ПРИКЛАДНАЯ МЕХАНИКА, МАТЕМАТИКА И ФИЗИКА

# GLACIER MOVEMENT MODELING USING AUTOMATIC REZONE FUNCTION IN FLAC

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ABSTRACT: The paper describes the engineering solution of glacier movement stoppage that went into the open pit. The planed excavation of ice masses from the frontal part of the glacier activated its movement. The maximum velocity was about 5 meters per day. This situation caused great concern for the safety of people working in the pit. After the situation analysis the decision was found in buttress construction made of dumps which could stop the glacier. A *FLAC* model was created to give buttress configuration and stability assessment and answer the question what will be in the moment of glacier and buttress contact. The modeling difficulty was in high glacier movement velocity. This caused the necessity of automatic rezone function use. This model should consider different materials and stages of the buttress construction. The pace of buttress construction had to be agreed on and chosen that the buttress was completed before the glacier slide into the pit.

## Introduction

The Kumtor open pit mine is located in Kyrgyz Republic. It is the largest gold mine in Central Asia. The open pit is on a great 4-km altitude in a permafrost area. Such high altitude is reaching the glaciers of Tien Shan. The open pit is situated in the way of two glaciers. Plan view of the pit and glaciers are illustrated in Figure 1.

With the expansion of the pit it was necessary to excavate the frontal part of glacier #1. This excavation touched ice masses which were lying on a horizontal part of the bed and was a natural buttress. Such intervention led the ice masses, which were on a sloping part of the bed, to slide in the direction of the pit. Typical calculated cross-section 1-1 describing materials and geometry is shown in Figure 2.

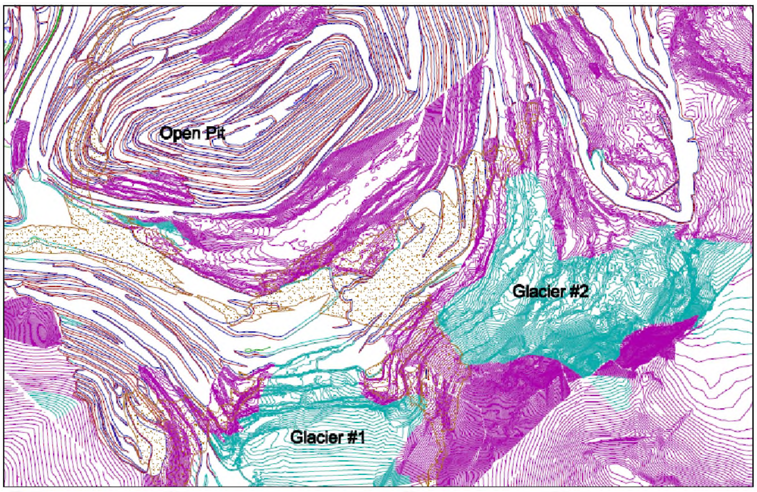



Figure 1. Plan view of Kumtor open pit and two glaciers.

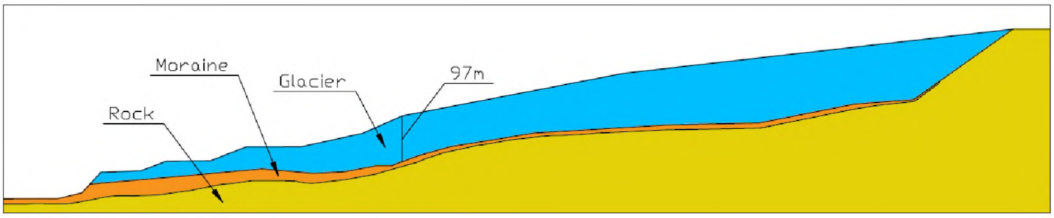



Figure 2. Cross-section 1-1 of the glacier.

The sliding velocity had very high values of 5 meters per day. This situation caused high concern of the company management for the safety of people who were working in the pit and continuation of mining operations. To continue the operation process the company started to take out the sliding ice masses, of course it was a temporary decision. Figure 3 illustrates the view of sliding glacier #1 into the open pit.

