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УДК 621.3

# STATIC AND SEISMIC STABILITY ANALYSIS OF KUMTOR'S TAILINGS DAM

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Kumtor gold mine is situated in the Kyrgyz Republic in Central Tien Shan Mountains at the altitude of 4000 meters in permafrost area. Construction and operation of the tailings dam started in 1995. In 1999 displacement of the dam to downstream side was detected. The dam height was 20 meters. Analysis of monitored data showed that displacement took place in ice rich loamy layer in the foundation on 4 meters depth. To stop this displacement they decided to excavate loamy layer beyond downstream and change it by construction shear key made of macro fragmental soil. The depth of shear was 5 meters. Fur the more the monitoring data showed that tailings dam continue to move on underlying soils. The additional geological investigation was done. It showed that more solid soil was located on the depth from 10 to 12 meters. The methodology of displacement stoppage was the same as previous. Worked out measures to stop the tailings dam displacement was accomplished in the period from 2006 to 2010. The goal of the research is to create numerical model in FLAC codes, forecast calculation of dam stability to 2016 when the dam height would be 42.7 meters, the dam seismic stability analysis with consideration of layered foundation.

**Keywords:** displacement, foundation, loamy layer, shear key, monitoring data, numerical modeling, back analysis, creep, assessment of seismic stability, soil condition, peak ground acceleration

# АНАЛИЗ СТАТИЧЕСКОЙ И СЕЙСМИЧЕСКОЙ УСТОЙЧИВОСТИ ДАМБЫ ХВОСТОХРАНИЛИЩА КУМТОР

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Золоторудное месторождение Кумтор расположено в КР в горах центрального Тянь-Шаня на высоте 4000 метров над уровнем моря в условиях вечной мерзлоты. Строительство и эксплуатация дамбы хвостохранилища началась в 1995 году. В 1999 году было обнаружено движение дамбы в сторону нижнего бьефа. Анализ данных мониторинга показал, что движение дамбы хвостохранилища происходит по слабому ледонасыщенному суглинистому прослою в основании на глубине 4 метров. Для остановки движения дамбы хвостохранилища было принято решение об экскавации слабого прослоя за низовым откосом и заменой его строительством упорного клина из крупнообломочного грунта. Глубина клина составила 5 метров. В последующем данные мониторинга показали, что дамба хвостохранилища продолжает двигаться, но уже по нижележащим грунтам. Были выполнены дополнительные инженерно-геологические изыскания, которые показали, что более прочные грунты находятся на глубине 10-12 метров. Методология остановки смещений осталась прежней, т.е. замена слабых грунтов на более прочные. Разработанные мероприятия по остановке смещений дамбы были реализованы в период с 2006 по 2010 годы. Целью данного исследования является создание численной модели в кодах FLAC, прогнозные расчеты устойчивости дамбы на 2016 год, когда высота дамбы составит 42,7 м, анализ сейсмической устойчивости дамбы с учетом слоистого основания.

**Ключевые слова:** смещения, основание, суглинистый прослой, упорный клин, данные наблюдений, численное моделирование, обратный анализ, ползучесть, оценка сейсмической устойчивости, грунтовый условия, пиковое ускорение на поверхности

## INTRODUCTION

The tailings dam is located in the bed of Ara-Bel River. Water of the river was redirected around the tailings dam through upper bypass canal with returning to the former bed below the dam. The tailings dam was designed with filling method of wastes lying. Dam filling was started in 1995. The dam is raised by stages to the downstream side. The dam body is filled with macrofragmental soil. The upstream and downstream sides are formed with gradient 1:3. There is impervious screen with the length 100 meters which is lying along the upstream and the bottom of reservoir. It’s made of polyethylene film of high density with thickness 1.5 millimeters. General view of the dam is shown in Figure 1.

