Investigation of riprap stability of a dam: risk assessment by InSAR method and rock mechanical test

Mehrnoosh Ghadimi\textsuperscript{a,b}

\textsuperscript{a}Department of Physical Geography, Faculty of Geography, University of Tehran, Iran; \textsuperscript{b}Institute of Seismology, Department of Geosciences and Geography, University of Helsinki, Finland

\textbf{ABSTRACT}

Riprap resistance is a widely used solution for protecting earth dams from erosion but riprap can be displaced on the dam surface. This study examines the stability of riprap in the Taleqan Dam, Iran using rock mechanical tests and InSAR technology. Uplift of dam stairs and erosion of the riprap material have been observed during field work at the study site, and samples have been gathered from three rock categories. The purpose of this study is to explore the factors influencing the deformation of the Taleqan Dam. The InSAR method has been employed for monitoring surface deformation and the Los Angeles ASTM C test was used to establish the cause of dam deformation. InSAR analysis was carried out using Sentinel-1A images from 2014 to 2019. The results revealed subsidence at an average rate of 4 mm/yr over that period. The results of Los Angeles ASTM C indicated that the Andesite riprap was more easily eroded, has a relatively low durability and specific weight, and low resistance erosion. Therefore it is unsuitable for use as a protection layer for the crest and lower sectors of the riprap. It can also be concluded that the inadequate durability of certain rock materials may potentially cause weathering, depression, reduced thickness and displacement of the riprap.

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\section{1. Introduction}

In order to prevent or reduce the likeliness of dam failures, it is vital to continuously monitor dams and reservoirs with unstable slopes (Reyes-Carmona et al. 2020). Riprap comprises rocky material emplaced to protect bridge abutments and other structures from erosion. It is frequently used to shield earth dams from reservoir waves that overtop the dam (Khan and Ahmad 2011), for example. The riprap materials include rock aggregates, essentially granular materials, which are applied to satisfy the requirements of the construction industry apropos of raw material. Rock
aggregates, therefore, play a significant role in the construction of the structures, including relevant roads, bridges, dams, and railroads (Liu et al. 2005). Furthermore, rock aggregates, characterised by their high quality and low costs, as well as environmentally friendly features and recirculation of materials, can be applied extensively to accommodate sustainable development (Kothyari and Singh 1996).

In terms of materials, applying weathered riprap rocks when constructing earth dams can potentially lead to difficulties and displacements. According to Figueroa Madero et al. (2014), compression and flexion tests can be employed to determine whether rock aggregates categorized as having high resistance to induced tensions are capable of causing rock deformation and fractures. In addition, numerous formulations have been put forth for relating the median weight of riprap \( W_{50} \) to wave height and slope (Hudson 1959; Ahrens 1981; Van der Meer 1988). Hartung and Scheuerlein (1970) proposed a series of stability equations accounting flow aeration on angular stones found on steep slopes. For this purpose, they integrated a wide series of observations of aerated flows over fixed rock beds along with stability equations proposed for rocks submerged underwater.

The effects of these riprap material factors were investigated by Ullmann (2000) in a series of experiments on embankments with slope values ranging from 0.2 to 0.3, characteristic size \( D_{50} \) varying from 24 to 99 mm, uniformity coefficient \( (C_u) \) and stone roundness \( (R) \) ranging from 1.21 to 1.33 and 76% to 95%, respectively. They find that the factors unit discharge, slope, uniformity coefficient and stone roundness can be combined into a function for assessing the size of a stable round-shaped stone. According to the results, the values should be approximately 47% larger than that of angular rocks in order to retain their stability under the same conditions for slope and unit discharge (Khan and Ahmad 2011). Similar riprap tests were conducted by Mishra (1998) on angular rippars situated on semi-prototype sized embankments with 50% slopes. The test was carried out as the result of erosion and exposure of bedding material due to rock movement.

InSAR monitoring has shown to be reliable not only in terms of identification of the areas and reservoir slopes with poor stability, but also for the purpose of tracking the changes taking place regarding the dam’s stability (Reyes-Carmona et al. 2020). According to the result of Sousa et al. (2014), by applying multi-temporal InSAR processing techniques to a series of radar images over the same region, it is possible to detect vertical movements of structures on the ground in the millimeter range, and therefore identify abnormal or excessive movement that indicates potential problems requiring detailed ground investigation.