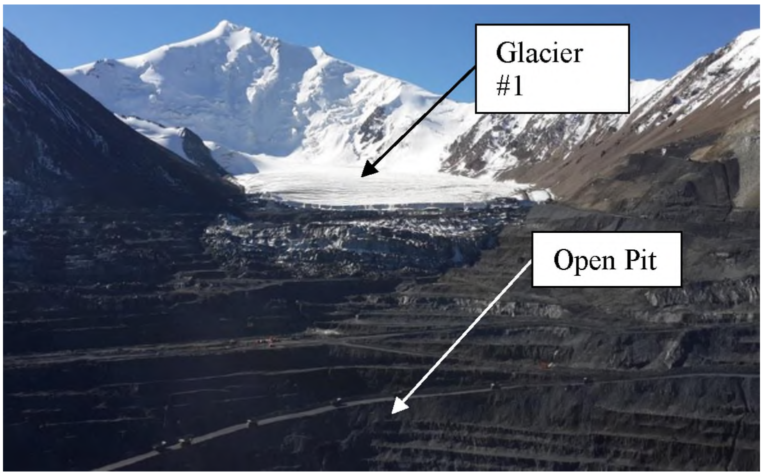



Figure 3. Sliding glacier #1 is moving into the open pit.

## THE CONCEPT OF NUMERICAL MODELING

The calculated cross-section 1-1 was defined by the analysis of monitoring displacement data. The direction of displacement vectors led to choosing this cross-section as a typical. Material properties with the exception of glacier active layer are listed in Table 1.

Table 1. Materials properties.

| | Density | Bulk modulus | Shear modulus | Cohesion | Friction angle | Tension |
|---|---|---|---|---|---|---|
| | $kg / m^3$ | Pa | Pa | kPa | degrees | kPa |
| Rock | 2850 | 1.33e9 | 6.1538e8 | 370 | 30 | 323 |
| Moraine | 2100 | 1.33e8 | 3.84e7 | 35 | 35 | 0 |
| Dumps | 2200 | 7.58e9 | 3.5e9 | 15 | 37 | 0 |
| Ice | 980 | 5.95e9 | 1.838e9 | 500 | 0 | 0 |

Glacier active layer is the layer on which the ice mass is moving. This layer was identified based on inclinometer observations. The properties of this active layer were estimated on the basis of back analysis. The results of comparison monitoring point #4000-9 displacement data and history point #4000 in the model are illustrated in Figure 4.

The back analysis was made from period of 1 January to 10 March of 2014. The cohesion in this active layer of ice was change from 500 kPa to 60 kPa. X-velocity contours distribution are plotted in Figure 5. Due to the fact that a velocity unit in *FLAC* (Itasca 2011) is m/sec the table of velocity unit conversion in m/day was created for better customer comprehension.

The automatic rezone function was used in the numerical model. To indicate materials in the model it was necessary to assign properties of one material group with different values in each zone. Without rezoning the model let to calculate only a very short period of time about two days before a “bad geometry” message appear.

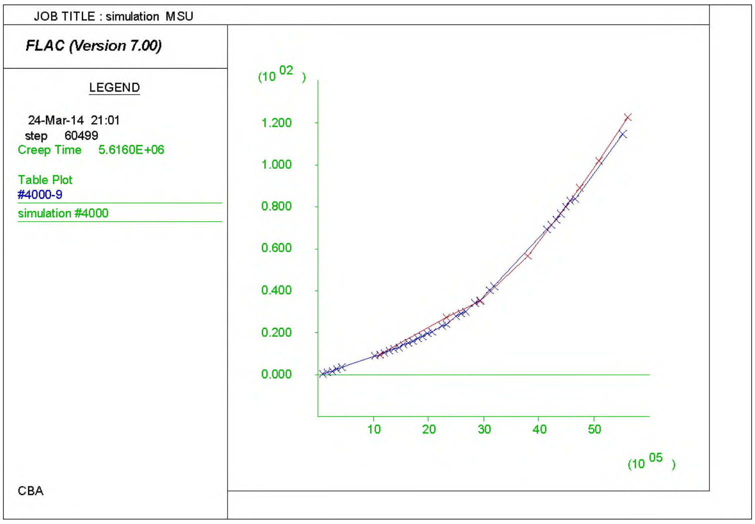
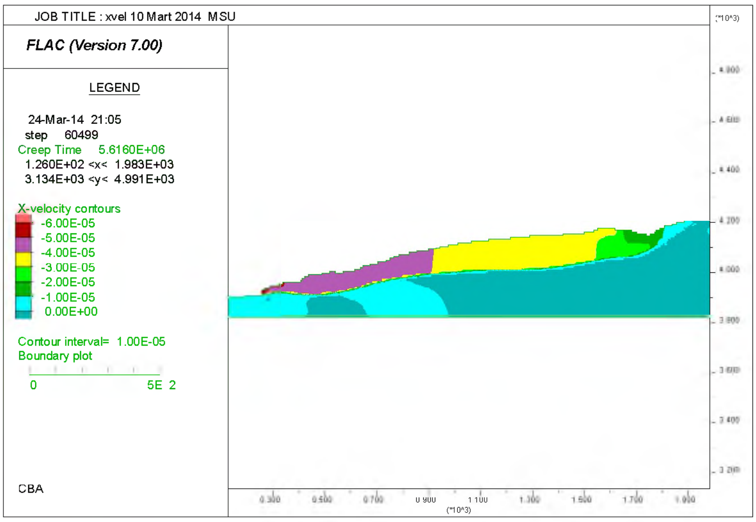