Figure 1. Kumtor tailings dam

In 1998, holes for installation inclinometers were drilled. At that time maximum height of the dam was 20 meters. Data of field observations showed that dam was moving to downstream side. Allocation of horizontal offset showed that displacement was caused by ice rich loamy layer in the foundation. In order to stop displacement the decision was made to remove loamy layer beyond downstream side and change it by construction of shear key from macrofragmental soil. In 2003, works for arrangement of shear key were performed. At that time dam height was 24.7 meters. Trench for shear key with depth 5 meters and slope ratio 1:1 had a length about 20.5 meters. Shear key depth was determined on the basis of analysis of horizontal offsets with consideration for meter long incut in soil which had no any displacement. Cantledge with 5 meters height was dumped on the shear key. Soil for organization of shear key, cantledge and dam body was selected from one pit. In the following the data of field observations showed that the measures which had been done did not lead to stoppage of the dam displacement. Temporary group of experts from Canadian consulting firm BGC Engineering INC and Institute of Geomechanics and Development of Mineral Resources (IGDMR) was created to solve this problem. The following are results of IGDMR. Tailings dam numerical model was performed in FLAC codes as a creep model. Regulatory requirements acting in Kyrgyz Republic about assessment of stability based on the value of factor of safety. In this case the factor of safety was calculated after creep modeling had been finished.

## NUMERICAL MODELING

Numerical modeling was performed using the program FLAC (Itasca 2011). The important stage of numerical modeling is selection of soil model, describing the relation between creep deformation and relaxation of stress. In the result of analysis of different models for description of rheological processes in soil, Norton's power law dependence was selected. Stress-strain analysis with consideration of rheological processes was based on the comparison of calculated displacements and monitoring data. Monitoring of displacement was made on the basis of inclinometers. Figure 2 (a) describes observed displacements according to inclinometer INC98-1 in period from 21.12.01 to 13.08.05.

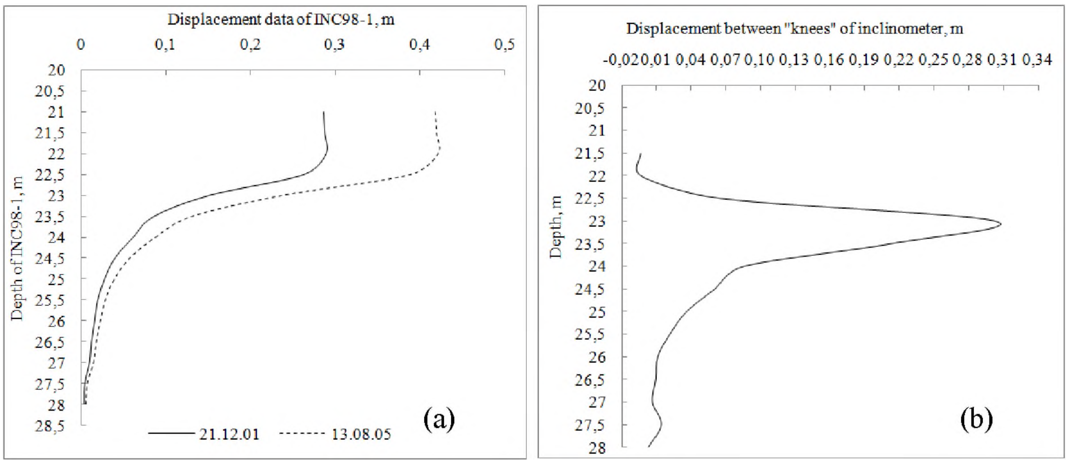

Figure 2. (a) INC98-1 inclinometer data; (b) allocation of deformation shift in loamy layer

The depth in meters from the dam crest is on vertical axis and total displacements in meters are on horizontal axis. The figure shows that the most intense displacements occur between 22 meters and 24 meters marks. Original ground level corresponds to 20 meters mark. Loamy layer has a various width from 6 to 10 meters. The largest deformation shift is observed in upper part of it within the limits of 2 meters. The roof of loamy layer is situated at a depth of 2 meters from ground surface. All shift indexes above this mark are virtually the same. That means that the dam body and two meters of natural soil above the loamy layer have lesser deformation shift. In order to find out on which depth and with what intensity deformation happens, schedule of inclinometer knees was built relative to each other and provided on Figure 2 (b). This figure shows that the largest deformation shift is registered at a depth from 2.5 to 4 meters (mark 22.5 - 24 meters). The most deformable layer has width about 1.5 meters. Below 4 meters (mark 24.0 meters) deformation shift drops evenly. Formation of rheological model is based on separation of calculated rheological layers within the limits of whole loamy layer with a capacity of 9 meters. In view of the fact that shifts in loamy layer occurred before installation of INC98-1, it is necessary to try to restore accumulated shifts from the beginning of the dam construction. Difference in shifts between layers defines by the value of deformation and this is the most important for assessment of resistance. Figure 3 provides restored shifts in separated layers of loamy layer on the basis of monitoring data. The results of layer shift approximation with coefficient of determination $R^2 = 0.995$ are also showed at Figure 3. Layer shift at the stage of the dam upbuilding during the period from 1999 to 2005 occur in a linear fashion. Model calibration was carried out by variation of rheological parameters A and n according to Norton's method. In this case n parameter is considered as constant and equal 3. The most exact approximation of the results was obtained by rheological model consists of six calculated layers which are provided on Figure 4.

