The assessment of possible deformations in the fault zone

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Abstract. One of the most relevant aspects for engineering geology regarding faults is the characterization of the changes induced by a fault and the assessment of possible fault movements. This zone cannot be clearly and well observed in field studies. However, it plays a negative role in the construction and operation of structures. In this zone, unfavorable phenomena, such as rock collapses, displacements, etc., may occur. The purpose of the present study is to estimate the size of fault changes, to reveal the peculiarities of stress distribution within the fault influence zone and to characterize free surface movements. The site of the Rogun HPP was chosen as the object of the study. Rogun HPP is located on Vakhsh River (Tajikistan) in a gorge of 400 - 500 m deep. The site of the dam, which will be about 350 m high, is located in a single tectonic block bounded by sub-parallel Ionakhsh and Gulizindan Regional Faults. The complex of Jurassic-Cretaceous sediments in this block lies monoclinically. According to the results of complex inclinometer-deformographic observations at the Rogun HPP site, the faults are tectonically active, with vertical displacements in 1-3 mm per year. In the scheme of numerical simulation, the width of the Ionakhsh Fault together with the crushing zone was taken as 20 m. For all rocks it was accepted: Young modulus – 3000 MPa; Poisson's ratio - 0.3; density - 2.6 g/cm³. Horizontal compressive tectonic force was given as 12 MPa. The simulation showed that the dynamic influence zone is limited to 200 m on the side of the lying wing and 70 m on the side of the hanging wing, and the concentration zones are located at the mouth and in the middle part of the fault on the side of the lying wing and between the hanging side of the fault and the bottom of the valley. The analysis of the movements of eight points of the surface showed that the direction of movement corresponds to observed in nature. The total amplitude of vertical displacements of two points at the valley is 0.51 m. The values of the resulting displacements on the different sides of the fault are 0.22 and 0.49 m. According to geological data, the width of tectonic breccia zone of the Ionakhsh Fault is 120 m. However, according to numerical simulation the influence zone is about 270 m. Thus, the simulation showed that the size of real fault influence zone is more than twice as large as that measured in nature.

1. Introduction

The influence of fault zones in engineering surveys is a rather complicated and poorly studied problem [1, 2]. The zones of fault dynamic influence, defined by Sherman [3] as dynamic influence areas, cannot be clearly and definitely fixed in situ. However, these zones can play a negative role in geological engineering.

The article considers the issue of determining the criterion for assessing the area influenced by a fault. With the help of numerical simulation, the following issues are considered - real fault zone geometry, location of stress concentration areas, movement of free surface, etc.
The purpose of the simulation was to estimate the size of fault area (dynamic impact area of fault), to identify the peculiarities of stress distribution within this area and to characterize the free surface movement in the main nodes. For this, firstly, the stress-strain state of fault zone under the action of gravitational force was studied; secondly, the same under the action of gravity and tectonic force; and thirdly, the direction and magnitude of free surface displacements (from stresses) under the action of gravity and tectonic. This was done with the help of numerical analysis based on the method of boundary elements. Calculations were performed for the 2D method of discontinuous displacements using an original software package developed by the specialists of the Faculty of Geology of Lomonosov Moscow State University [5]. The rock massif was considered as an isotropic linear-elastic space, taking into account the influence of the following factors: terrain features; fault disturbance of the massif; gravity; horizontal compression force simulating the tectonic force.

2. Geology of Rogun dam construction site
The Rogun dam site is located within the joint zone of two major structural regions of Central Asia - South-Western Tien Shan and Tajik Depression. Seismic activity of the territory is very high, up to 9. Located in the upstream of Vakhsh River in Tajikistan, the dam, about 350 m high, is located in a single tectonic block (figure 1), bounded by sub-parallel Ionakhsh and Gulizindan regional faults of second order.

![Figure 1](image1.png)

**Figure 1.** Google Earth image of the Rogun dam construction site. Red lines – I - Ionakhsh Fault, II - Gulizindan Fault, 3 – Fault No.35 and another feathering faults. Orange line - the contour of the dam. Green line – cross-section. Location of fault zones is indicated by the results of space image interpretation.

