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M.Sc. In Civil Engineering

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**PREDICTING ROCK TOPPLING BEHAVIOUR USING
ANIMATION SOFTWARE**

**M.Sc. THESIS
IN
CIVIL ENGINEERING**

**BY
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M.Sc. Thesis

In

**Civil Engineering
Gaziantep University**

Supervisor

Prof. Dr. Hanifi Çanakci

By

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January 2022



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**PREDICTING ROCK TOPPLING BEHAVIOR USING ANIMATION
SOFTWARE**

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ABSTRACT

PREDICTING ROCK TOPPLING BEHAVIOUR USING ANIMATION SOFTWARE

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Blender is a software used in the film and computer games industries to realistically animate a physical system and produce animation films. In this paper, it is shown that media can be faithfully modeled using rigid body physics. Rock toppling and soil sliding are issues confusing the designers in selecting the alternative roots of roads due to miss availability of exact predictions. The animation program is used to simulate a rock toppling model to evaluate the results and find the prediction capacity of the software. For this purpose, BLENDER simulations were modeled to simulate cases in two different studies made by (Wyllie and Mah., 2004) and (Guo et al.,2017), and the results are then compared with said study results. Results showed that Blender as a computer software seems to be a tool to predict rock toppling behavior.

Keywords: Rock toppling, BLENDER Software, Simulation, 3D animation.

ÖZET

ANİMASYON YAZILIMI KULLANARAK KAYA DEVİRME DAVRANIŞINI ÖNGÖRME

ÇELİK, Elnaz D.

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Blender, fiziksel bir sistemi gerçekçi bir şekilde canlandırmak ve animasyon filmleri üretmek için film ve bilgisayar oyunları endüstrilerinde kullanılan bir yazılımdır. Bu yazıda, medyanın katı cisim fiziği kullanılarak aslına uygun olarak modellenebileceği gösterilmiştir. Kaya devrilmesi ve zemin kayması, kesin tahminlerin eksik olması nedeniyle alternatif yol köklerinin seçiminde tasarımcıların kafasını karıştıran sorunlardır. Animasyon programı, sonuçları değerlendirmek ve yazılımın tahmin kapasitesini bulmak için bir kaya devrilme modelini simüle etmek için kullanılır. Bu amaçla (Wyllie ve Mah., 2004) ve (Guo ve diğerleri, 2017) tarafından yapılan iki farklı çalışmada, BLENDER simülasyonları modellenmiş ve daha sonra söz konusu çalışma sonuçları ile karşılaştırılmıştır. Sonuçlar, bir bilgisayar yazılımı olarak Blender'ın kaya devrilme davranışını tahmin etmek için bir araç gibi görüldüğünü gösterdi.

Anahtar Kelimeler: Kaya Devirme, BLENDER, Simülasyon, 3D animasyon.



"Dedicated to my family"

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LIST OF ABBREVIATIONS

UDEC Universal Distinct Element Code



CHAPTER I

INTRODUCTION

1.1 General

Some man-made structures like highways, railways, houses and even structures like wind turbines that take place in mountainous areas are exposed to many natural hazards like landslides, toppling failures, rock falls and even volcanic activities, all of which have all kinds of consequences that range from loss of life to economic loss that stems from destruction caused to the structures themselves, any equipment present on site, vehicles on the road or even hospitality costs for people injured during the incident. Rock toppling failure one of the natural disasters with more common occurrence.

Rock toppling failure is one of the most common hazardous instability of rock slopes that engineers and researchers are facing with. If an excavation is to be made toppling failure, if not taken into account and proper safety measures weren't taken, will cause considerable damage and may cause loss of life among people. In civil Engineering, the main sectors dealing with toppling failure are highways, pipelines, sewers and irrigation channels, and later buildings (Pritchard and Savigny, 1990; Pritchard and Savigny, 1991; Sageseta, et al ,2001; Terzaghi, 1950; Zambak, 1983; Wyllie & Mah., 2005.

Geological disasters occur when natural geological processes have an impact on our operations, whether they result in casualties or economic losses. A potential disaster is a geological disaster. Newfoundland and Labrador is fortunate in that this type of impact is minor in comparison to many other places of the world..