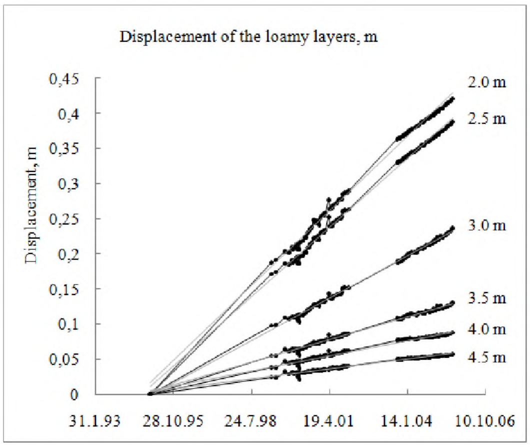

Figure 3. Horizontal displacement of loamy layers at depth from 2.0 to 4.5 meters based on INC98-1

Figure 5 displays comparison of calculated displacement and observation data according to INC98-1 to 2004 inclusively. The calculation data matched well with monitoring data obtained on basic shifting layers, situated at a depth 22.5, 23.0 and 23.5 meters. Calibration test of 2004 was associated with the fact that in 2008 shifts have some departure from linear fashion.

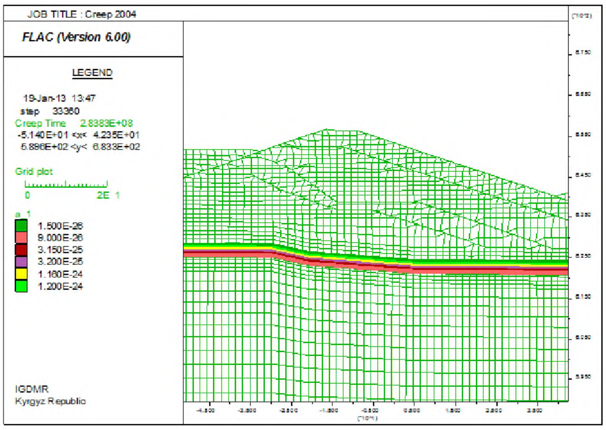

Figure 4. Calculated layers of dam foundation for 2004

The correction of A index in the middle layer in 2004 allowed reaching the optimal approximation. In view of the fact that the last model hadn't correction of A index, it can believed that all the following calculations have prognostic character. The construction of the dam will be finished in 2016. Figure 6 displays the results of horizontal displacement forecast by layers according to INC98-1 for 2016 inclusively. Loamy layer, outspreading under the dam body and shear key of 2003 cannot be removed. The key feature in character of horizontal displacement allocation is that the shifts in loamy layer under the dam areas continue, and shifts in areas where it was removed stop. Figure 7 provides total horizontal displacement for the end of 2016. The largest horizontal offsets concentrated in the area where loamy layer cannot be removed. In this area total horizontal offsets to the end of 2016 are less than 80 centimeters. In the area where loamy layer was removed and shear key was built, horizontal offsets are less than 20 centimeters. It points to the fact that stopping measures for dam shifting caused by rheological processes in loamy layer are effective. The question how to calculate factor of safety for a model of geotechnical object with rheological processes remains open. For evaluation of overall stability we use the following method. The main differential characteristic from early performed calculation of dam stability is that now we take into account alteration of soils strength properties for loamy layer from deformation shift value, obtained as a result of rheological process modeling. In other words, stability of the dam is evaluated with consideration of time effect. The basis of coefficient of stability calculation has two principal points [5]:

