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Evaluating the Effect of Strong Earthquake on Slope Instability

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Abstract

In this paper, the effect of strong earthquakes on slope instability has been evaluated in the range of dam reservoir Zirdan (North of Chabahar) in Iran. For this propose, the information of tectonical position, stratigraphy, structural features, seismicity and instability potential of the province of Makran have been studied. The research methodology of the analysis is based on Rock Pack software and Morgenstern-Price stability method. The required data has been obtained and summarized through field research and experimental results. Maximum Likelihood Estimation (MLE) method has been used for investigation. Then, annual risk of earthquakes has been considered by stochastic model. Further, Soft Bounds Model has been utilized for determining the seismic event magnitude in the radius of 100 Km in the dam site. Afterwards the return period seismic event was calculated by HZ2 software. The stability analysis of dam reservoir slopes has been carried out by slide software. Moreover, slopes were analyzed in saturation and seismic conditions. The analysis indicates that reservoir slopes of the Zirdan Dam are unstable under severe seismic loads. Necessary slope stability measures are recommended based on the results.

1. Introduction

The Makran province is located in a high risk seismic zone between Iranian and Arabian plates. It was affected by the Ms =8.0 Makran Pakistan earthquake on November 27, 1945. The Dashtyari area is affected due to the presence of Zirdan, Ghasr-e-Ghand, Dinar Kalak, Nabaksh and Makran Coastal faults. According to a research conducted by the Pajouhab-Abfan company, in the event of a strong earthquake, the slopes of the reservoir area of

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the Zirdan Dam will be unstable, leading to a high probability of landslides. Sliding of the slopes can cause clogging of sluice or intake gates which can result in fractures in the dam and hence escape of water from the dam and flooding of the surrounding area.

2. Geological and tectonic setting near the Zirdan dam (Makran)

The Alpine-Himalayan belt is one of the most active orogenic belts on Earth. It is part of the Makran subduction zone. The Makran zone age is between the Late Triassic to the Early Cretaceous is located in the Iran platform (Glennie et al., 1990). It is located east to the Pakistan border and has oceanic crust with an average thickness of about 7 km. The area comprises sequence of sediments of thickness about 10000 m. along the north-south, sedimentary cover on the basement is younger that due to the subduction of oceanic crust and being driven on the new continental sediments. Because of subduction in the Makran region, faulting is still active and earth continues to rise. From the perspective of geology, the study area is located in the Makran tectonic province and South West Raratab anticlines. There are two sedimentary formations, including Sodich and Minab in this area which lead to highly unstable slopes in the reservoir area of Zirdan Dam. The Sodich alluvial or Sodich formations include a series of coarse grained sediment on top and a part of fine-grained sand in below the Gray color with radiometric age 6000 years BC (Vita-Finzi, 1979). Seismic activity is high in the Makran subduction zone along with occurrence of large earthquakes and the return period (125 to 250 years) is relatively long. There are earthquakes in area with component of strike-slip and thrust like the earthquake on November 27, 1945 in Pasini, measuring 8.2 on the Richter scale, has been the most severe earthquake ever registered in the area. It can probably be explained by subduction of oceanic crust and the geotechnical boundary (Dorostyian et al., 2005). The most important faults within a radius of 100 km of the study area are Ghais-e-Ghand, Makran Coastal, Bolando, Zirdan, Nabaksh and Dinar kalak.

2.1. Characteristics of Zirdan Dam

The dam site is located on the river Kaju, approximately 150 km north of the city of Chabahar, Sistan and Balochestan Province, Southestern Iran (Lat: 25°34’ and Long: 60°55’) as shown in Fig. 1. Constructed by Jahan-Kosar Company, the dam regulates river Kaju, controls floods, and supplies irrigation needs. Zirdan R.C.C Dam with 64.5 m high from the river bed. The crest length is 350 m, and the width on the foundation is 66 m. The volume of the reservoir at maximum operational level of 271 m is 200 million cubic meters, and the length of the lake at maximum operational level is around 60 km. The dam was constructed between 2002 and 2010, and filling started on January 21, 2004. Makran sediments often contain a variety of sandstone, shale, mudstone, shale phyllite and siltstone. The reservoir of dam, Zirdan area is composed of fourth period Quaternary alluvial sediments and sediments of present age.