The canyon sides of the Vakhsh River are composed of sediments of Cretaceous age and are represented by unevenly interspersed sandstones and siltstones with interlayers of argillites. The layers are monoclinal to the lower basin, close to the vertical, with a north-eastern extension. The territory of Rogun dam site is broken up by numerous faults of different orders. All the facilities of the Rogun HPP are located in a large, relatively stable block of rocks, bounded by two major faults - Ionakhsh and Fault No. 35.
The site of the Rogun HPP is located directly in Ionakhsh Fault influence zone (figure 2), which crosses the river at the upper wedge of the dam. Here, the fault falls to the southeast at an angle of 75-80°, as longitudinal fault.

![Figure 2](image1.png)

**Figure 2.** Left bank of Vakhsh River (Rogun dam site). Red pointers show saddle point dedicated to Ionakhsh Fault.

In the upstream of the Rogun dam, the Ionakhsh Fault is represented by two fault planes limiting the subzone of crushing and mylonitization. The max distance between the planes is up to 80 m. The zones are fill in tectonic clay, with the width of the main plane (southeast) reaching 1.5 m and the secondary plane (northwest) reaching 0.3 m.

The Fault No. 35 is a thrust fault (figure 3). The observed influence zone reaches 30 m, and the plane of this fault is represented by a clay layer of 10 - 15 cm. In the fault zones local groundwater pressures up to 10 - 15 m are recorded.

![Figure 3](image2.png)

**Figure 3.** Left bank of Vakhsh River (Rogun dam site). Red lines – visible zone of Fault No 35.
Based on the results of complex inclinometric-deformographic observations at the site [4], it was shown that this fault is tectonically active. Vertical relative displacements longitudinally to the Ionakhsh Fault edges, in 1-3 mm per year, have been recorded.

3. Simulation methodology

The calculation scheme was based on the geological materials of the engineering geological survey of the Rogun HPP site carried out by "Hydroproject" Institute, Russia.

Any calculations are associated with a significant schematization of the geological section [5]. And with a homogeneous structure of the rock massif and simple configuration of geological boundaries, the calculations are the most reliable [2]. Real rock massifs are mostly heterogeneous. In our case, the heterogeneity is due to layered terrigenous sand-clay rocks and tectonic faults developed in the massif. These heterogeneities are several orders of magnitude smaller than the studied fault. From the point of view of fault formation, a media can be considered quasi-homogeneous if the size of individual massifs and blocks composing it, which differ in their physical and mechanical properties, is an order of magnitude smaller than the linear size of dislocations. The larger is the dislocation, the larger the volume of the medium it captures, the more quasi-homogeneous the medium and, therefore, the more energy is required for its destruction. Therefore, to study the main, basic object - the fault - we do not take inhomogeneities into account, i.e. we consider the massif as an isotropic linearly deformable media, obeying the requirements of the linear theory of elasticity. We represent the fault as a slot-like fracture, which has two surfaces, or two banks, as infinitely close to each other. To solve a problem of this type, we used the method of discontinuous displacements, which is based on the analytical solution of the problem of an infinite x,y plane in which displacements suffer a constant in magnitude discontinuity within a finite segment.

All faults, breaking through rock massifs, are of finite length. Attenuating at great depth, they either flatten out, forming a lystric-type rupture, or pass into a zone of intense crushing of rocks.

No data on the depth of penetration of the Ionakhsh fault were found during engineering and geological surveys at this site [1]. Therefore, in the model, the fault is represented in such a way that it is open on the surface and closed at some depth. We can assert this due to the fact that, starting from a certain depth, there is friction on the displacement, which increases with depth. And due to this, from a certain depth the fracture zone practically does not differ from the surrounding massif in its mechanical characteristics. This allows us to fix the lower end of the fault in numerical analysis. The authors are aware that such schematization of the fault is not identified with its real end. Such assumptions make it possible to obtain a representation of stress distribution for the "extreme" case. The presence of a filler in the fault will only "soften" the picture of stress distribution and decrease their values.

