Journal of Geotechnical Geology
Zahedan Branch, Islamic Azad University
Vol.12 (2016), No.2 (169-178)
geotech.iauzah.ac.ir

Zahedan Branch,
Islamic Azad University

Stability analysis and numerical modelling of toppling failure of discontinuous rock slope (A Case study)

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Received: 14 Nov. 2016; accepted 16 Jan. 2016; available online: 25 May. 2017

Abstract

On the north-side of Phase 7 gas flare site located in South Pars Gas Complex (SPGC), Assalouyeh, Iran has a discontinuous rock slope that due to tectonic activity has been vertical mode folded. Also, the coastal climate caused to weathering of mass and occurring toppling failure in this slope. This instability causes some problems in accessing the flare site. So, this slope need to stability analysis and stabilization. In order to stability analysis of this discontinuous rock slope, utilized the distinct elements method (DEM). The modelling process of toppling failures in UDEC is divided to geometrical and mechanical modelling. The result of modelling has good agreement with the toppling failures definition and process.

Keywords: Toppling failure, Rock slope, Discrete element method, Stability analysis, Geological engineering.

1. Introduction

Discontinuous rock slopes are faced with a variety of failure scenarios such as planar, massive, wedge or toppling failures (Azarafza et al. 2013; 2014 a,b,c; 2015). Toppling failure is one of the instability moods that enforced by gravity (Hürlimann et al., 2006) which occurs in two ductile and brittle mechanisms (Chen and Huang 2004). In rock slopes when the discontinuities strike approximately parallel with slope surface, the toppling failure befalls (Tu et al. 2007). Goodman and Bray based on the geometric and orientation of discontinuities in the rock mass recognized three types of toppling failures: flexural, block, and block-flexural (Goodman and Bray 1976). Toppling failure was defined by Hoek and Bray as the "rotation of columns or blocks of rocks about some fixed base" (Hoek and Bray 1981). The Fig. 1 showed the different types of toppling failures that may be encountered in the field.

The toppling mechanism is illustrated and discussed by different researchers. The occurrence of toppling failure is quite complex and in the nature always occurs in combined essence (e.g. Cruden and Hu, 1994; Sjöberg, 2000; Nichol et al. 2002; Wyllie and Mah, 2005; Tu et al. 2007; Liu et al. 2008; Jiang et al. 2015). An example of the complexity of this event is given in Fig. 2.

Goodman and Bray (1976) have comprehensive described for toppling failures different types and Wyllie and Mah (2005) have provided appropriate expression. The toppling aspect used in his expression in Fig. 3 has been brought.

2. Numerical Method (Discrete Element Methods)

The principal tasks of numerical discrete systems modelling is characterize the fracture systems (geometrical and behavior), granular media and multi-bodies systems in a computational model. The discrete element method (DEM) by definition of separate units as rock blocks, solid particles, structural elements or members, the geometrical models are generated. In mechanical analysis, the statical and dynamical conditions are formulated on the contacts between units and their deformation mechanisms monitored (Jing and Stephansson 2007). The Fig. 4 demonstrates the discontinuous rock mass simulation by DEM method.

The DEM originally developed early 1970s - 1980s for solving geological problems specially the geological engineering on movement and deformation of rock blocks or solid particle systems (Jing and Hudson 2002). Cundall (1971) was introduced a discrete modelling approaches to simulation of the blocky rock masses movements and useable for soils which were modelled as discs (Cundall and Strack 1979). Later, this method for spherical and polyhedral blocks in both soil and rock systems was used (Potyondy and Cundall 2004). The DEM approach rapidly developing for variety of applications in rock mechanics, soil mechanics, ice mechanics, structural analysis, granular materials, material processing, fluid mechanics, multi-body systems, robot simulation, computer animation, etc. This extends due to the following three reasons (Jing and Stephansson 2007):

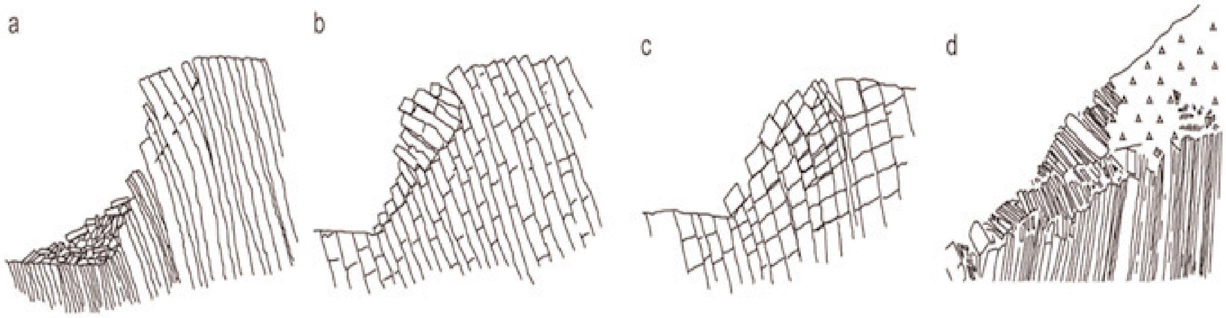

Figure. 1 Toppling modes: (a) flexural toppling, (b) block toppling, (c) block-flexural toppling modified (Goodman and Bray 1976), (d) under dip toppling modified (Cruden and Hu 1994)