Fig. 1. Location of the studied area in the Iran.
3. Research Methodology

Since this paper aims at evaluating the effect of strong earthquake on slope instability in the range of dam reservoir, this is an analytical-descriptive research from the viewpoint of nature. The tool for gathering the data and testing hypotheses in this research are: initially, accessible data such as geological reports, geotechnical data and test results of soil and rock mechanics. Afterwards, dam reservoir area networking and mapping operations have been done at six stations in different scale at 1:100. Next, also the necessary data has been gathered based on modified classification by Bieniawski (55), categories and RMR values were determined. In addition, determining necessary seismic specifications at the dam site for the useful life of 50 years by using the Seismic Risk III software. Moreover, utilizing the data obtained from field, machine drilling, laboratory results and computations and processing by Roc Pack III software and Slide. At the end, detection of sliding of rock masses and suitable dip on the reservoir dam was evaluated for possible earthquake loads.

4. Data Analysis

4.1. Estimation Seismic Parameters of MLE Maximum Likelihood Estimation Method

In order to estimate seismicity parameters, the Gutenberg Richter equation is used. The parameters include Mmax, λ and β. λ is the annual rate of occurrence of earthquakes (Kijko and Sellevoll, 1989), Mmax is the maximum earthquake that a fault can generate (Ward, 1997) and β is expressed by the Gothenburg equation. The parameters for the study region have been calculated based on method by Kijko and Sellevoll (1992). In this paper, seismic catalogs for the study region processed for incomplete macro seismic data and heterogeneity of magnitude scale are used. For earthquake hazard assessment, stochastic model of earthquake occurrence considering Poissonion distribution is used. Soft Bounds Model is used in order to determine the magnitude of seismic events in 100 km radius around the dam site, based on the theory by Tinti and Mulargia (1985). The seismic parameters for the study area (λ, Mmax, β and b-value), in addition to the return period of earthquakes with different time periods, are calculated with the help of HZ2 software. These parameters are estimated as per equation (1) and (2) and return period of earthquakes of magnitude 5, 5.5, 6, and 6.5 are 20, 49, 75 and 233 years respectively.

\[ \beta = 1.72 + 0.11 (b = 0.73 + 0.4) \]  
[1]
\[ \lambda = 4.72 + 1.08 \text{ (for } M_{\text{MIN}} = 3.00) \]  
[2]

4.1.2. Estimation of Maximum Horizontal Ground Acceleration

An area of 100 km radius around the study region has been considered for the study. The potential seismic sources within the area have been identified in connection with the active faults and analyzed by SeisRiskIII software. Horizontal ground acceleration rate usually is chosen in, two limit with probability risk 64% and 10% that is called the first limit Design Basis Level (DBL) and second limit Maximum Design Level (MDL). To calculate the horizontal ground acceleration considering different values of useful life, the attenuation relation by Campbell and Bozorgnia (2003) is used. The results obtained from computing the possibility seismic hazard of the study area, assuming useful life 25, 50 and 100 years are presented in Table 1. As can be seen in the table during the useful life 50 years with probability of the event 64% DBL horizontal ground acceleration equals to 0.19 g. While in useful life of 50 years and with probability of the event 10% horizontal ground acceleration equals to 0.25 g.

Table 1. Maximum horizontal ground acceleration in the area dam Zirdan to probabilities calculating method (according to per cent g).

| Evaluation time period | Maximum horizontal ground acceleration with probability event 64% | Maximum possible earthquake (MDL) with probability event 10% |
|------------------------|---------------------------------------------------------------|-------------------------------------------------------------|
| 50 years               | 0.19 g                                                       | 0.25 g                                                       |
4.2. Mechanical Properties of Rocks in Reservoir of Dam

Results of triaxial tests indicate the average internal friction angle $\Phi$ of samples is 16 degrees, cohesions $c$ equals 43 kN /m$^2$ and density 20 kN/m$^3$. According to the modified classification Rock Mass Rating by Bieniawski, mudstone and siltstone of Zirdan reservoir obtained 16 score in class 5 and based on that it is placed very weak rock (Fig 2). Therefore, coefficient of cohesion of these sediments is less than 100 and internal friction $\Phi$ for whole rock mass less than 15 degree.