Figure 4. Comparison of displacement monitoring data and history point.




| m / sec | m / day |
|---|---|
| 6.00e-5 | 5.18 |
| 5.00e-5 | 4.32 |
| 4.00e-5 | 3.46 |
| 3.00e-5 | 2.59 |
| 2.00e-5 | 1.73 |
| 1.00e-5 | 0.86 |

Figure 5. X-velocity contours distribution and table of velocity unit conversion.

## MEASURES AIMED TO REDUCE VELOCITY OF THE GLACIER MOVEMENT

The geomechanical engineers of the Kumtor Company asked us to give an assessment of two prospective decisions to reduce the sliding velocity of the glacier or stop it: 1) excavation of the glacier to reduce ice masses lying on the sloping part of the bed and increasing the safety distance between the glacier and the open pit; and 2) buttress construction made of dumps in the glacier’s way before the open pit which will prevent glacier sliding.

### Glacier excavation

The location of monthly glacier excavation steps are shown in Figure 6. They were proposed by Kumtor’s geotechnical engineers. The area of these steps corresponds to excavation capacity of equipment.

The main difficulty of this calculation is that excavation steps were indicated on a static cross-section but in reality the glacier is moving rapidly. The solution to this problem was found in porting calculated surface of glacier after every excavation in CAD software. After that, the area of excavation was applied to new calculated geometry and the best fit of excavation was searched.

Every matching was discussed with Kumtor geotechnical engineers. Figure 7 illustrates x-velocity distribution contours at the end of April.

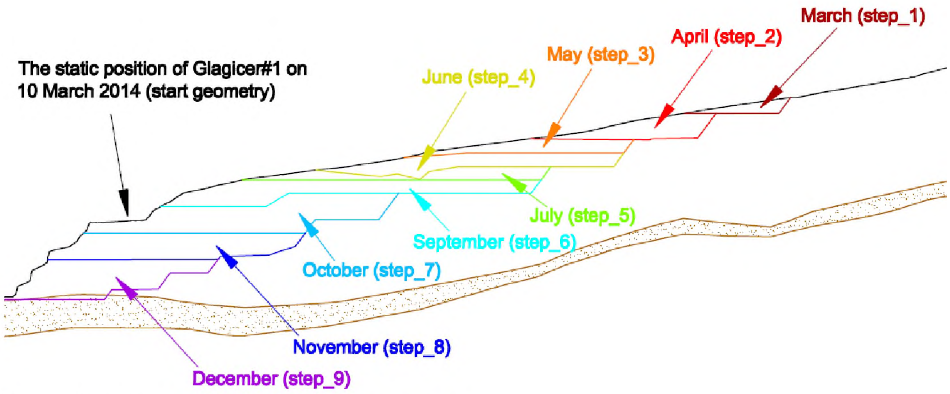
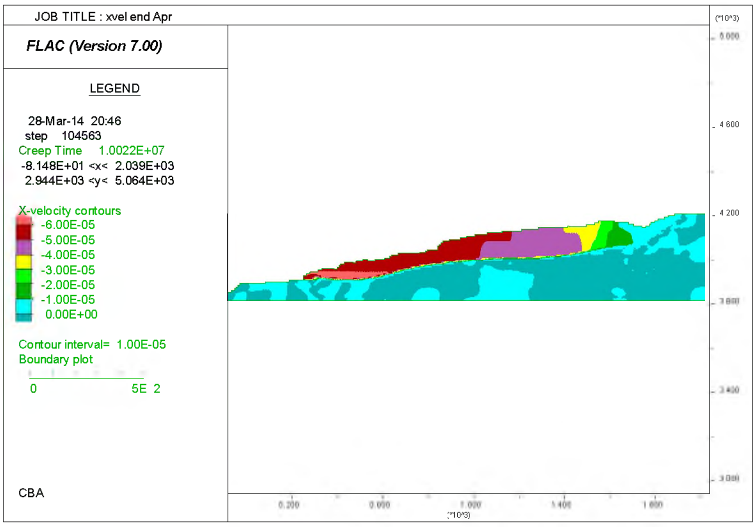



Figure 6. Monthly glacier excavation steps.