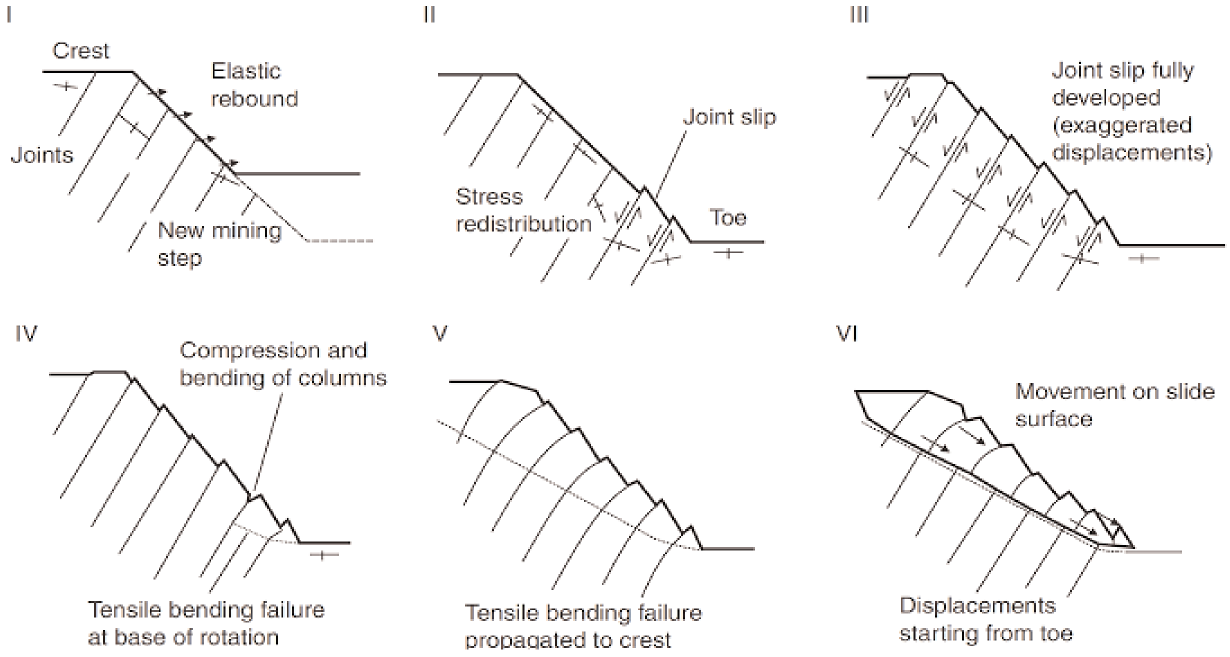

Figure 2. Complexity toppling failure mechanism in slopes (Sjöberg 2000)

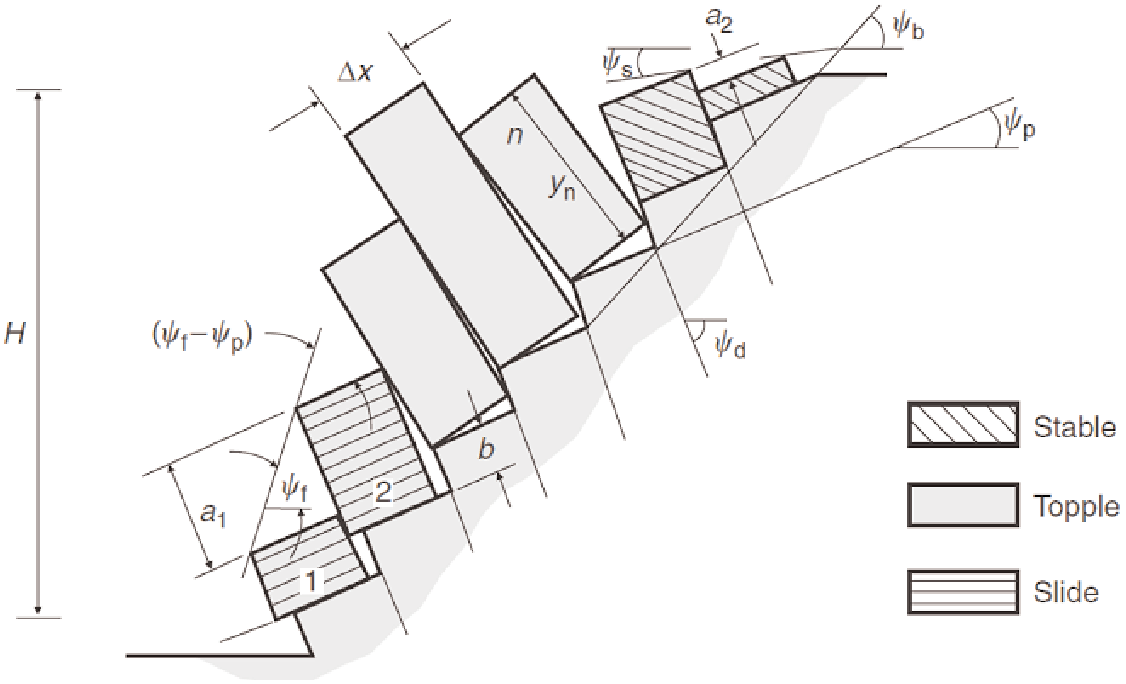

Figure 3. Model of toppling analysis on a stepped base (Goodman and Bray, 1976; Wyllie and Mah, 2005)