Figure 1.1 Example of rock blocks exposed to toppling failure



Figure 1.2 Toppling failure close to the road

To predict the toppling failure behavior and the places where it could potentially happen, according to latest studies and discoveries, simulations are necessary and will improve the quality of the engineering solutions made for these problems. In recent years, significant advancements were made to enhance the simulating capabilities to increase their accuracy when used in the engineering field. (A. KHOSHNAW., 2019)

The computer software (BLENDER) was initially released 27 years ago on January 2nd 1994. Blender is licensed as GNU GPL, it is a free open-source 3D animation

program that is used for modeling, animation, simulation, rendering and motion tracking. (Foundation Blender, 2021).

In this study, a comparison between a (BLENDER) computer program simulation and the laboratory was made to test the prediction capabilities of (BLENDER) computer program when it comes to simulating disasters like rock toppling failure especially on the highways. A model was designed in the laboratory to copy a study made in the rock slope engineering book and then modeled in (BLENDER) software. All results are compared to find the limits of (BLENDER) software.

1.2 Objectives

In this study, a simulation between BLENDER computer program and the studies mentioned before tested to predict the opportunities and the disasters that occur during different types of rock toppling failures in slopes especially in the highways. For this purpose, the direct problems should be addressed to solve the parameters which effect the physical motion of particles through computer programing software and environment control. Two models have been designed in BLENDER computer software to replicate the rock toppling failure studies made in (Wyllie and Mah., 2004) and (Guo et al.,2017). The results from the BLENDER computer program are taken and compared with the results of the studies.

1.3 Thesis organization

The project has been organized into five chapters. The second chapter consists of a literature review on geotechnical problems of geological hazards for rock toppling failures. The third chapter explains methodology and the process of each study examined in this work. The fourth chapter presents the results gained from the comparison between the BLENDER software models and the models given in the studies and discussing them. At the end chapter five provides the conclusions and recommendations for future problems and researches.

CHAPTER II

LITERATURE REVIEW

2.1. General

When natural geological processes have an impact on our activities, geological disasters occur, whether they cause casualties or economic losses. Geological disaster is a potential disaster. The fortunate thing about Newfoundland and Labrador is that this type of impact is relatively small compared to many other parts of the world. This is mainly due to its location in an area where earthquakes are relatively inactive, and its population density is low. However, geological disasters and hazards still bring significant economic and social costs to the province. If hazards are identified, these disasters can be avoided or prevented to varying degrees.

Engineering geologists that have obtained education and training in geography and geo-process interpretation, geo-structure interactions, and geological hazard mitigation are typically used to analyze geological hazards. Engineering geologists provide guidance and design for geological hazards mitigation. Local communities can also benefit from disaster mitigation planners who can help them identify methods to reduce the impact of catastrophes and build plans to put them into action. (A. KHOSHNAW., 2019)

Resettlement can help to avoid geological dangers, and retaining walls can help to increase the slope's stability. Retaining walls can be built using mud walls, shear pins, back connections, soil nails or soil anchors, ground pillars, coasts, and streams. The soil or rock itself can be improved by forceful compaction, grouting or concrete, and mechanically stabilized soil, in addition to using revetment and ripraps to avoid erosion. Deep bases, tunnels, outward and sub-drainage structures, and other occurrences are

examples of different reasoning systems. To protect and prevent individuals from danger, planning strategies include eliminating the development of regulations near hazardous places and enacting building codes. (A. KHOSHNAW., 2019)



Figure 2.1 Example of a landslide and a toppling failure

Weathering and excavation can both have an impact on the rock slope, and weathering can also be influenced by an archaeological site. The stress released by the archaeological site may generate new fissures in the rock and widen existing ones (Hack and Price, 1997). As a result, the rock will lose its strength and become more malleable (Momeni et al., 2015). As a result, the rock incline's safety factor is weakened, and stability is lost. In highland locations, landslides, especially falling rocks, pose a major threat to populations and transportation networks (Cruden and Varnes, 1996). Deterministic or probabilistic analysis based on 3D modeling can be used to estimate the maximum travel space and related kinetic energy of rock masses of various sizes in a local or regional context (Guzzetti et al., 2002). (A. KHOSHNAW., 2019)

The rock slope can be affected by both weathering and excavation, and weathering can be influenced by an archaeological site. The ancient site's tension may cause new fissures in the rock to form, as well as widening existing ones (Hack and Price, 1997). As a result, the rock will become weaker and more pliable (Momeni et al., 2015).