Fig. 2. Diagram circles Mohr and failure triaxial tests on dry state

4.3. Physical Properties of Joints/Faults

More than 300 joints were measured in and around six stations in the study area. Mostly the joints are in limestones, sandstones and shales of Miocene. The joint data is presented in Stereonets as shown in Fig. 3. Based on this method, in each of desired stations 4 joint sets were selected (Table 2). In this research, fracture mapping in 6 intended stations was performed using two methods Line mapping and Window mapping. During joint mapping operations, all required specifications inclusive length, distance, opening, filling, roughness, erosion, adhesion and water seepage fractures surface were measured. Finally, data was obtained, including physical characteristics for 300 fractures, is categorized in Table 3.

Table 2. Geometric characteristics of selected fracture surfaces on zirdan reservoir.

| Station | Rock units | Geometric characteristics of selected fracture surfaces | Layering |
|---------|------------|-------------------------------------------------------|----------|
|         |            | Joint sets 1                                           |          |
|         |            | Dr.293/44                                             | Dr.300/75|
| St.1    | Sandstone  | Dr.227/60                                             | -        |
| St.2    | Sandstone  | Dr.279/60                                             | Dr.300/75|
| St.3    | Siltstone  | Dr.266/38                                             | -        |
| St.4    | Sandstone  | Dr.335/53                                             | Dr.315/75|
| St.5    | Sandstone  | Dr.302/60                                             | Dr.310/78|
| St.6    | Siltstone  | Dr.36/32                                              | Dr.256/35|
|         |            | Dr.295/42                                             | Dr.317/72|
|         |            | Dr.46/64                                              |          |

Table 3. Fractures physical properties on the reservoir left coast of Zirdan.

| Station | Name of joint sets | Length (m) | Distance (cm) | Opening (mm) | Filling | Roughness | Erosion | Continuous (%) | Seepage |
|---------|-------------------|------------|---------------|--------------|---------|-----------|---------|----------------|---------|
| St. 4   | Joint sets1       | 19-5       | 100-60        | 30-10        | Soil    | Rough     | Lot     | 90             | Humid   |
|         | Joint sets2       | 17-8       | 150-80        | 10-5         | Soil    | Rough     | Lot     | 95             | Dry     |
|         | Joint sets3       | 20-4       | 120-50        | 2-1          | -       | Rough     | Lot     | 85             | Dry     |
|         | Joint sets4       | 19-4       | 150-400       | 15-10        | -       | Rough     | Lot     | 95             | Dry     |
4.4. Analysis of Slide

Information related to selected fractures measured in the reservoir of dam are shown in Tables 2 and 3. This helps for stability of slopes. Furthermore, it allows stability analysis of rock mass as three-dimensional by Stereonet. This helps in identifying possible undesirable orientations in rock slopes and the geometry of the slide. Frequently stereonet analysis, is related to Kinematic analysis. Kinematics, is a branch of dynamics in which movement or potential of motion in the rock mass is evaluated. So in Stereonet, plane of rupture potential, wedge or toppling can be detected. The joint data was used to carry out Kinematic Analysis to find potential failure surface and mechanism (Hagan & Bulow, 2000).

4.4.1. Sliding Plane

Kinematic analysis is based on theory by Markland and it was assumed plane rupture is downwards. Undoubtedly Markland test, is a valuable tool for the detection of discontinuities in plane failure and eliminate discontinuity non-effective of the process (Hoek & Diederichs 2006). Moreover, at different circumstances given the friction angle and slope face coordinate, critical zone can be identified and instability potential of each block can be evaluated (Roberds and Leroi, 2002). Rock pack III Software provides the necessary facilities to perform mentioned analysis. Therefore, all analyses in this section have been performed using this software. However, this analysis assumes that all discontinuities are connected to each other, but that is not the case in practice. Even a small percentage of healthy rock along the discontinuity drastically reduces the probability of rupture along the discontinuity (Kangi et al., 2009). Firstly, the data in Table 2 are compiled to the software and based on Markland method. Four categories of main discontinuities have been recognized. In view of the friction angle and slope face in the dam left anchorage, the left coast and the right coast reservoir Zirdan, critical zone and location of the line of greatest dip fractures has been shown with geometrical characteristics (Dr:262/37, Dr:102/45, Dr:42/40 (Fig.3). Analysis of diagram suggests that the ability of sliding allow the fractures surface. Thus if no seismic loading is considered, up to dip of 60 degrees, a safety factor of 2.07 is obtained (Table 4). But for earthquake events with horizontal acceleration 0.19 g, dams with slopes more than 65 degrees is unstable and sliding planes with tension joints occur.