InSAR works on the basis of applying measurements of changes in phases between different satellite radar images with the same observational geometry (interferograms) obtained at different time intervals in order to measure land surface deformation (Ferretti et al. 2007). For this purpose, the InSAR method uses time series techniques, such as the Permanent Scatterers in SAR interferometry (PS-InSAR) (Ferretti et al. 2001; Hooper and Zebker 2007), and Small Baseline subset SBAS (Berardino et al. 2002).

Although various studies have examined the stability of embankment dams in different areas around the globe, including La Vinuela, Spain (Ruiz-Armenteros et al.
Castello della Pietra d’Amico, Italy (Pipitone et al. 2018), Aswan, Egypt (Miky 2019), Darbandikhan, Iraq (Al-Husseinawi et al. 2018), Noreeland, Sweden, and Norland, Troms and Vest-Agder, Norway (Ullo et al. 2019), dam monitoring procedures require long-term time series observations in order to accurately identify the causes of subsidence and the subsequent effects (Alavi 1996). With this in mind, the present study presents an analysis of geo-mechanical features of the riprap rocks used in the Taleqan Dam in Iran and its connection to displacements within the dam. The present study also uses the InSAR method to estimate rates of riprap erosion and the rate of displacement of the embankment dam. In this study, for the first time, to the best of my knowledge, riprap layer erosion induced dam deformation was successfully quantified using InSAR.

2. Definition of the field of study

The Taleqan dam and reservoir was constructed in 2001, located around 90 km from the northwestern part of Tehran, Iran (Figure 1a and b.). The study area consists of a variety of stratigraphic units ranging from sedimentary rocks (limestone, shale, marl, and gypsum conglomerate) and igneous rocks (basalt and intermediates like Andesite, and pyroclastic rocks such as tuff and agglomerate) to Quaternary sediments (amphibolite, gravel, alluvial fans, and Quaternary alluvium) (Figure 1b). The area also includes both thrust and reverse faults positioned in the vicinity of the Taleqan Dam.

The Taleqan catchment basin extends as far as the Taleqan fault in the south to the Kandovan fault from the north (Figure 1b). The area selected for dam construction is primarily exposed to risks of overthrust, landslide, and induced seismicity from reservoir waters. In addition to tectonic factors, erosional factors (chemical and mechanical) could also play important roles in possible dam deformation. Given the mechanical properties of the bedrock in the dam area, in conjunction with the rather dynamic tectonic conditions of the region, it is essential to closely monitor seismic activities (Signes et al. 2016).
The spillway of the Taleqan Dam has been constructed on the left side of the downstream slope of the dam and within a rock bed. The Taleqan Dam is a soil-rockfill dam (Figure 2) with a clay core whose crown is as long as 1111 m and as wide as 12 m. The useful volume of the reservoir upstream of the dam is 320 m$^3$ according to the 'Behaviour report of the Taleqan Dam' published by the Regional Water Company of Iran in 2016 (hereafter referred as 'BRTD').

The distribution zobe of riprap rock is 1036 m long, with predominant winds in the Taleqan Dam area oriented in a northwest-southeast direction. Further details of the riprap are provided by the manufacturing company (Table 1).

3. Methodology

3.1. Field survey

We collected samples of existing rock materials within the riprap layer to measure the properties of riprap material. The materials used in the upper riprap layer of the Taleqan Dam consist of three categories of rocks: (Trachyte, Andesite, Tuffite). Samples were gathered from each category, with the exclusion of one from which no samples were collected due to extreme weathering. It is noteworthy that each defined category contributed to similar shares (10 to 20%) of the constituents of the target riprap. Various comprehensive mechanical and durability tests were then performed on each of the three sampled categories.

3.2. Sample description

The tests were carried out on three riprap rock types: Andesite, trachyte, and tuffite. Test specimens were extracted in one of the three different operations: core drilling performed in an electromechanical coring machine to produce core specimens with specific dimension, cutting using diamond saws to obtain cubic samples, or crushing using jaw crushers to produce a particular size fraction of the aggregate material.