-Units identification (e.g. rock blocks, material particles, fracture systems, etc.)
-Equations formulation and solution of the individual units (according to conceptualization requirement)
-Varying contacts or connectivity detection and updating between the units as the consequences of their motions and deformations

The DEM use the different solution strategies for different formulations. The main difference is related to the material deformability order (Camones et al. 2013). For rigid (elastic) body analysis, using finite difference procedure to solve the rigid body system dynamic equations of displacement or dynamic relaxation procedure for a quasi-static problem. For

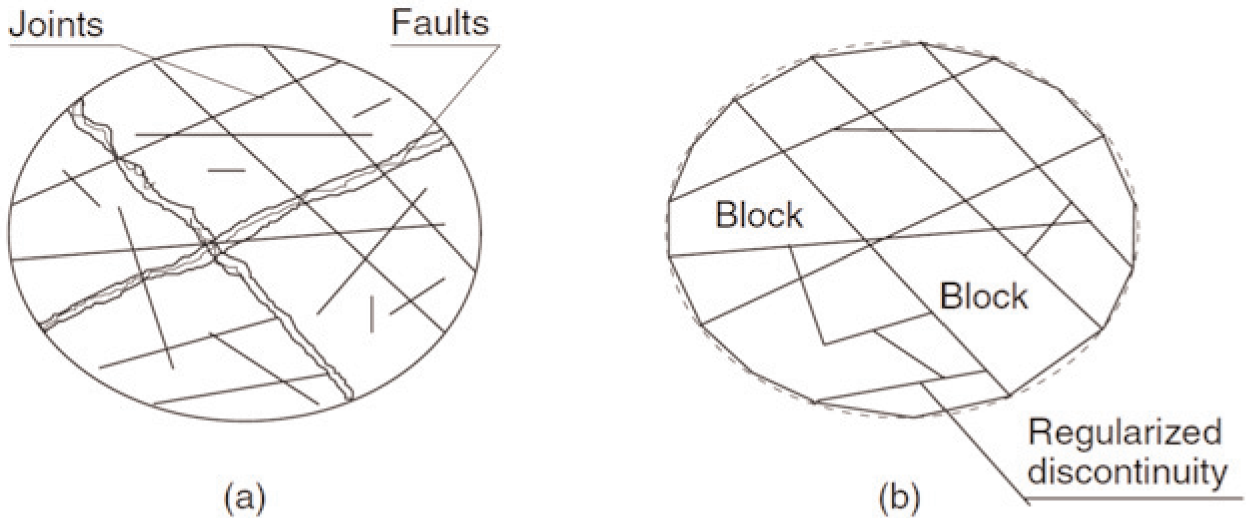

Figure 4. The modelled mass: (a) discontinuous rock mass, (b) DEM model (Jing, 2003)

Figure 5. A studied slope location

deformable (plastic or elasto-plastic) body analysis, using explicit and implicit finite difference discretization solution of material procedure to solve the deformable body system (Jing and Stephansson 2007). Cundall and Hart (1989) define the DEM analysis process as:

-Allow finite displacements and rotations of units

-Recognize new contacts between units during calculations, spontaneously

The main representative unequivocal DEM codes are the UDEC and 3DEC softwares developed by the ITASCA Consulting Group for 2D and 3D solving problems involve in engineering geology and geotechnics fields (Itasca 2008a, c). The UDEC is shorthand of Universal Distinct Element Code and the two-dimensional distinct-element method based numerical program for modelling of discontinuous/semi-discontinuous media with FISH programming language (Itasca 2008 b). In this study used the UDEC software to simulation of studied discontinuous rock slope.

3. The Studied Area

3.1. Studied slope location

The studied discontinuous rock slope is located at 12 m in the north-side of Phase 7 gas flare site of South Pars Gas Complex (SPGC) in Assalouyeh, SW of Iran (Fig. 5), its coordinates are $27^{o}32^{'}31.52^{''}$N and $52^{o}35^{'}19.88^{''}$E. Climatic conditions, sultry and high humidity has caused to high weathering of the slope. According to geological map of the Assalouyeh, this slope composed of jointed marlstone with a high percentage of lime and some clay from Aghajari formation. This formation known as upper member Fars group consists of three "fine", "medium" and "coarse" grained sedimental facies, marlstone with brown calcareous sandstone, pink to red marl with veins of gypsum and clay (Aghanabati 2004). The geological map of the South Pars Zone is shown in Fig. 6.