| Seismic loading          | Safety factors | Dip 60 degrees | Dip 65 degrees | Dip 70 degrees |
|--------------------------|----------------|----------------|----------------|----------------|
| Without seismic loading  | 2.07           | 1.72           | 1.51           |
| Horizontal acceleration g=0.19 | 1.68           | 1.38           | 1.21           |
| Horizontal acceleration g=0.25 | 1.58           | 1.3            | 1.13           |

Fig. 3. (a) Planar slide potential associated with tensile fracture to the parallel fracture (the left Coast of reservoir Zirdan) (b) Model of fracture surfaces in spaghetti model (the left Coast of reservoir Zirdan)
4.4.1. Wedge Slide Analysis

Wedge rupture in comparison with sliding planes are created at more diverse geometric and geological conditions (Hoek & Bray 2005). Therefore, stability of rock slopes is particularly important in view of wedge slides. For this purpose, after analysis of stereo- graphic projections, the wedge slide potential of blocks can be identified. Using topographic conditions, fracture geometric specifications, physical and mechanical properties of the rock mass and side loads, including seismic loads; the safety factor is calculated for each wedge of rock (Krahn, 2003). Results of the studies on the dam left anchorage and the left coast reservoir Zirdan indicate that the intersection fracture surfaces in the rock mass, created wedge-shaped block numerous that have sliding potential is only two blocks B1 and B2 (Fig. 4). According geometric models, sliding rock blocks occurred parallel to the line intersection fracture surfaces.

![Fig.4](image)

**Fig.4. (a) Wedge slide potential of block B1.(b) Wedge slide potential of block B2**

4.4.2. Sliding With Simple Circular Cutting Surface

Numerical stability analysis of circular cutting surface was done by a number of researchers previously. In this research, the method of Grid search and Pattern search is used to find the fracture critical surface. Several softwares exist for analyzing the stability of slopes. Slide Software is used in this studies. In this section of the paper, green marl central part of the reservoir Zirdan was analyzed by this software.

4.4.2.1. Analysis Method

For slope stability analysis methods, the critical fracture surface is selected. Further, combination of random search based on methods of Monte Carlo (Krahn, 2003) have simple structure from random search and optimization techniques (Krahn, 2003). Static stability analysis method based on the relationship between normal and shear forces on each of sliding under slices be used (Fig. 5). The Morgenstern and Price (1965) method which considers all determining parameters, provided with the lowest possible error. In this paper slopes stability analysis has been conducted using slide software. The calculations are performed according to the Limiting equilibrium method and output safety factor resulting from torque equilibrium method. Thus, data related to structures and boreholes and in cases may accordance with geotechnical borehole.

![Fig.5](image)

**Fig.5. Relationship between normal and shear forces on a sliding slice (Krahn, 2003)**
4.2.2. Circle Sliding Potential in the Central Part of the Reservoir

Stability analysis of green marl and heavily crushed parts of the reservoir is conducted according to the method Morgenstern and Price (1965). This method is based on two main factors, safety equation and range of shear forces / normal forces on sliding slices. Additionally, this analysis of simple circular sliding surface is associated with the \((FS, vs, \lambda)\) assumption of equilibrium, independent moments inside the shear slices. Therefore, sliding mass rotates as a free body during sliding. In this part results of test of density, cohesion and friction angle, as soil properties and crushed rock of the central part of the reservoir are analyzed by the slide software. The results show that mentioned slopes with dip 20 degrees, are stable in dry state and without seismic loads. But with seismic loads with horizontal acceleration 0.19 g, safety factor is reduced up to 1.31 and caused slopes to be unstable (Fig. 6 and 7). Also the increase of slope dip causes the instability of the left coast reservoir. Accordingly, the factors of safety decreases with increase of dip of the slope and horizontal acceleration. Seismic loads of horizontal acceleration 0.19 and 0.25 g as shown in Table 5.