The Los Angeles ASTM C127-12 standard was used to analyse density, and resistance of coarse aggregates was assessed with respect to abrasion and impact. The relative density and absorption of the aggregates were investigated based on the ASTM C88-05 standard. Aggregate soundness was estimated based on sodium sulphate or magnesium sulphate standard soundness tests (Abt et al. 2008). The required samples in the preliminary stages were collected in accordance with the ASTM D75/D75M-09 standard.

Figure 2. Cross section of the Taleqan Dam, the ratios show slopes of the Taleqan Dam surfaces.
Table 1. The weight, dimension and thickness of the riprap grains.

| Wind velocity (m/s) | Weight of grains $W_{\text{max}}$ (kg) | Weight of grains $W_{50}$ (kg) | Weight of grains $W_{\text{min}}$ (kg) | Dimension of grains $D_{\text{max}}$ (m) | Dimension of grains $D_{\text{min}}$ (m) | Thickness of grains $T$ (m) |
|---------------------|----------------------------------------|--------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------|
| 40.5                | 916.37                                 | 1393.76                        | 229.094                                | 0.793                                  | 0.286                                  | 0.758                      |
standard (Alavi 1996). Experiments were conducted on the riprap rocks using to Equations 1 and 2 (Hudson 1959) to characterize the riprap rock properties:

\[
W_{50} = \left( \frac{\gamma H_s^3}{3.62(G_s - 1)^3} \right) \frac{(\cot \alpha)^2}{3} \tag{1}
\]

Where \( W_{50} \) is the mean weight of rocks per ton, \( G_s \) is the specific weight of rock, \( \gamma \) is the unit of volume of each rock in tons/m\(^3\), and \( H_s \) is the height of the target wave per meter. The measured values were: \( G_s = 2.65, \gamma = 2.4, H_s = 0.936, \cot \alpha = 2, \) and \( W_{50} = 76 \) kg.

\[
D_{50} = \left( \frac{7}{5} \times \frac{W_{50}}{\gamma} \right)^{2/3} \tag{2}
\]

Based on the measured values, \( D_{50} \) (50 mm diameter core size) was calculated at 0.35.

The thickness of the riprap layer, as maintained by observations, must be at least 1.5 times the average rock material size, in which case should be 0.53 or above in this study. The minimum and maximum material weights were calculated as shown below in accordance with observations to determine material granularity (Table 2).

As the \( D_{100} \) and \( D_{10} \) diameters were calculated as Table 2:

\[
W_{\max} = 4W_{50} \quad W_{\max} = W_{100} \quad W_{\min} = \frac{W_{50}}{8} \quad W_{\min} = W_{10}
\]

\[
D_{100} = 256 \text{ mm} \quad D_{10} = 17 \text{ mm}
\]

The dimensions and weight of the riprap were also re-measured using the Hudson and Jackson method (1962). The results are presented in Table 2.

### 3.3. GMTSAR process

GMTSAR was used to execute a wide-area analysis over the Taleqan Dam, utilising 102 available Sentinel-1, C-band (5.6 cm wavelength) single-look, complex-scene images in ascending order (red box in Figure 1a). The spatial resolution of the obtained images was 5 m × 20 m. Synthetic fringes were also simulated in order to eliminate topographic effects on the interferograms using the (~90 m) Shuttle Radar Topography Model (SRTM) digital elevation model (DEM).

GMTSAR first extracts the orbital information in the pre-processing step from the raw data and then estimates the Doppler centroid. After image focusing, slave images are aligned to the master. As co-registration accuracy better than 0.01 pixels is required in the long-track direction, GMTSAR uses the precise orbits (aux_porb) for initial co-registration and the enhanced spectral diversity (ESD) method for removing
the co-registration error at bursts to achieve the desired precision (Prats-Iraola et al. 2012). Following this step, the interferograms are generated and corrected for topography, and orbital artifacts are removed to derive flattened interferograms. Then, a low-pass filter is applied to the flattened interferogram before applying SNAPHU to unwrap the phase. Finally, the unwrapped interferograms are geocoded. We also estimate and remove a phase ramp from all images, which could be present due to residual orbital errors and long-wavelength atmospheric signals.