3.2. Engineering geological characteristics

The gas flare site of Phase 7 of South Pars Gas Complex is located on the southeastern limb of

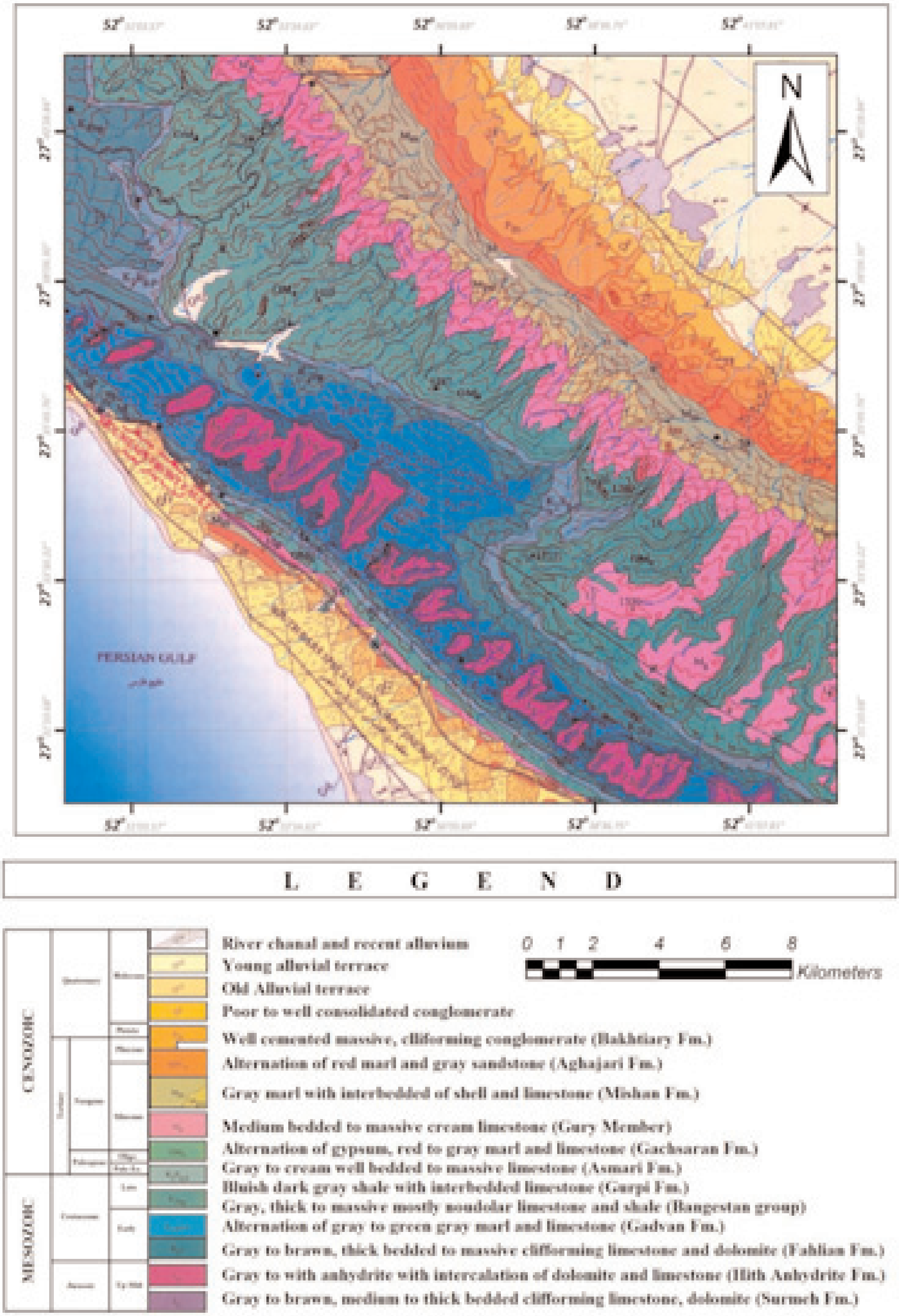

Figure 6. A geological map of studied area - part of Shirino map (GSI, 2009)

Assalouyeh anticline. The strike direction of this anticline is NW-SE and same with Zagros Belt. The reason for the establishment this and other regional anticlines similar direction with the Zagros, motion of Arabian plate to Central Iran and Eurasian plates in NE-SW direction. The studied areas faults are classified into three main sets according to strike direction NW-SE, N-S and NE-SW. About the studied slope, no faults pass through that. A view of the studied slope is shown in Fig. 7. The properties of the slope masses are presented in Table 1. According to geological engineering studies, these rock mass are classified and presented in Table 2.