| Seismic loading       | Safety factors |
|-----------------------|----------------|
|                       | Dip 20 degrees | Dip 25 degrees | Dip 30 degrees |
| Without seismic       | 1.37           | 1.30           | 1.21           |
| Horizontal acceleration g=0.19 | 1.31           | 1.18           | 0.83           |
| Horizontal acceleration g=0.25 | 1.28           | 0.98           | 0.65           |

Fig. 6. Comparison of safety factor sliding circle at green marl and heavily crushed central parts of the reservoir with 20 degree dip, in normal conditions and under seismic loading with horizontal acceleration 0.19 g.

Fig. 7. Comparison of safety factor sliding circle at green marl and heavily crushed central parts of the reservoir with 25 degree dip, in normal conditions and under seismic loading with horizontal acceleration 0.19 g.

5. Conclusions

The left anchorage of dam and the left coast of reservoir of Zirdan has the greatest potential to fail compared with other parts of reservoir. One of the factors that increase instability on the left coast of reservoir, is the existence
of green marl at the central part of reservoir as well as presence of the 4 categories of selected fractures in the rock mass, forming plane and wedge failures. The results of the seismic analysis by Kijko model showed that the return period of earthquake events in this area evaluated for an earthquake of magnitude 6 on Richter scale is 233 years. Also seismic parameter estimation by the Campbell method in Zirdan dam area, shows that for the useful life of 50 years and earthquake probability event DBL 64%, horizontal acceleration is equal to 0.19 g. While for the useful life of 50 years and probability event MDL 10%, horizontal acceleration is equal 0.25 g. Stability analysis of rock blocks as planar and wedge, implies the left coast reservoir and the dam left anchorage have slide potential due to the special situation of fracture systems. Accordingly, the left coast reservoir to dip 70 degrees without seismic loading sliding is stable against the plane slides. But earthquake event with horizontal acceleration 0.19g, slopes more than dip 65 degrees are unstable. Further, out of several rock blocks, only blocks B1 and B2 are having the sliding potential and unstable conditions. Analysis done on green marl and heavily crushed parts of the reservoir shows this section with dip 20 degrees, are stable in dry state and without seismic loads. But with seismic loads with horizontal acceleration 0.19 g, safety factor is reduced up to 1.31 and unstable slopes are caused. So green marl dip greater than 20 degrees, which forms the central part of reservoir represent the unstable condition. Suggested dip of marl deposits in the vicinity of the dam structure be reduced to less than 20 degrees.