Phase analysis was carried out using GMTSAR (Shanker and Zebker 2007) and a displacement timeseries was derived using the Small Baseline Subset method (Berardino et al. 2002; Hooper 2008).

4. Results

4.1. Qualitative analysis of the riprap material

Geomechanical parameters were obtained from the standard ASTM C170 uniaxial resistance test under dry and saturated scenarios. For all collected samples the results show that the mean uniaxial erosion resistances of rock samples are 431 and 237 kg/cm² for dry and saturated scenarios, respectively. The minimum and maximum uniaxial resistance values under saturation are also obtained at 129 and 393 kg/cm², respectively. This indicates low resistivity erosion of samples according to the ISRM 1979 standard (Table 3). The USACE recommended value of 500 kg/cm² also indicates the low resistance of the studied materials.

4.2. Real and virtual specific weights and water absorption rate

The values obtained in this study for real and virtual specific weights as well as water absorption rate for the sample riprap rocks (Table 4) were calculated using the ASTM C127 and C128 standards. Given the recommended rate of 2.5% for water absorption, the absorption rate of nuclear samples is higher than the maximum allowed value (Table 4).

4.3. Rock compositions and mechanical properties

According to the results from microscopic analysis of the rocks using the STM C294, the samples are categorized into four different types including: Terracotta tuff, Andesite tuff, detrital igneous, and pyroclastic rocks (Figure 3).
4.3.1. Abrasion resistance tests
Results from rock material resistance tests based on the ASTM C131 standard using a Los Angeles device on rock sample types placed the minimum and maximum abrasive resistance of the rocks (obtained after 500 rounds) at 31% and 46% respectively, with 80% of the samples having a resistance level below the recommended value of 45%. The results from the abrasion resistance test varied on the border of permissible and non-permissible. This shows that evaluation processes are acceptable.

4.3.2. Durability
Given the significance of durability of rock materials used in the riprap layer, durability tests were carried out under different experimental conditions. The results are presented in Table 2. According to the recommendation of authentic international references (BRTD 2016), rock materials used in riprap layers must satisfy the technical specifications required from a concrete aggregate. Thus, the presented permissible values in this study are in accordance with the Iranian Concrete Regulations (BRTD 2016).

4.3.3. Soundness test
Soundness tests, which are tests of resistance against sulphate cycles, were conducted in accordance with the ASTM C88 standard in order to evaluate the resistance of rock materials against atmospheric factors. According to the findings, the mean weight loss of materials using sodium sulphate after 5 cycles is 36%, with minimum and maximum average values of 13.4 and 73.8%. Given the recommended by the standard value of 12%, the evaluated soundness of the materials is as low for the samples.

4.3.4. Erodible rock durability
The erodible rock durability test was conducted to assess the durability of rocks against subsequent wet and dry periods in accordance with ISRM standards. The minimum observed erodible rock durability was 87%, with an average value of 92.5% for all samples. This reflects the high erodible durability observed among riprap rocks of the Taleqan Dam.

4.3.5. Melting and frost resistance
Resistance of rock materials against subsequent melting and freezing scenarios were estimated using periodic melt-frost tests. The maximum weight loss observed among samples is 21% after 16 cycles, while the average value was measured at 12.8%. In consideration of the recommended weight loss of 10%, it can be said that the rock materials used in the riprap layer of the Taleqan Dam are durable in terms of resistance to melting and frost.

| Table 4. Results from experiments conducted on riprap rocks sample from the Taleqan Dam. |
|-------------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Real specific weights | Virtual specific weights | Minimum value | Maximum value | Minimum Water absorption rate | Maximum Water absorption rate |
| 2.68 tons/m³ | 2.4 tons/m³ | 2.58 tons/m³ | 2.21 tons/m³ | 4.4 % | 6.5 % |
| Real specific weights | Virtual specific weights | Minimum value | Maximum value | Minimum Water absorption rate | Maximum Water absorption rate |
| 2.68 tons/m³ | 2.4 tons/m³ | 2.58 tons/m³ | 2.21 tons/m³ | 4.4 % | 6.5 % |

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4.4. GMTSAR

InSAR analysis using the time-series technique is helpful to make spatially dense calculations of surface deformations occurring on the crest and downstream sectors of the embankment.