4. Stability analysis

In order to stability analyze for this slope, used the discrete element method and UDEC software. These approaches have been mentioned in the previous sections. The modelling was performed as the following steps:

-Geometrical modelling

-Model of boundary conditions

-Model of mechanical properties definition and behavior allocation

-Mechanical modelling and stability analysis

In geometrical modelling the rock masses all discontinuities are simulated. Then with the assistance of the parameters provided in the Tables 1 and 2, the boundary conditions, mechanical properties and behavior are defined. In the final stage, the mechanical model solved and stability of the slope analyzed. For the mechanical modelling and stability analysis, the material of slope is rigid and linear elastic behavior is valid. The results of modelling and stability analysis are presented in figurs 8 to 12.

Figure 7. A view of the studied slope

Table 1. The studied slope mass physical and mechanical properties

No	Parameter	Unit	Value
1	Cohesion (C)	MPa	1.1
2	Internal friction ( )	degree	29
3	Unit weight (ρ)	kN/m^3	18.70
4	Young's modulus (E)	GPa	70
5	Shear modulus (G)	MPa	28
6	Bulk modulus (k)	MPa	45
7	Tensile strength	MPa	0.097
8	Poisson's ratio (υ)	-	0.24
9	Normal joint stiffness (Kn)	GPa	3.9
10	Shear joint stiffness (Ks)	GPa	25

5. Conclusions

The north-side discontinuous rock slope of Phase 7 gas flare site is the flexural toppling type of failure. This slope according to geological engineering investigation was considered partly stable. The reason of this stability is rock blocks interlocking. But the geological conditions are influence the stability. In rock slopes, even when the slope is globally stable, local toppling deformation is possible. So the instability analysis is quite reasonable.

Table 2. Rock mass classification of studied slope

Classification	**RMR (Bieniawski 1989)**	**SMR (Romana et al. 2003)**
Description	**43** **(IV/ fair rock)**	**55.6** **(IIIa/ fair rock)**

The UDEC software and DEM approaches are powerful tools to calculation of deformation and displacement in fractured rock slopes. This application allows specifying the displacement geometry and deformation analysis. In this study with the step toppling failure analysis, can be determine the entire process from creation to motion and loss. In this modelling initially with the creation shear zones in