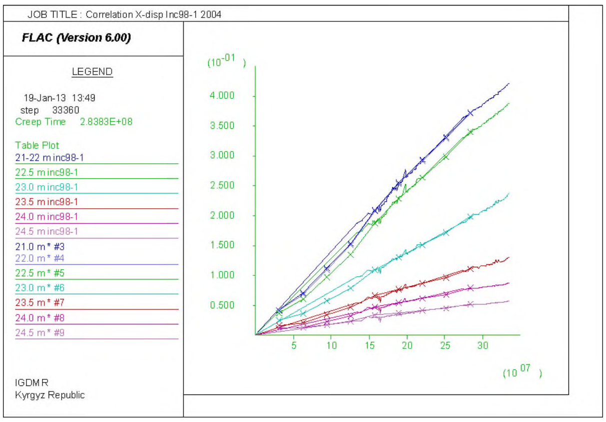

Figure 5. Comparison of numerical results with monitoring data according to INC98-1 for 2004

- If a structure is a subject to continuous rheological processes, then the moment of beginning of stability loss will be defined not by time rheological processes duration, but formation of surface of failure, along which soil reached critical deformation;
- As rheological processes of deformation shift in various points of structure are various, overall stability of structure shall be calculated on the basis of deformation shift distribution with determination of areas where deformation reached limit values.

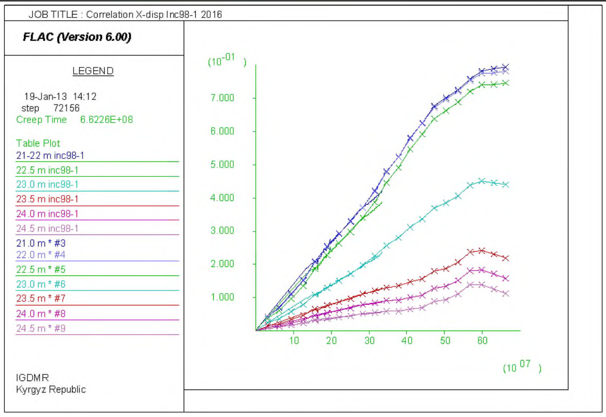

Figure 6. Forecast results of horizontal displacements of the layers for 2016

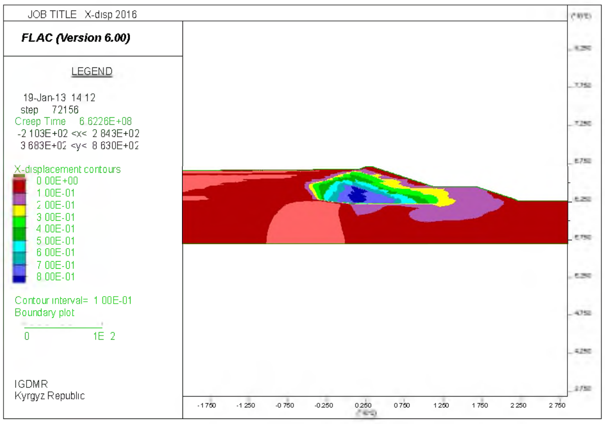

Figure 7. Horizontal displacement for the end of 2016

Zaretskiy points out that for soils there is a critical strain of form alteration [3]. On the basis of experiments with sand clay for Nurekskaya dam strain intensity was about 14%. Maslov pointed out that upon achievement of deformation shift about 13-16 %, cohesive soil does not resist shifting anymore. This circumstance for assessment of resistance upon calculation of creeping was realized as follows. If it's necessary to evaluate stability of dam in certain period of time, then we define the area in loamy layer, in which the amount of deformation reached limit value. The limit value of deformation shift is 13%. This value was selected as the smallest among all values provided in literary sources. It is accepted that this area doesn't resist to shifting. In this area strength properties cohesion and friction angle are set to zero. Special function was developed in FISH programming language for exact area separation where soil doesn't resist shifting and maximum deformation reached value of 0.13. Figure 8 (a) provides picture of maximum deformation shifts for 2016. The largest deformation shifts concentrated in loamy layer. Figure 8 (b) as an example, describes friction angle distribution for the same geometry after the function was used. After that we used standard procedure for factor of safety calculation proposed by Dawson and Roth 1999. The minimum factor of safety value is 1.36 for 2016 dam body. Note that shear-strain rate contours doesn't have exit to free surface and doesn't form closed region.