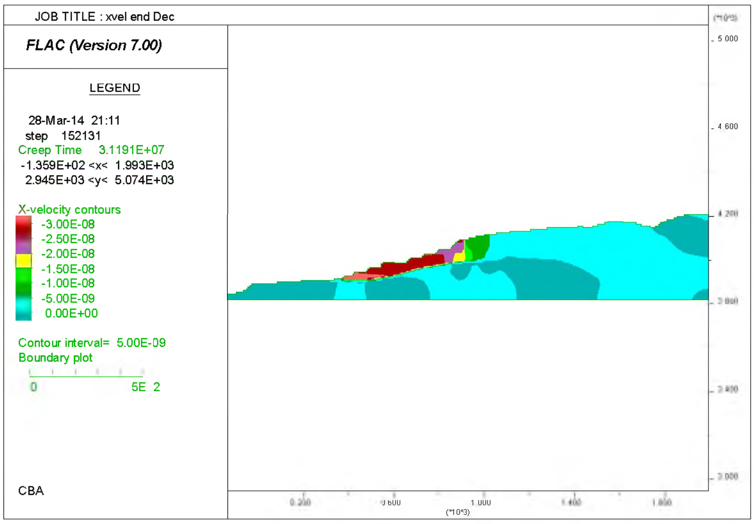

| m / sec | m / day |
|---|---|
| 6.00e-5 | 5.18 |
| 5.00e-5 | 4.32 |
| 4.00e-5 | 3.46 |
| 3.00e-5 | 2.59 |
| 2.00e-5 | 1.73 |
| 1.00e-5 | 0.86 |

Figure 7. X-velocity contours distribution to the end of April.

After the April excavation the following steps reduce the x-velocity each month. Figure 8 illustrates x-velocity distribution contours at the end of December. The variant of excavation leads to glacier x-velocity reduction starting from step of June. The unloading of ice masses can be classified as effective measure but of course it should be reviewed in conjunction with questions of feasibility and economic efficiency. From the technical point of view this variant of glacier velocity reduction was not accepted due to high fracturing of glacier surface and inability to reach the excavation locations.

## Buttress construction

The alternative variant of glacier velocity reduction is buttress construction in front of the glacier. It is necessary to note the buttress construction for containment of the glacier is a unique engineering solution. It's clear that containment of the glacier movement is possible only with steady state of the buttress. Stability of the buttress is dependent on several factors. The main factors are: properties of filling material of buttress body with consideration of softening, density of filling, the position of ground water surface, angles of buttress slopes, quality of buttress and foundation contact, geometric dimensions, etc. For realization and stability assessment of buttress construction the numerical model in *FLAC* codes again must include automatic rezone function due to high velocity of the glacier.




| m / sec | m / day |
|---|---|
| 3.00e-8 | 0.108 |
| 2.50e-8 | 0.09 |
| 2.00e-8 | 0.072 |
| 1.50e-8 | 0.054 |

Figure 8. X-velocity contours distribution to the end of December.

The calculation must be done with considering the time and stages of prospective works. The prospective works are excavation of approaching ice masses for preparation of construction site and buttress construction itself. The model takes into account the behavior of the glacier after the contact with buttress. Before the simulation of real geometry some test models were created to check the possibility of realization and detection of any problems. After a few rezoning operations *FLAC* was sending an error of zero or negative density in one or more zones. This problem was solved by adding an additional operator which checked the density and other properties after each rezone operation (introduction and application of *FLAC* auto-rezone logic, Technical Memorandum, Itasca Consulting Group). The Figure 9 illustrates results of test model calculations. Test model consists of three different types of material and simulates the effect of creeping of soft material on a solid barrier.

After the test models confirmed that this simulation is possible in *FLAC* the calculations with real geometry were started. Figure 10 illustrates the activities of foundation preparation for buttress construction on March 15. X-velocity distribution contours for the period of foundation preparation is plotted in Figure 11.

After the foundation had been prepared the construction of buttress was started. The construction stages of buttress have three main periods depending on technical possibilities. All the construction stages are shown in Figure 12. The first stage of buttress construction, up to the mark 3920 m, was planned to be accomplished by 22 March. The second stage of buttress construction, up to the mark 3940 m, was planned to be accomplished by 4 April. During this construction stage contact of the glacier and the buttress occurred. The values of glacier's x-velocity were still high and based on numerical simulation are in the range of 4.32 m/d to 5.18 m/d. The results of calculations on 4 April showed that when the ice masses coming up to buttress they started to move up along the slope of the buttress. Figure 13 illustrates the formed sliding surface. This figure provides a good view of how the ice pushes the buttress and goes up on it. The third stage of buttress construction, up to the mark 3990 m, was planned to be accomplished by 30 April. The construction of buttress to the mark 3990 m reduced the velocity of glacier movement especially in front of buttress upper slope.