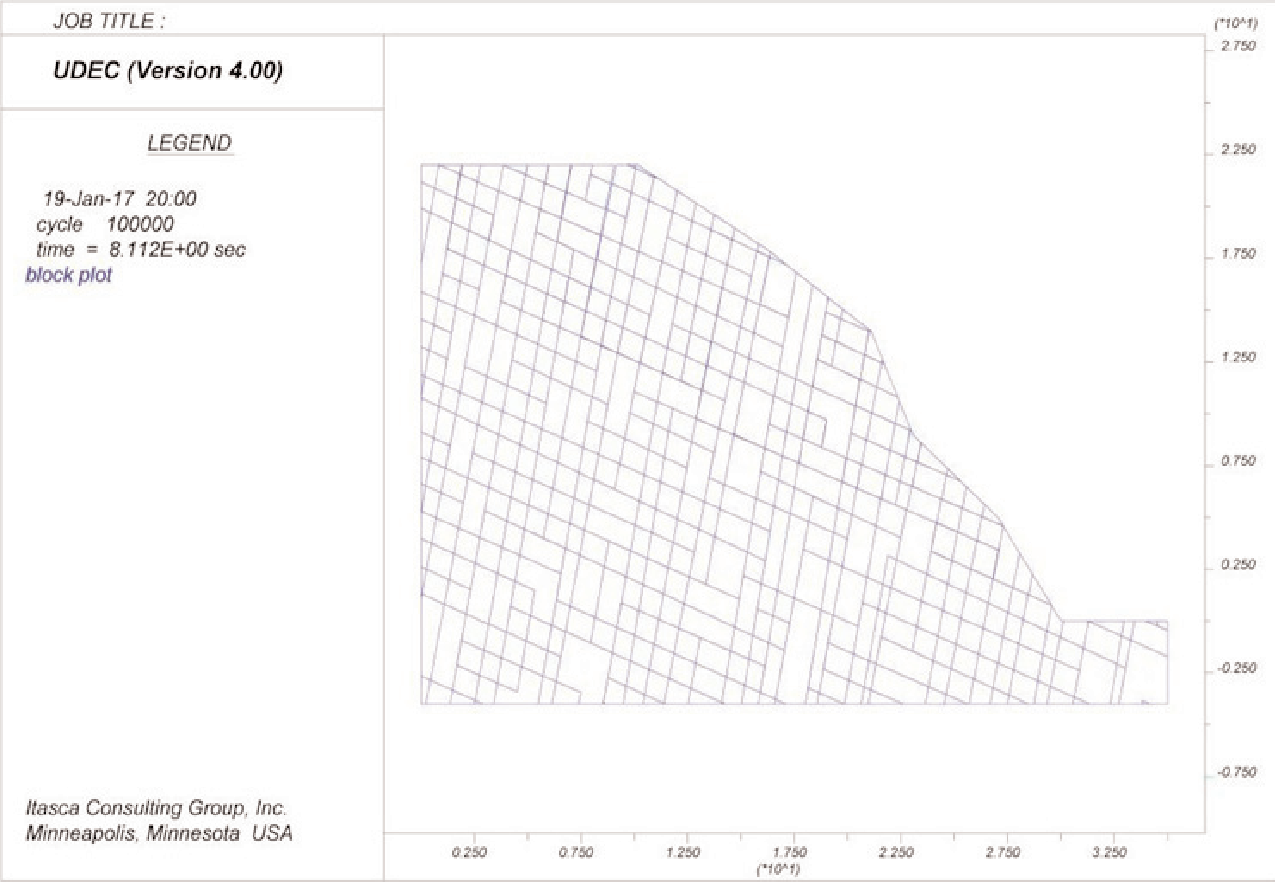

Figure 8. Geometrical model preparation of studied slope

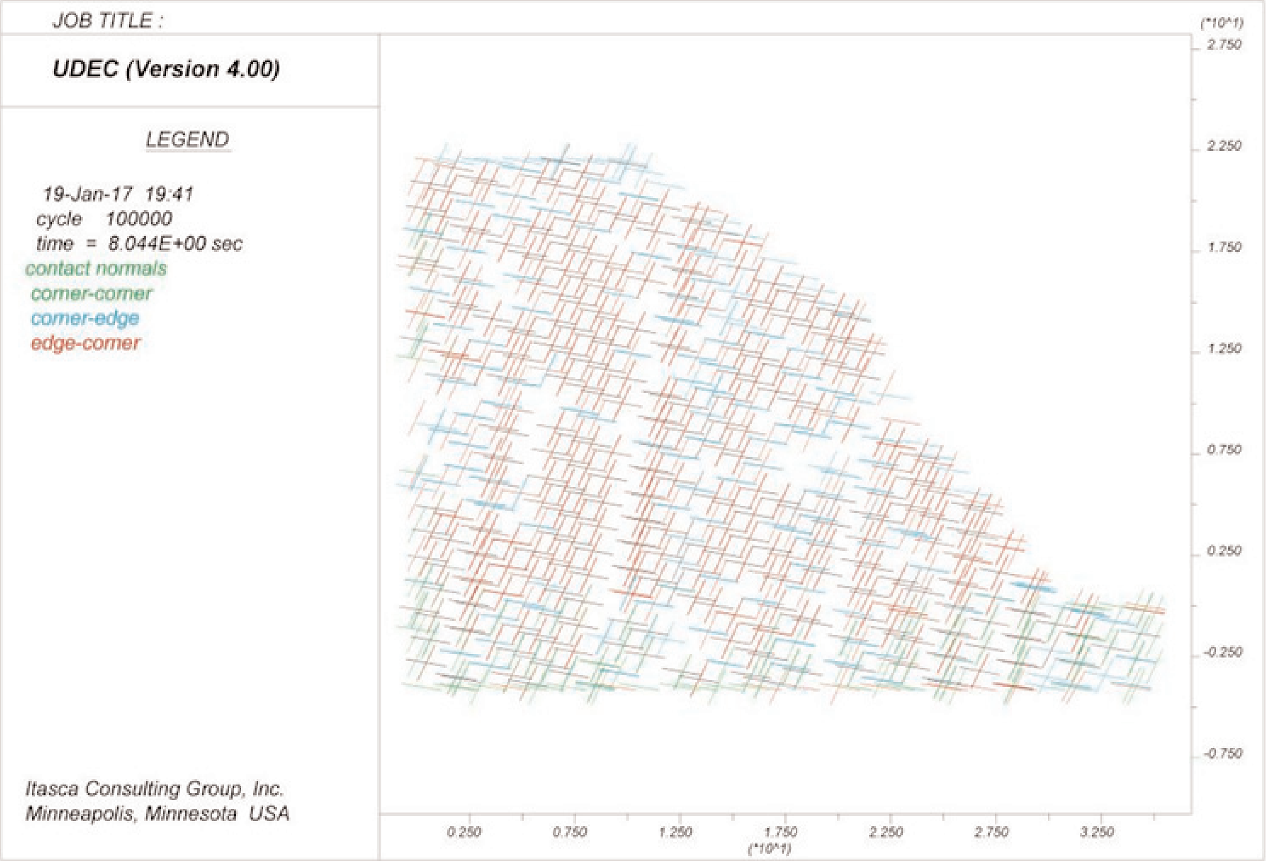

Figure 9. Model of contacts distribution

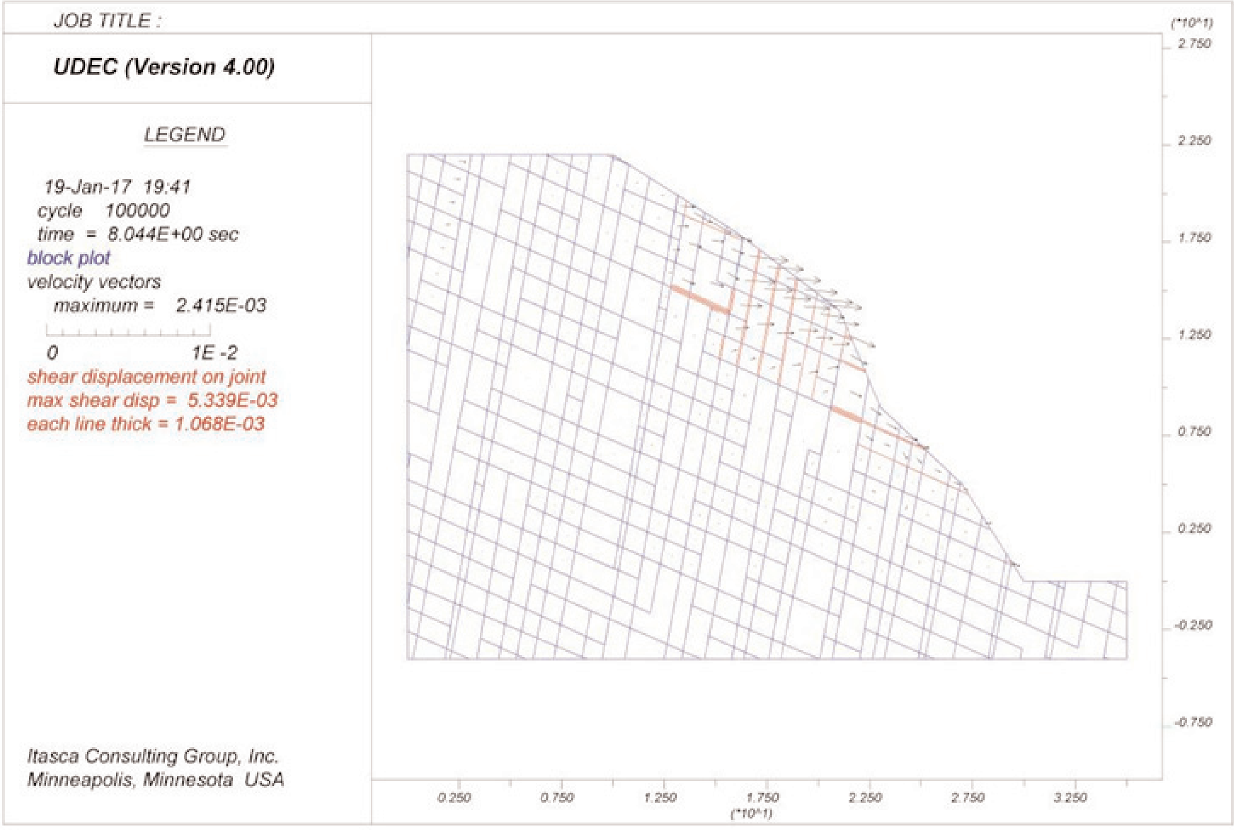

Figure 10. Mechanical modelling preparation of studied slope