The width of the Ionakhsh Fault together with the crushing zone accompanying it on the surface was taken to 20 m. The data obtained during surveys were used to select the calculated indices of rock properties of the massif. As the majority of rocks composing the slope are characterized by close values of density and Poisson's coefficient, in the calculation scheme for all rocks it is accepted: Young modulus - 3000 MPa; Poisson's coefficient - 0.3; density - 2.6 g/cm³. Horizontal compressive tectonic stresses, acting according to [4], obtained by geological and structural tectonic in-site measurements, were given equal to 12 MPa. Figure 4 shows the scheme and the results of the study of stresses and displacements in the valley complicated by the fault. The application of elasticity theory is an assumption. In this regard, the main goal of the numerical analysis was to obtain a physical representation, and the meaning of this analysis was a qualitative simulation rather than a quantitative one.
4. Dynamic influence fault zone and potential failure volume assessment according to numerical simulation

The calculations showed that the dynamic influence zone is limited to 200 m on the side of the lying block and 70 m on the side of the hanging block. The concentration zones are located at the mouth and in the middle part of the fault on the side of the lying block and between the hanging side of the fault and the bottom of the valley. The analysis of the movements of the eight points (at the top of both slopes, at the mouth (both banks) and at the end of the rupture structure, and at the bottom of the valley) of the free surface shows that the direction of movement corresponds to observed in the massif and has thrust fault nature. To check the correctness of the calculated results, the displacements of the free surface were evaluated. The deformation marks located on the surface were monitored.

The total amplitude of vertical displacements of two points at the bottom of the valley is 0.51 m (figure 5). Vectors of two neighboring elements' displacements at the valley floor are directed upwards. The values of the resulting displacements on the different sides of the rupture are equal to 0.22 and 0.49 m, respectively. Vectors of displacement of the extreme elements in the upper parts of the slope from one side and from the other are directed towards the valley and are 0.09 and 0.12 m respectively. The direction of upward displacement vectors is explained by the unloading phenomenon when the weight of the overlying rocks is removed. Analysis of displacements of free surface elements shows that in the mouth of the fault the left (lying) board moves downwards, towards the opposite wing by 0.36 m. The vector of element displacement in the mouth of the hanging side is directed upwards and makes 0.55 m. Thus, one-time total vertical amplitude of displacements in the fault (under the action of compressive tectonic stress of 12 MPa), according to the calculations makes 0.81 m. That does not correspond to the values of field studies. According to Starkov [4], the annual value...
of displacements along the Ionakhsh fault is 2 mm. The solution of the inverse problem makes it possible to estimate the value of horizontal compression as 0.1 MPa using this amplitude. The obtained difference in the amplitude value (0.81 and 0.02 m) can be explained by schematization assumptions and to a greater extent by the absence of friction in the fracture structure zone. However, it should be emphasized that the direction of displacements corresponds to those observed in the massif and has a upthrust nature.

According to engineering and geological surveys, the width of tectonic breccia zone of the Ionakhsh Fault is equal up to 80 m, and with the zone of increased cracking the influence of the fault may increase up to 120 m. However, according to calculations, the width of dynamic influence zone of the Ionakhsh Fault can be much wider and is about 270 m. Thus, the numerical simulation showed that the zone of stress-strain state change exceeds the zone of changed rocks observed in the massif. Moreover, on the side of the lying block zone of altered stress-strain state is more than twice as much as that of the hanging block. Accordingly, the real zone of fault influence exceeds directly measured more than two times.

5. Conclusions
1. The boundary element method makes it possible to characterize stresses in the rock massifs and free surface movement in the presence of fault.
2. BEM can be used to predict the location of areas of high compressive and tensile stresses in the fault dynamic zone.
3. By means of numerical simulation the area of near-fault changes was estimated, and thus the width of the dynamic influence zone was determined.
4. The width of the zone of elastic transformations caused by the fault obtained with the help of calculations is 2.17 times more than the width of the zone we can see in nature.
5. On the basis of comparison of dynamic influence zone width, received at calculations, with the “nature” width we can observed on the site, it is possible to assert, that the zone of dynamic influence...
of fault includes not only observed changes of rocks (crushing and cracking), but also area of the stress-strain state changed.

6. The presented results are just a preliminary estimate of the size of the potential zone that can be unsustainable within Rogun dam site.

7. Within this area, during the construction, unfavorable phenomena (rock bumps, spalling, inrush, etc.) may occur.

References

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