It provides a convenient way to assess patterns of structural stability in their entirety, which could otherwise be quite challenging if performed using spatially dispersed land-based geodetic calculations. This is demonstrated in comparisons of the differences between velocity maps obtained using both a geodetic approach and InSAR analysis of Sentinel-1A images for 2014. The mean velocity from Sentinel-1 images between 2014 and 2019 show LOS velocities of up to 4 mm/yr.

Average LOS velocity maps obtained using GMTSAR processing on Sentinel-1A images are presented in Figure 4a and b. The baseline network for the Small Baseline time series analysis is shown in Figure 5.
Our InSAR results imply that vertical displacement has taken place on the Taleqan Dam downstream slope since 2014 based on Sentinel-1A imagery. Figure 6 shows the result of Sentinel-1A data analysis, micro geodesy, and fluctuations in water level, indicating a maximum RMSE (4.72) and minimum RMSE (0.96) calculated between Sentinel-1A and micro geodesy. For the purpose of comparison against the InSAR data, pillars (D1, D3, TC1 and TC2) were chosen due to their high displacement on the dam body.

The results of micro geodesy (BRTD 2016) show the water level in 2014 (1749 m) and 2019 (1780 m), and that the vertical displacement of the pillars appears to be proportional to the water level (Figure 6). Such changes can be explained by elastic behavior. In the third time period, due to the occurrence of the 1780 m water level and a 31 m (1780-1749 m) water level difference, the displacement has moved downstream. At this stage, no abnormal behavior in the horizontal displacements was observed. With respect to the vertical displacement, determined by levelling of the pillars, it is seen that the highest vertical displacement takes place for the pillars located adjacent to the crest; the closer the pillar is to the dam’s downstream base, the smaller is the displacement. The vertical displacements are independent of the water level (Figure 6).

The Sentinel-1A time series is consistent with the terrestrial surveying network’s behavior. Therefore, the water height is not related to the deformation, and the deformation of the dam is only caused by the corrosion of the dam.

The SAR data processing was carried out to interpret the deformation in the riprap layer of the Taleqan Dam. To verify the signal present in the InSAR results, we compared the results solely to relevant geodetic data.

5. Discussion
As demonstrated by Hussin and Poole (2010), despite the qualitative nature of the proposed physical method, it can be used to predict the mechanical response and
behavior of aggregates. Various textural factors, such as the grain interlocking rate and mineral contact can also have major effects on the mechanical features of materials (Akesson et al. 2001).

It can be argued, therefore, that the deformation that occurred over the five-year period (2014-2019) in the downstream sectors of the embankment riprap at the Taleqan Dam result from mechanical breakdown of the riprap, with signs of further deformation. The majority of the deformation is confined to the dam downstream slope, although the rate of deformation is higher near the crest of the dam.

The soil expansion takes place where the spillway concrete wall and clay core meet. According to Figure 7, soil expansion with negative numbers implies that the clay core and spillway concrete wall are in a stable situation with no disintegration in the dam.

In the histograms of D1 and D2, the pillar points follow an opposite trend, which could originate from their proximity to the dam abutment and sides and their lower embankment height (BRTD 2016).

The instrumentation data including settlement data (Figure 8) confirm no changes taken place in the dam’s body (BRTD 2016).

Comparisons between the results obtained from InSAR analysis and rock property measurements show that the deformation that occurred within the riprap is the result of weathering, erosion, and mechanical crushing. As the volumetric percentage of each type of material used in the riprap varies between 10% to 20%, a uniform distribution of material was considered for the riprap constituents. The assumption is made that the material would be completely crushed and depressed following erosion of the riprap layer and more vulnerable material.