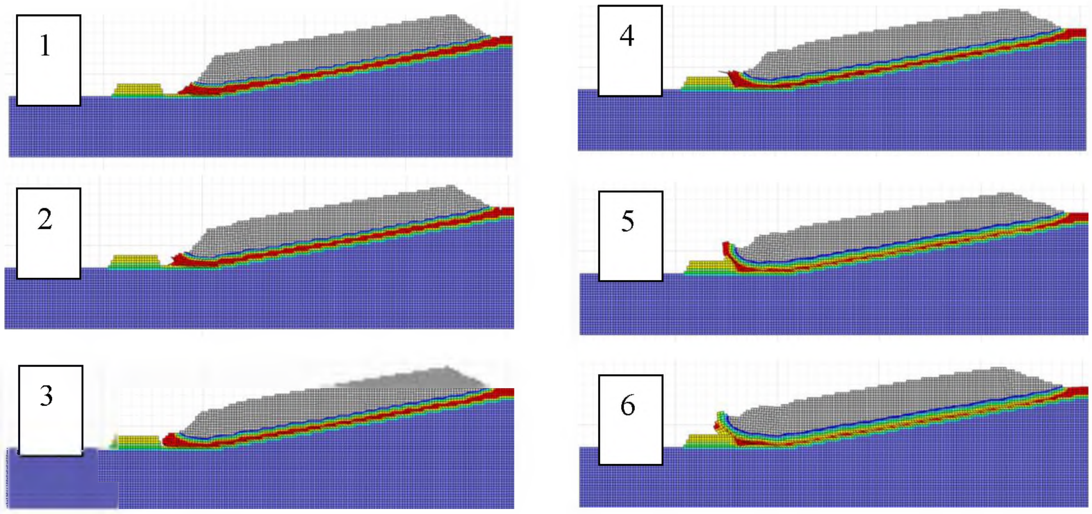



Figure 9. Steps of test model calculation process.

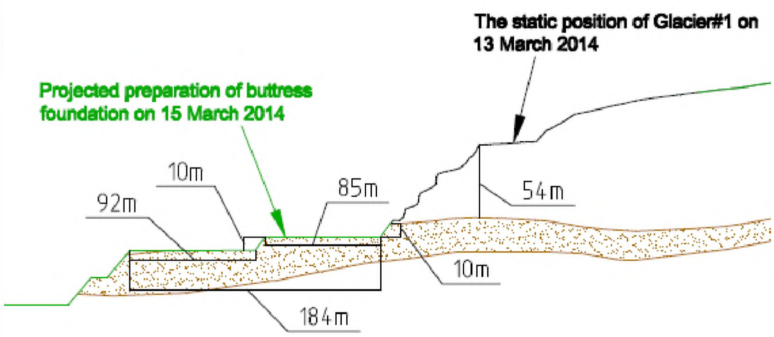
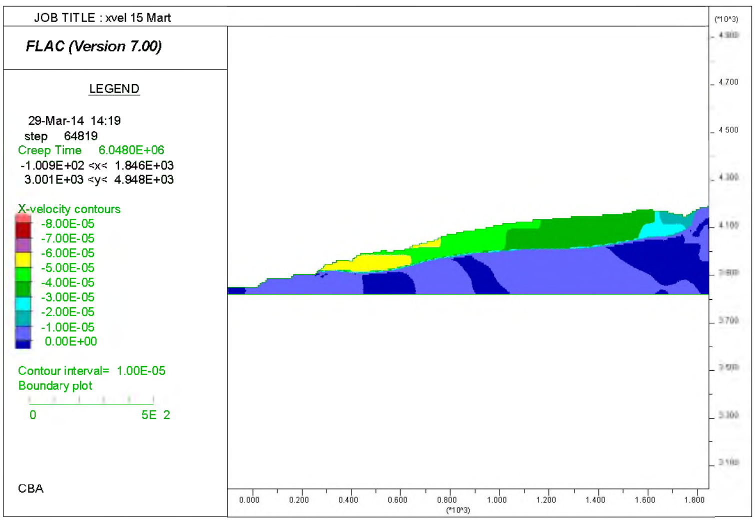



Figure 10. Foundation preparation for buttress construction.




| m / sec | m / day |
|---|---|
| 7.00e-5 | 6.05 |
| 6.00e-5 | 5.18 |
| 5.00e-5 | 4.32 |

Figure 11. X-velocity contours distribution for the period of foundation preparation.

There was a decrease in the overall x-velocity. Figure 14 shows x-velocity distribution contours at 30 April after the buttress construction was completed. Attention is called to the phenomenon of glacier frontal part penetration into the buttress body. Such penetration will cause decompaction of soil in buttress body. That will reduce the ability of buttress to resist a shift from the pushing glacier.

