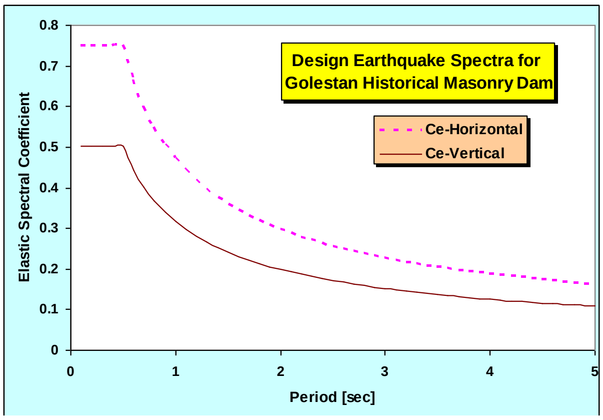

**Figure 5- Horizontal and vertical smoothed site specific spectra for Golestan historical masonry dam**

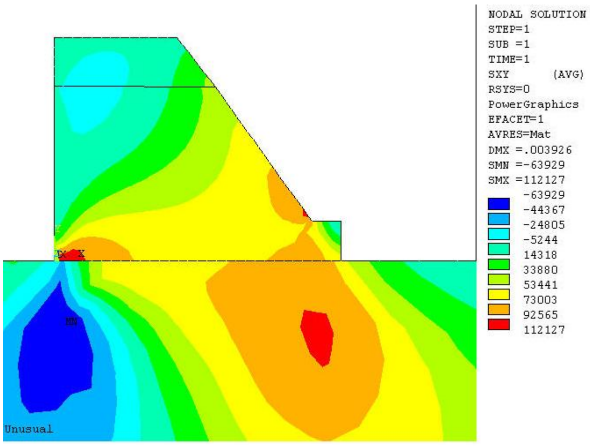

**Figure 6- Maximum shear stress obtained from spectrum analysis based on SRSS mode combination (SI Units)**

## 3.3 RETROFIT DESIGN SCHEME

It has been tried to select some rehabilitation methods, which does not affect the historical features of the dam while not affecting the environment and the daily serviceability status of the system. The selected rehabilitation scheme has been demonstrated in figure 7. Contact grouting in the horizontal interface of the old and new parts and also the dam and its foundation was performed in order to increase the shear capacity in these two horizontal surfaces during earthquake. The upstream wall was retrofitted using near surface reinforcement as shown in the figure.

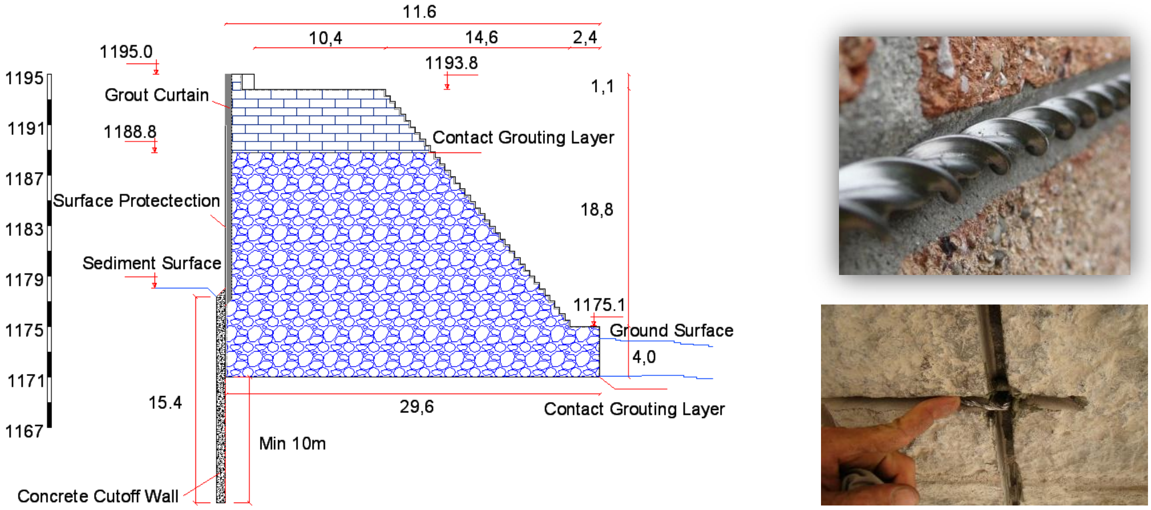

**Figure 7– Final retrofit scheme used for the rehabilitation of the Golestan historical masonry dam and near surface reinforcement for upstream treatment**

In order to solve the uncontrolled seepage and pore pressure problem, a two part cut off curtain was designed. As shown in figure 7 at the upstream of the dam a sediment layer with the average thickness of 7.5 meters exists. The removal of whole sediment layer was estimated to be too costly. As the reservoir near the dam body is dry for about 5 months per year it was decided to use a two-part sealing curtain at the upstream. The exposed part was sealed using surface sealing materials and surface shell grouting with the average thickness of 0.5 meter. For the remaining part which under sediment level and also for the foundation, a conventional concrete cutoff wall was selected. At the intersection of the two sealing part a transition seal was executed which has been schematically shown in figure 7.