Figure 5. The baseline network for the Sentinel-1A small baseline time series analysis. The x axis represents the temporal baseline and the y axis represents the perpendicular baseline.
The breakdown and transport of the riprap is foreseen to occur in three phases: the first phase comprises weathering and crushing, followed by limited fragmentation of both weathered and non-weathered materials, and finally displacement and rotation of materials in the empty spaces resulting in movement in the material and filling of empty spaces by movement under their own weight. It should be noted that the proposed mechanism represents a simple scenario with the assumption of uniform distribution of rock material in the riprap, whereas in real conditions, the overall distribution or the distribution of one type of material may not be uniform. However, an important objective here is to ensure that erosion and crushing of the

Figure 6. Comparison of terrestrial surveying points. TC1 and TC2 high displacement values and D1 & D2 (dam crest) with Sentinel-1A. The blue points show the water level compared with Sentinel-1A results.

Figure 7. Time-dependent behaviour of soil displacement and reservoir water level.
ripap material downstream occurs as a result of the weight of the material itself followed by subsequent atmospheric factors in the following years. Due to fragmentation and changes in the size of riprap rocks, the friction angle and therefore the shear strength of the riprap can decrease, causing the formation of a sliding area in the wake of decreased sustainability in the riprap layer or at the contact surface between the riprap and surrounding materials (shell materials). This can cause a slide in either the constituent materials or contact surface of the riprap along the downstream slope, prior to the movement of the riprap itself. Such deformations can in turn cause total sliding or overturn of the riprap. On the other hand, erosion of the constituent materials can deprive the riprap of the performance required for protective purposes.

Figure 8. a: Settlement data recorded for the Taleqan Dam. b: Settlement data for only the 2017-2018 time period.
According to the United States Army Corps of Engineers (USACE) regulation 110-02-2302, rock constituents on riprap installed on dams must be intact and of high quality with weight loss of less than 40% in wear tests, weight loss of less than 5% in sodium sulphate solution, a real specific weight more than 2.6 tons per meter squared, a water absorption rate below 1%, and a saturated uniaxial compressive strength above 500 kg/cm² (Figueroa Madero et al. 2014).

As stated by Mukhopadhyay et al. (2006), the various properties of coarse aggregates, including physical, mechanical, and chemical features, and their effects on the performance of concrete materials, are characterised by their impact on strength, shrinkage, creep, and bond strength of the corresponding material. The effects of physical factors are generally observed in the mixing, placing, finishing, hardening, and other related attributes for pavement and construction material. Mechanical factors, on the other hand, can be used to estimate the degree to which aggregates can resist external loads and stresses for further assessment of the hardened behaviour of concrete. Finally, chemical factors of aggregates reflect the internal chemical composition specific to the aggregate, which determine how the aggregate interacts chemically with water and concrete pore solution. Geological factors play an important role in determining the performance of crushed rock aggregates and their characteristic behaviour (Woods et al. 1960).

6. Conclusion

In this work, we performed a SBAS time-series analysis to quantify deformation of the Taleqan Dam in Iran. For this purpose, InSAR methods were used in combination with geodetic data to plan and optimize the installation and to position the monitoring stations. The results show, water height is not correlated with dam deformation, so the deformation of the dam is caused by the erosion of the dam. This demonstrates that SAR data allows us to link the InSAR remote sensing technique to the structural engineering of dams. SAR measurements need to be analysed together with ancillary data for interpreting the observed seasonal displacement.

The results of this research indicate that part of the rock material used in the riprap layer of the Taleqan Dam, such as Andesite stones, have a relatively low durability and specific weight as well as low erosion resistance. These qualities render them unsuitable for use as protection layers for the crest and downstream sectors of the dam embankment. The inadequate durability of certain rock materials may potentially cause weathering, depression, and reduced riprap thickness.

Alongside the mechanical test of riprap layer suggesting rock breakdown is likely, our InSAR processing show detailed evidence of the related deformation on the crest and downstream sectors of the riprap. In other words, the physical dimensions and features of the riprap material may be appropriate, but their mechanical properties have resulted in damage and gradual erosion during the years following the construction of the dam.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

The data that support the findings of this study are available from the corresponding author [M. Ghadimi], upon request.

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