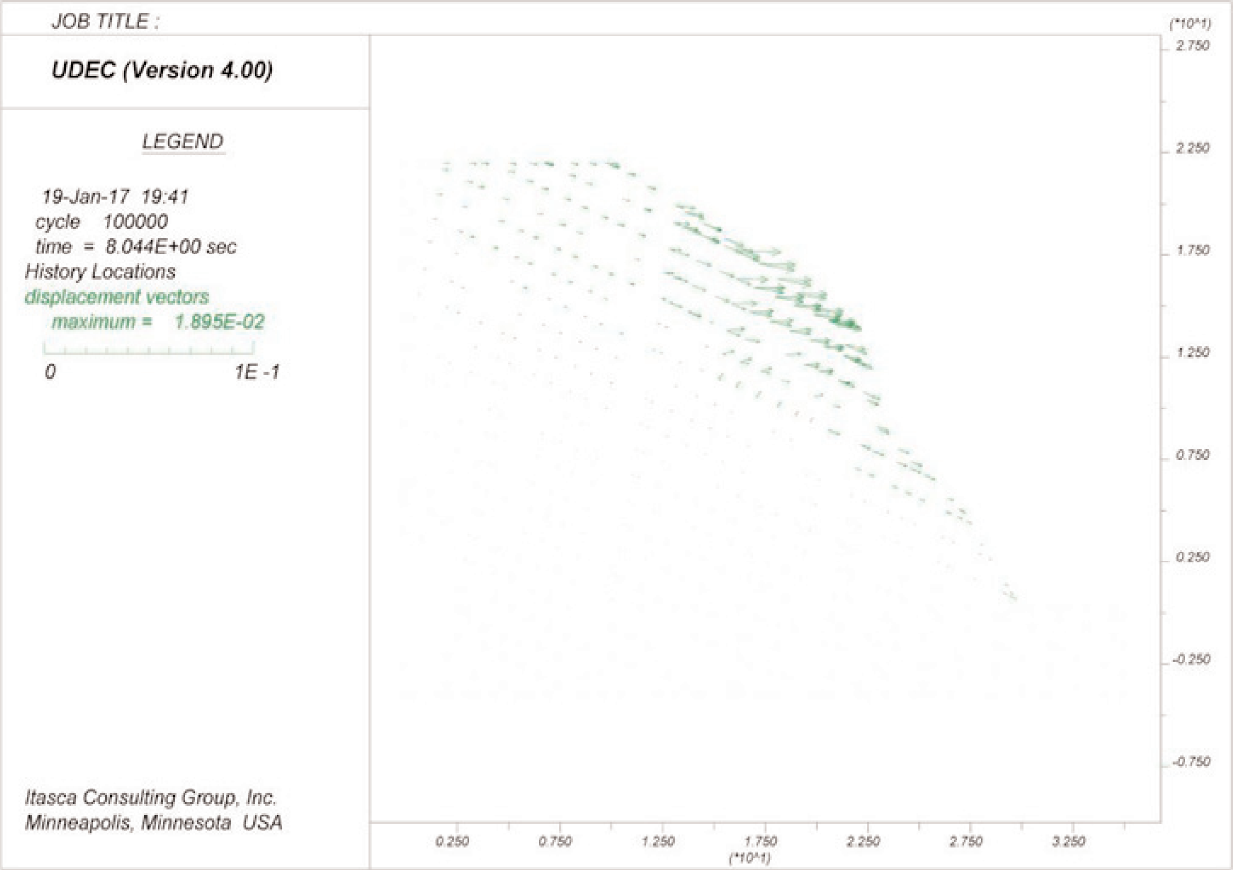

Figure 11. Model of total displacement vector distribution

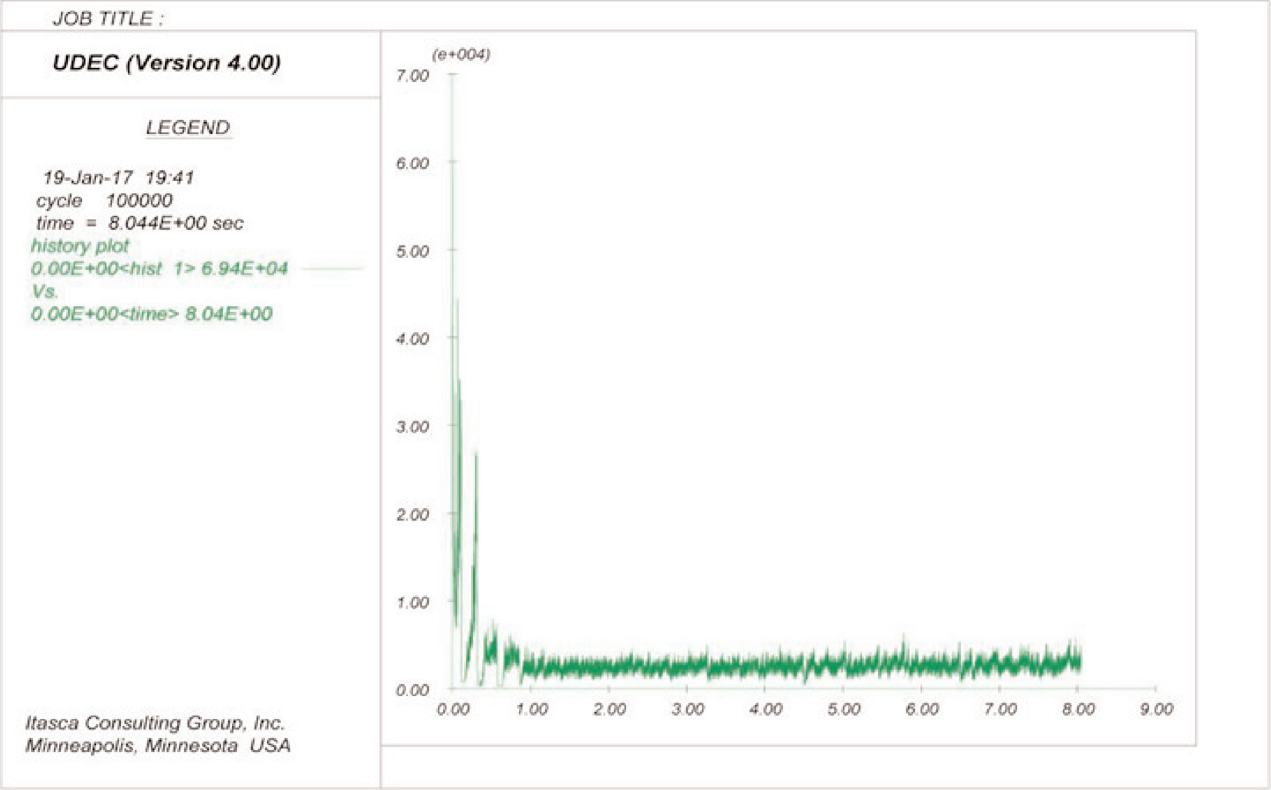

Figure 12. Unbalance forces histogram of failure mechanism

the rock blocks milieu, movement and displacement is given to blocks. On the other hand blocks under their weight rotated around the bases on below discontinuous. This result of modelling is consistent with the toppling failure process definition.

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