### 3.4 PREDICTION OF NONLINEAR RESPONSE

Similar nonlinear model was used to assess the crack potentials in the dam body. The step-by-step analysis under seismic and dead loads was carried out, using a force-based convergence criterion, until failure of several elements due to cracking or crushing led to deterioration of the stiffness matrix, and the procedure became unstable. Figure 8 shows crack potential found in the dam section before and after retrofit. The crack pattern shown for the retrofitted case was obtained by increasing the load in the nonlinear analysis by 66 percent more than the maximum credible load. Base shear – crest displacement for the two conditions has also been presented in figure 9. It can be seen from the results that the ultimate deformation capacity is not considerably changed as a strength based method was employed for the retrofit design. The results also showed that no distributed crash zone was created. Thus seismic retrofit works should be concentrated at the upstream zone of the dam same where as water proofing works should be executed. Comparing the linear and nonlinear analyses results the maximum behavior factor of 1.7 may be used for equivalent analysis.

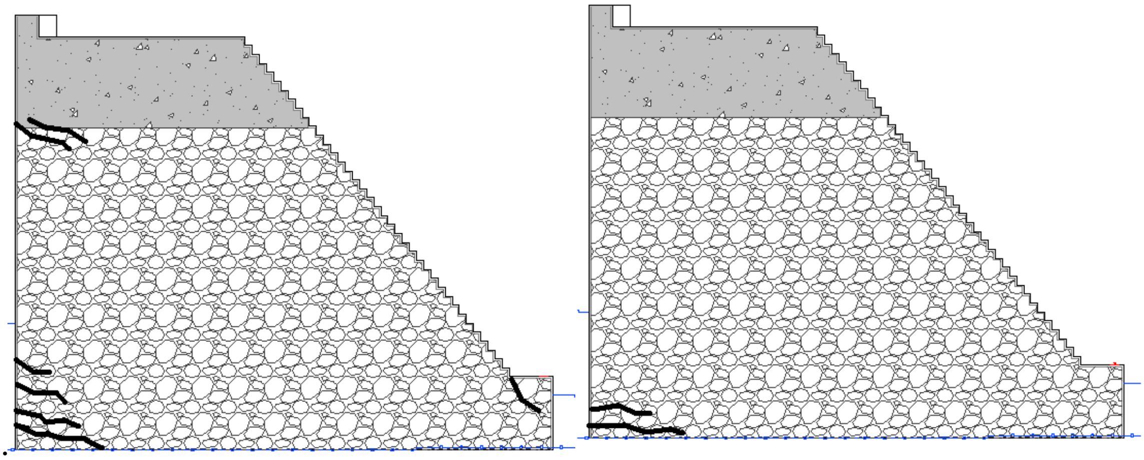

**Figure 8- Expected crack pattern found in the dam section at the ultimate limit state before and after retrofit**

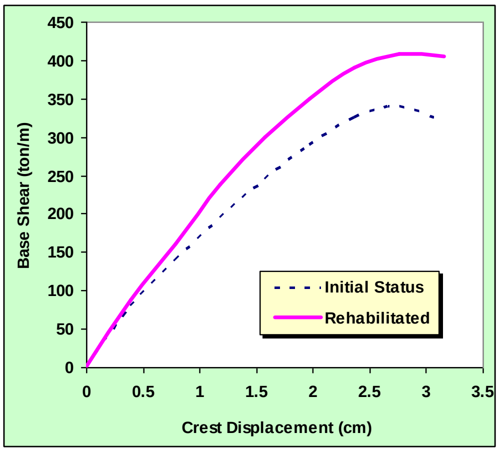

**Figure 9- Base shear – crest displacement curve for the dam before and after retrofit**

**Figure 10- Acceptable performance of the retrofitted dam under 1398 flood, an environmental friendly retrofit including the upstream, downstream, crest, spillway and bottom outlet**

## 4. CONCLUDING REMARKS

Rehabilitation of existing environmental structures such as old dams proposes very restrict requirements for environment friendly behavior. This study discussed seismic qualification, analysis and rehabilitation of Golestan historical masonry dam in north east Iran. Results of experimental study for existing and grouted masonry were presented and compared. The results were used for evaluation of dynamic stability and nonlinear response analysis. Based on the experimental and analytical results, retrofit designs were presented in detail. The design and related material were so selected that not to affect the historical features of the dam structures and also not to affect the environment. Following design and construction recommendations were found to be for seismic retrofit of historical masonry dams:

- Pore water pressure and uplift have a considerable effect on the seismic instability of historical masonry dams. It was shown in case study that water proofing retrofit scheme can considerably improve the seismic behavior of masonry dam structure.
- Most of the historical masonry dams encounter sliding problems at the foundation level during earthquake. Partial or full contact grouting at the dam foundation interface will solve this problem. In case of partial grouting the most effective area for contact grouting was found to be around the dam toe. From construction point of view, grouting at the upstream side of the dam foundation interface would often be very costly due to existing sedimentation.
- As discussed in the paper the grout material properties and grouting procedure and pressure should be carefully determined. The grout material for each historical masonry structure must be

chemically consistent with the existing material. For execution a two-step procedure was used so as not to create fracture and crack opening in the media.

- Nonlinear response assessment showed that effective local grouting of old masonry could improve the material strength and global behavior. For the case study dam, material compressive and tensile strength increased at least 50 percents while the global performance was improved more than 30 percents.
- Nonlinear analyses showed that cracking in old masonry gravity dams has similar patterns in ultimate load condition and thus leads to similar failure modes. No distributed crash zone was observed in the results. Thus, seismic rehabilitation for such structure will mostly be concentrated at the upstream zone.
- The most important problem in modeling of historical masonry dams is the great uncertainty of the material properties. Grout pressure and nondestructive tests revealed that the old masonry dam, which has had long leakage problem, would have a highly non-homogenous media. For the case study grout pressure tests showed that, the void volume varied from one to 10 percents. It was clearly observed that the mechanical properties also varied for different zones.

For our case, conservative parameters were selected for analysis and design; however,models that are more accurate would be necessary to be developed by the researchers.

## 5. ACKNOWLEDGMENT

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