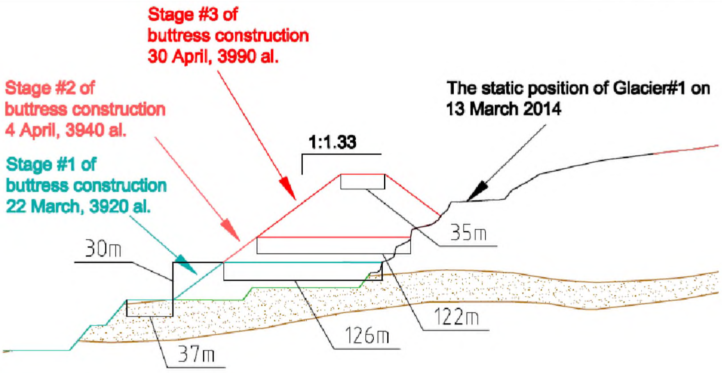



Figure 12. Buttress geometry and construction stages.

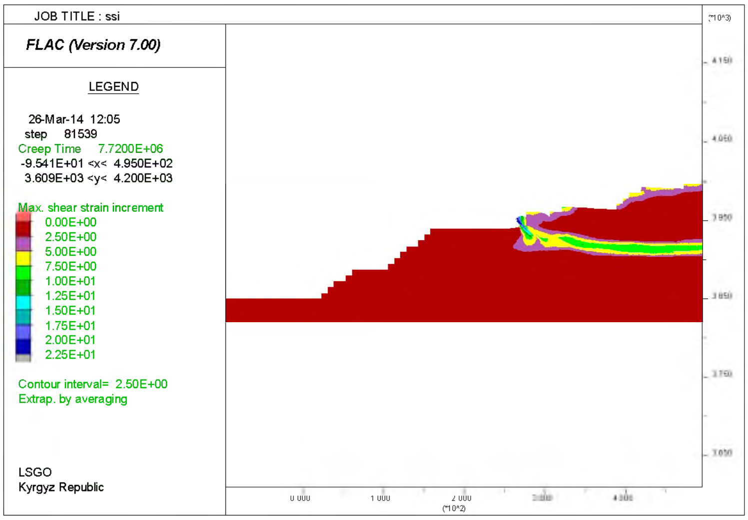
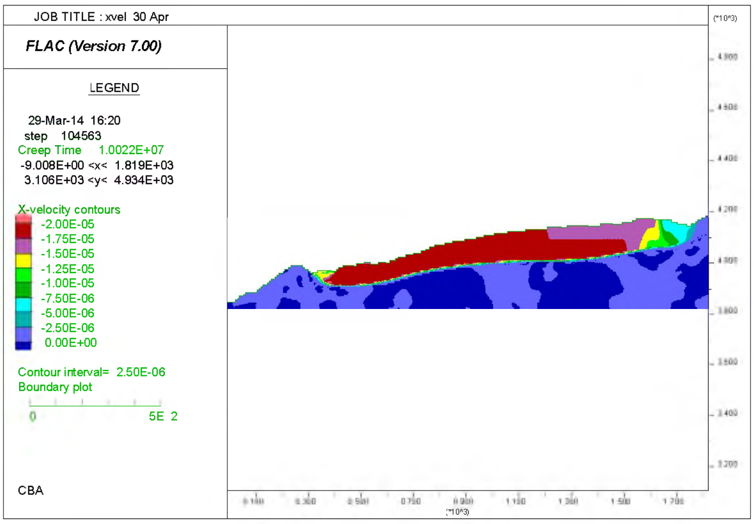


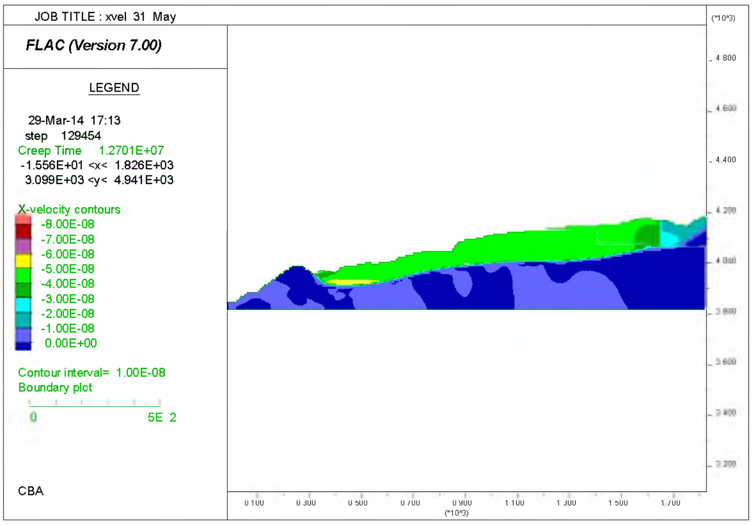

Figure 13. Distribution contours of shear strain.




| m / sec | m / day |
|---|---|
| 2.00e-5 | 1.73 |
| 1.75e-5 | 1.51 |
| 1.50e-5 | 1.30 |

Figure 14. X-velocity contours distribution to the end of April.