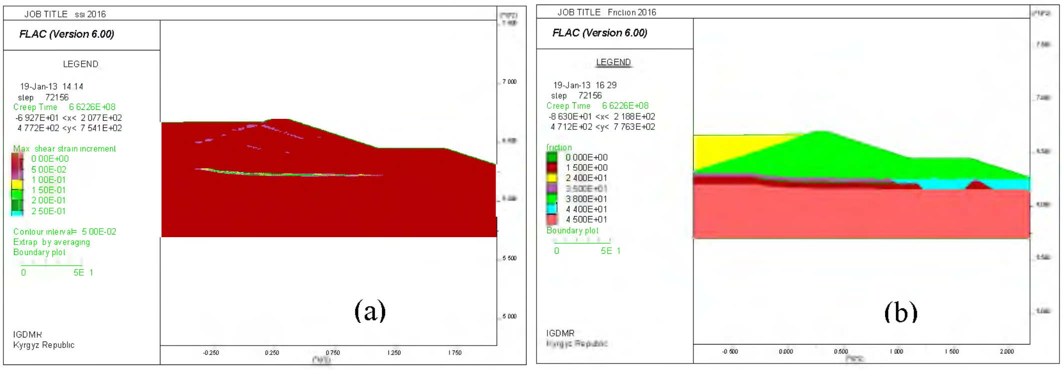

Figure 8. (a) Maximum deformation shifts; (b) friction angle distribution

Kyrgyz Republic is a seismic active country. Seismic stability assessment of the dam was based on dynamic theory [8]. It was made on the basis of calculated deformations analysis. The limit state of the dam is characterized by the presence of damage (vertical crest displacement, cracks etc.) which can lead to disturbance of the dam with following overflow of the pulp [9]. We selected two criteria of seismic stability. The first criterion is vertical dam crest displacement. Vertical crest displacement during earthquake must not exceed reserve between the crest and the level of the water in upstream. The second criterion is connected with shear-strains. This criterion is based on comparison of limit shear-strains and shear-strains which evolving in dam body during earthquake. The formation of surface of failure is related with the increase of plastic shear-strain increments to value 2 – 5 % [7]. Slope failure occurs when surface of failure cross the dam body and has an exit to slope face. Thus, for overflow of the pulp this exit should be on upstream under the water level. The earthquake motion is considered to occur when the reservoir level is at fool pool. Pore-pressure calculation is important part, it determine pore-pressure distribution on the upstream side of the dam and in the soils corresponding to the reservoir elevation. Figure 9 displays the pore-pressure distribution and phreatic surface location through the dam and foundation at steady state. The area where the dam was built according to the confirmed “Map of seismic zoning of Kyrgyz Republic” classified as zone with 8 points of intensity and repeatability

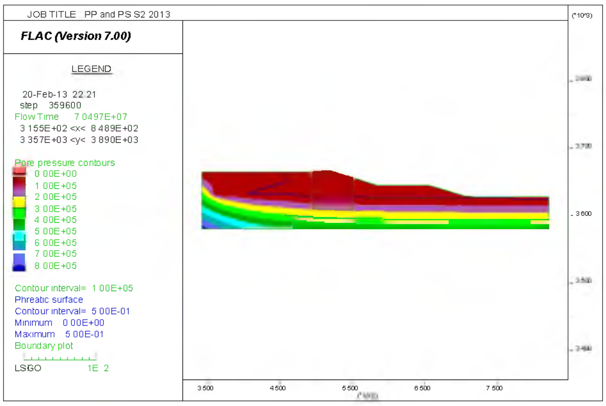

Figure 9. Pore-pressure distribution and phreatic surface

1 earthquake per 500 years. In the reports on feasibility study of the project there is an analysis of Kumtor mine seismic ground motion. This analysis based on methodology of evaluation of such factors as location of active faults and their parameters and distance from these faults and construction site. As a result peak ground acceleration for seismic analysis has a value 0.3g [1]. For understanding the influence of weak ice rich loamy layer on seismic stability the modeling of the foundation was made [2]. On the first stage the deconvolution analysis that is performed to obtain the appropriate input motion was made without weak layer [6]. On the second stage weak layer was set. In dynamic simulation the strong motion of Kobe (Japan) earthquake was used. It has duration 40.88 seconds and several peaks that make it acceptable for dynamic analysis. The soil conditions of the dam foundation lead to dynamic amplification [4]. Peak ground acceleration increased from 0.3g to 0.34g. Also the character of frequencies was changed. The Figure 10 displays acceleration time histories on the surface