References

[1] N.N.Ambraseys,C.P. Melville, A History of Persian Earthquakes, Cambridge University Press, London, 1982, pp. 219.
[2] H.A.Babaei, H.Araghishi, M.Purkermanei, A.Adeib, Three-dimensional model Makran basement, Twenty-Sixth Meeting of Geological Sciences the Geological Survey of, Iran, 2008.
[3] A.W.Bishop 1955, The use of the slope circle in the stability analysis of slopes, Geotechnique 5, 1955, pp. 7-17.
[4] K.W.Campbell,Y.Bozorgnia, Updated near-source ground motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra, Bull. Seism. Soc. Am 93, 2003, pp. 314-331.
[5] D.H.Chung, D.L. Berneuter, Regional relationships among earthquake magnitude scales", Rev.Geophys. Space Phys19, 1981, pp. 649-663.
[6] A.Dorostiyan, M.Gheyetanchi, Study characteristics and seismic activity the region of Makran, 38th Annual Meeting of Geological Society of Iran, 2005.
[7] W.Fellenius, Calculation of the Stability of Earth Dams, Proceedings of the Second Congress of Large Dams 4, 1936, pp. 445-462.
[8] K.W.Glenie, M.W.Hughes Clarke, M.G.A.Bouef,W.F.H. Pilaar4, B.M.Reinhardt, Inter-relationship of Makran-Oman Mountains belts of convergence, Geological Society, London, Special Publications; 1990; Vol.: 49; pp. 773-786.
[9] E.Hoek, J.Bny, Rock Slope Engineering (4th edition), Duncan C. Whylle and Christopher W. Mah, 2005, p. 431.
[10] E.Hoek, M.S.Diederichs, Empirical estimation of rock mass modulus", Int. J. Rock Mech.Min. Sci 43 (2), 2006, pp. 203–215.
[11] N.Janbu, Applications of composite slip surfaces for stability analysis", Proceedings of the European Conference on the Stability of Earth Slopes, Stockholm 3,1954, pp. 39-43.
[12] A.Kangi, N.Heidari, Reservoir-induced Seismicity in Karun III Dam (Southwestern Iran), Journal of Seismology 12 (4), 2008, pp. 350-361.
[13] A.Kangi, M. Purkermanei, S.Mirzaei, The role of fractures in seismic loading conditions on the west wall instability west wall of Sarcheshmeh Copper Mine, Journal of Applied Geology, 7year(1), 2010, pp. 63-76.
[14] A.Kangi, J. Rahnama rad, N.Sadat khah, A. Rohani, Rajaduon river slope instability under seismic loading (North Genaveh), Journal of Applied Geology, 7 year, (3), 2009, pp. 240-252.
[15] A.Kijko, M.A. Sellevoll, Estimation of Earthquake Hazard Parameters from Incomplete Data Files. Part II, Incorporation of Magnitude Heterogeneity, Bull. Seismol. Soc. Am. 82, 1992, pp. 120–134.
[16] A.Kijko, Estimation of the maximum earthquake magnitude, Mmax", Pure & Applied Geophysics PAGEOPH 161 (8), 2004, pp. 1655-1681.
[17] A.Kijko, M.A. Sellevoll, Estimation ofEarthquake Hazard Parameters from Incomplete Data Files, Part I, Utilization of Extreme and Complete Catalogues with Different Threshold Magnitudes, Bull.Seismol. Soc. Am 79, 1989, pp. 645–654.
[18] J.Krahn, The 2001 R.M. Hardy Lecture: The limits of limit equilibrium analyses, Canadian Geotechnical Journal 40 (3), 2003, pp. 643–660.
[19] X.Le Pichon, Sea-floor spreading and continental drift, Journal of Geophysical Research 73, 1968, pp. 3661–3697.
[20] N.R.Morgenstern, V.E.Price, The analysis of the stability of general slip surfaces, Geotechnique15, 1965, pp. 79-93.
[21] W.Page, J.Alt, L.L. Cluff, G. Pfalke, Evidence for the Recurrence of Large Magnitude Earthquakes Along the Makran Coast of Iran and Pakistan, Tectonophysics 52, 1979, pp. 533-547.
[22] C.Robert, G.Casella, Monte Carlo Statistical Methods, 2nd ed., Springer-Verlag, New York, 2004.
[23] C.Robert, G.Casella, Introducing Monte Carlo Methods with R, Springer-Verlag, New York, 2009.
[24] E.Spencer, A Method of Analysis of Embankments assuming Parallel Interstices Forces, Geotechnique 17 (1), 1967, pp. 11-26.
[25] S.Tinti, F.Mulargia, Effects of magnitude uncertainties on estimating the parameters in the Gutenberg-Richter frequency-magnitude law, Bull. Seism. Soc. Am 75, 1985, pp. 1681-1697.
[26] C.Virta-finzi, Contributions to the Quaternary Geology of Southern Iran, G.S.of Iran, 1979, rep.No.47; p. 52.
[27] S.N.Ward, More on Mmax", Bull. Seismol. Soc.Am.87, 1997, pp. 1199–1208.
[28] C.F.Watts, D.R.Gilliam, M.D.Hrovatic, H.Hong, ROCKPACK III for Windows Rock Slope Stability Computerized Analysis Package.California Consulting Geologists, Radford University Office, (540), 2003, pp. 831-5637.
[29] Working Group Consulting Engineers Pajouhab-Abfn. Seismotectonics and Seismic Hazard Assessment report on dam Zirdan. Phase II Studies Zirdan Dam, 1997.