At the end of May x-velocity of the glacier movement was greatly reduce. Figure 15 illustrates x-velocity distribution contours to the end of May. The penetration of ice into the buttress body and formed shear strain contours are plotted in Figure 16. After the buttress construction, the excavation work was planned. The excavation of ice will take place above the sloping part of the glacier's bed. Such comprehensive approach leads to complete stoppage of glacier movement.




| m / sec | m / day |
|---|---|
| 6.00e-8 | 0.216 |
| 5.00e-8 | 0.18 |
| 4.00e-8 | 0.144 |

Figure 15. X-velocity contours distribution to the end of May.

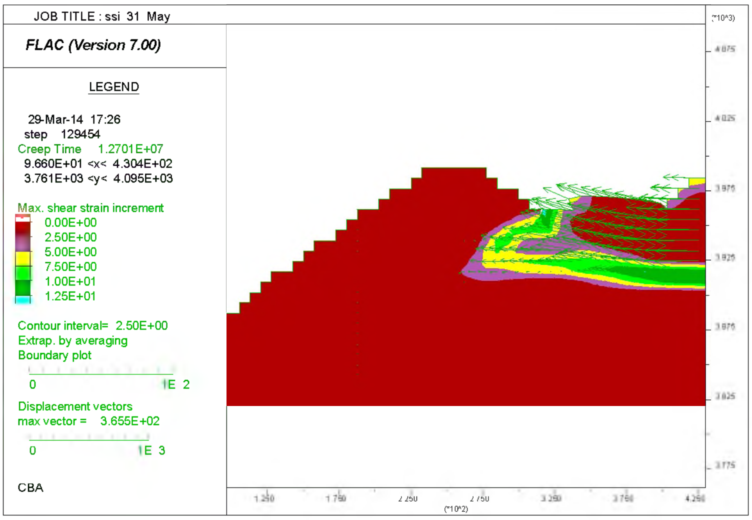



Figure 16. Distribution contours of shear strain.

To analyze stability of buttress with effect of ice penetration and reduction of strength properties of body soil the individual numerical modeling was performed. The numerical modeling of buttress took into account time factor and construction stages. Also it was considered the glacier acting on the upper slope of the buttress would be a source of filtration processes in buttress body. The cohesion of active glacier layer was reduced from 60 kPa to 15 kPa to generate more pushing pressure. To simulate the effect of soil decompaction the cohesion of dumps which are the buttress body material was reduced from 15 kPa to zero and friction angle from 35 degrees to 15 degrees in the area where shear strain increment is higher than 0.2. It was performed with special *FISH* function. The position of phreatic surface also effects on buttress stability. Because of difficulties in determination where the glacier will form filtration processes in buttress body the simulation considered several phreatic surface positions. These calculations showed that stability of buttress provided if phreatic surface is lower than 3927-m mark under the buttress crest. The results of buttress stability calculations identified the necessity of additional filling which is illustrated in Figure 17. This filling will increase the overall buttress stability and provide stable state with phreatic surface position on the 3950-m mark. The high management and geotechnical engineers of Kumtor Company chose the variant of buttress construction and agreed about addition filling on down slope of the buttress. All the necessary works were completed on time. Construction stages of end of March and middle of April are shown on the Figure 18. The effect of ice going up on construction stage number two and penetrate in buttress body which was obtained by calculation in *FLAC* was confirmed. The buttress is well monitored with all required equipment such as inclinometers, piezometers, and surface monitoring points. It prevents sliding of the glacier into the open pit more than a year.

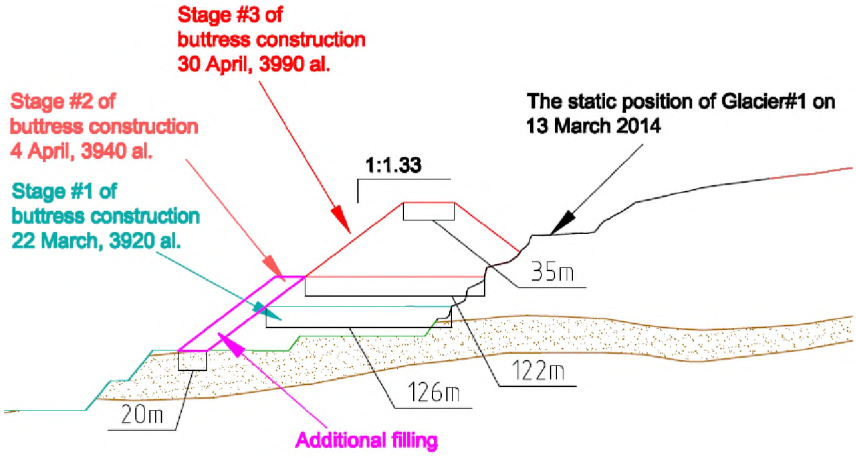



Figure 17. Additional filling in buttress construction.