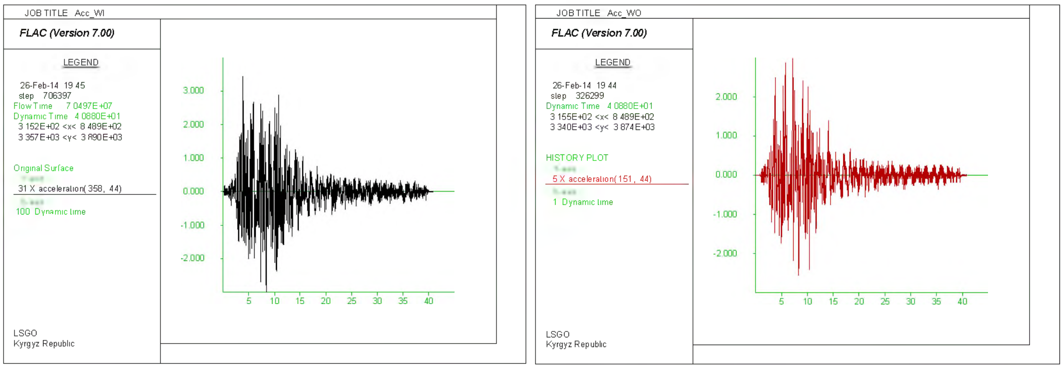

Figure 10. Acceleration time histories on the surface of the foundation

with (black line) and without (red line) weak loamy layer. The Figure 11 displays power spectrum of accelerations in three different locations of the model. For the better reading power spectrum were remade from FLAC to Excel. Red line indicates power spectrum of input Kobe acceleration. The dominant frequency is approximately 0.6 Hz, the highest frequency component is less than 8 Hz, and the majority of the frequencies are less than 6 Hz. The blue line is a power spectrum of acceleration on foundation surface. The highest frequency is 0.6 Hz and the second peak is 3.6 Hz. The black line is power spectrum of acceleration on the crest of the dam. The highest frequency is 0.6 Hz and the second peak is 2.8 Hz. Displacement of the dam after 40.88 seconds is primarily concentrated along upstream slope. This is shown in the Figure 11. The maximum displacement is 50 centimeters. Downstream side has a less value of the displacement due to the shear key efficiency.

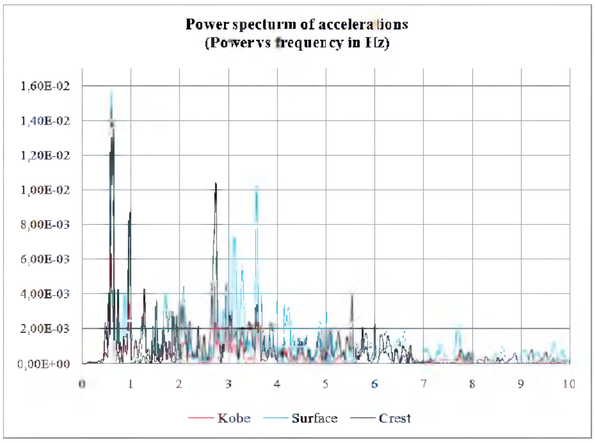

Figure 10. Power spectrum of accelerations

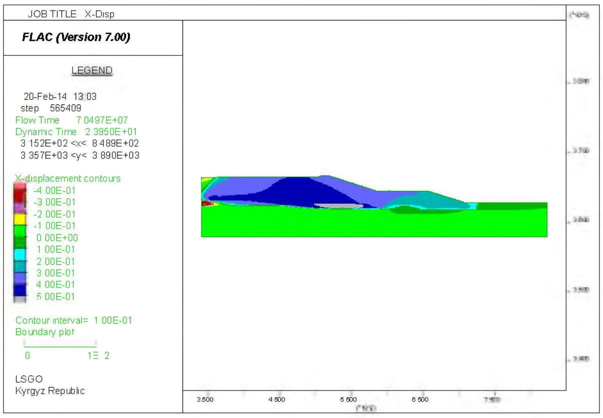

Figure 11. Horizontal displacement contours

Figure 12 shows the plot of horizontal (green line) and vertical (blue line) displacements of the crest.

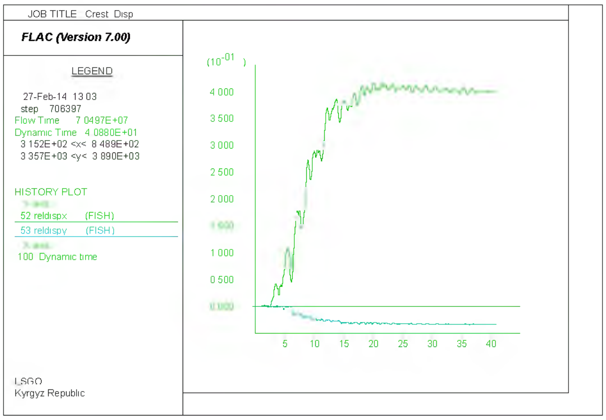

Figure 12. Crest dam displacement

The maximum value of horizontal crest displacement is 42 centimeters and vertical 3.3 centimeters. The value of maximum shear-strain occurred during seismic loading is stored with special FISH function. The Figure 13 displays the maximum shear-strain increment contours after 40.88 seconds. The maximum value of shear-strain is 50% in weak loamy layer. This level of deformations shows that loamy layer reached the limits and it doesn't resist shifting anymore. Calculation showed that the condition of slope failure, when the formed surface of failure crosses the dam body and has an exit on slope face did not happen. None of the selected criteria of dam failure took place. Seismic stability of the dam was confirmed.

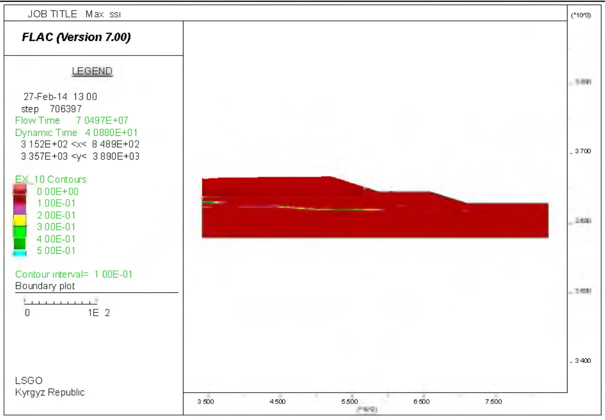

Figure 13. Maximum shear-strain increment contours after 40.88 seconds of seismic loading

**Results:** Numerical model of the dam was created with consideration of rheological processes and displacement monitoring data. Good correlation between monitoring data and calculated displacement was achieved. Forecast stability analysis to 2016 with factor of safety calculation to 42.7 dam height has been done. Seismic stability analysis based on dynamic theory including layered foundation was accomplished. The results of numerical calculation and last displacement monitoring data confirm the efficiency of the measures that were made and also provide seismic stability.

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УДК 34..06.:656.826:656.136

# ОЦЕНКА РАБОТЫ ВСПОМОГАТЕЛЬНОЙ ТОРМОЗНОЙ СИСТЕМЫ СЕДЕЛЬНОГО АВТОПОЕЗДА С ПОЛУПРИЦЕПОМ

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Цель статьи- получить результаты и оценить работу вспомогательной тормозной системы седельного автопоезда марки MAN TGS с полуприцепом «ФРЮЕХАУФ-TF34T13RBA» по требованиям ГОСТ путем проведения экспериментальных исследований в горных условиях на перевале Тоо-Ашуу. Экспериментальные исследования показали, что вспомогательная тормозная система полностью соответствует требованиям ГОСТ и обеспечивает движение со скоростью V=30±2 км/час на уклоне 8% протяженностью 12 км.

**Ключевые слова:** тормозной путь, критическая скорость, занос, опрокидывание, транспортный поток, криволинейное движение, метематическая модель, интенсивность движения.