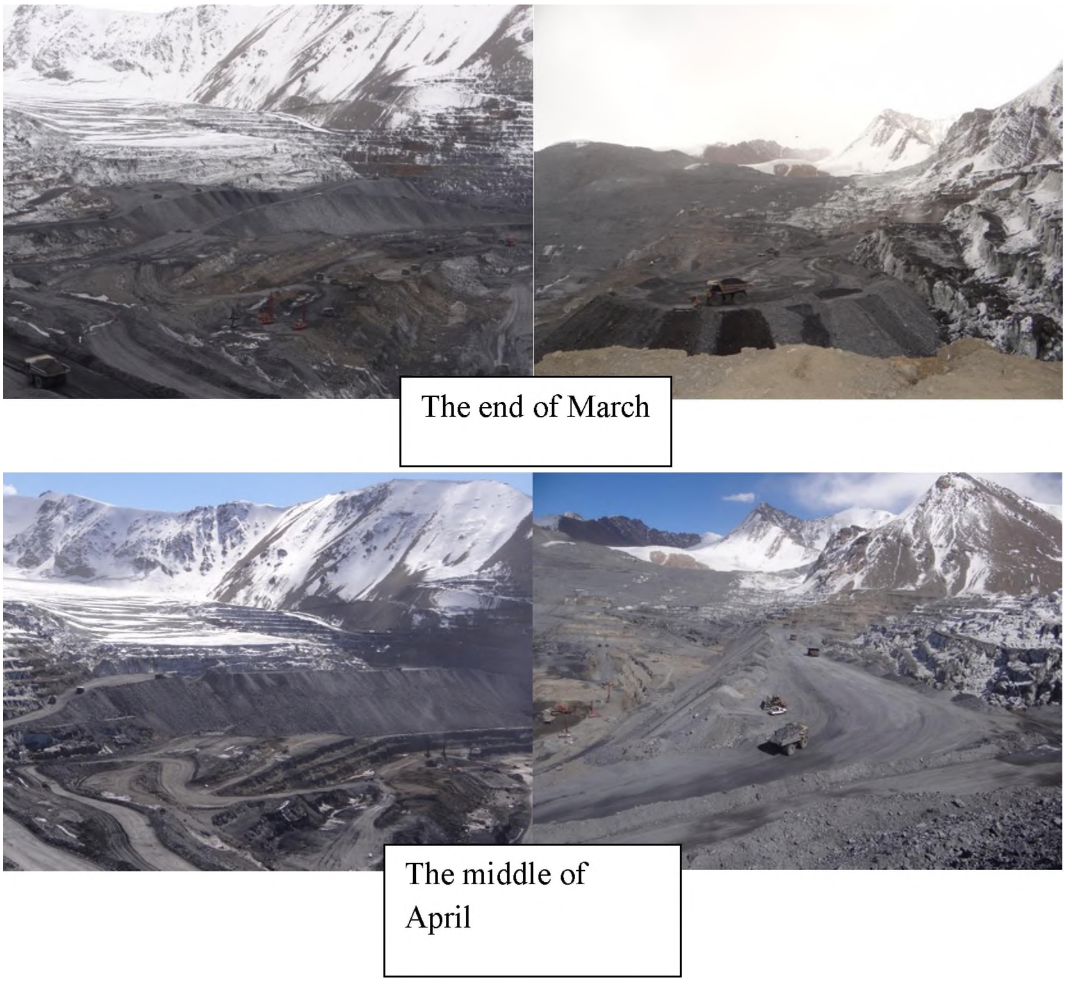



Figure 18. Photos of buttress construction stages.

## CONCLUSION

Numerical modeling with the rezone function in *FLAC* allowed us to solve the unique problem, stopping the glacier movement into the open pit and improving safety of mining operations. The automatic rezone function was a necessity due to high velocity values of sliding 5 meters per day. Numerical modeling helped to find out the features of the glacier and the buttress behavior during their contact, give an assessment of buttress stability and make adjustments to its geometry, and take into account the decrease in strength properties as a result of glacier penetration into buttress body.

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