2.2. Rock toppling failure

Toppling failures are invariably seen in the rocky masses that have a dominating set of discontinuity (typically bedding or foliation) that runs parallel with the slope and dips inwards. This is one among the most popular typical failure modes in natural or excavated rock slopes, such as those caused by construction such as hydropower plants, open-pit mines, railways, and other engineering projects. Several toppling incidents have happened in recent years following earthquakes, resulting in massive losses of lives and infrastructure. The Wenchuan earthquake, for example, caused landslides in Xiaojianping and Guantan, both of which had an anti-dipping design. A dammed lake created by the Xiaojianping landslide with deposits of roughly 6,000,000 m³ is an example of a disaster that strikes suddenly and causes catastrophic devastation. (Guo et al., 2017)

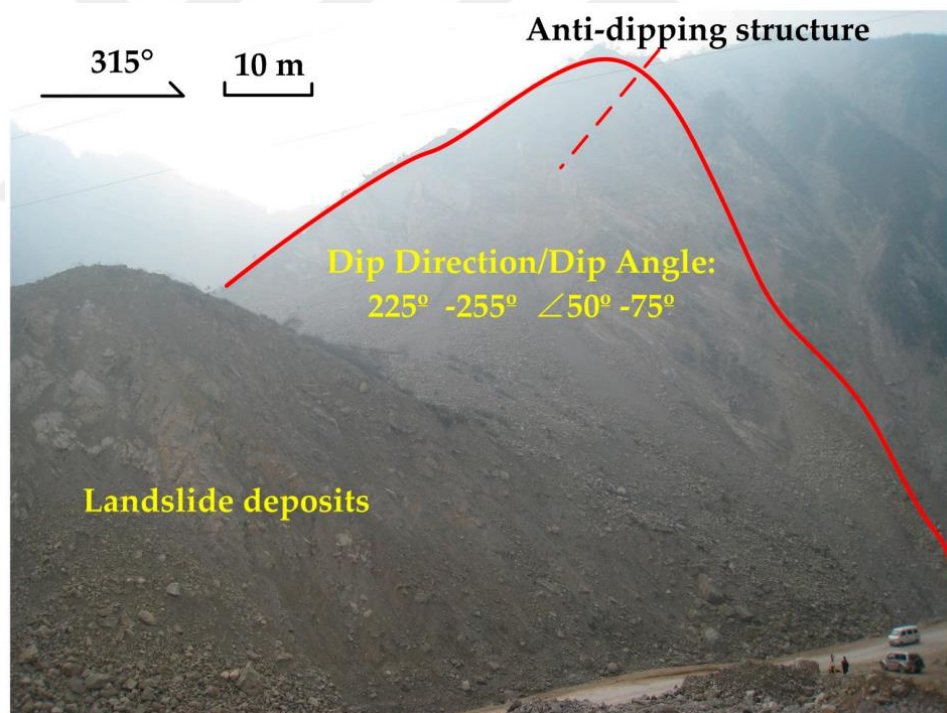


Figure 2.2 Example of a landslide caused by an earthquake.

2.2.1. Types of toppling failure

The types of rock overturning failure are usually divided into three types: block toppling, flexural toppling and block-flexural toppling.

The distinction between the different types of toppling is important because there are two different stability analysis methods for toppling failure -block toppling and flexural toppling - and it is necessary to use the appropriate analysis in the design when conducting analysis and research on toppling failure.

2.2.1.1. Block toppling

In strong rock, block toppling occurs when a sequence of deep-cut discontinuities creates individual columns, and the second set of extensively separated orthogonal joints dictates column height, as illustrated in Figure 2.3. The strains from the longer overturning columns drive the smaller columns that make up the slope's toe forward, allowing for more toppling higher up the slope. A stepped surface that rises from one cross joint to the next is typical of failure. This type of collapse is common in geological environments including bedded sandstone and columnar basalt with well-developed orthogonal jointing.

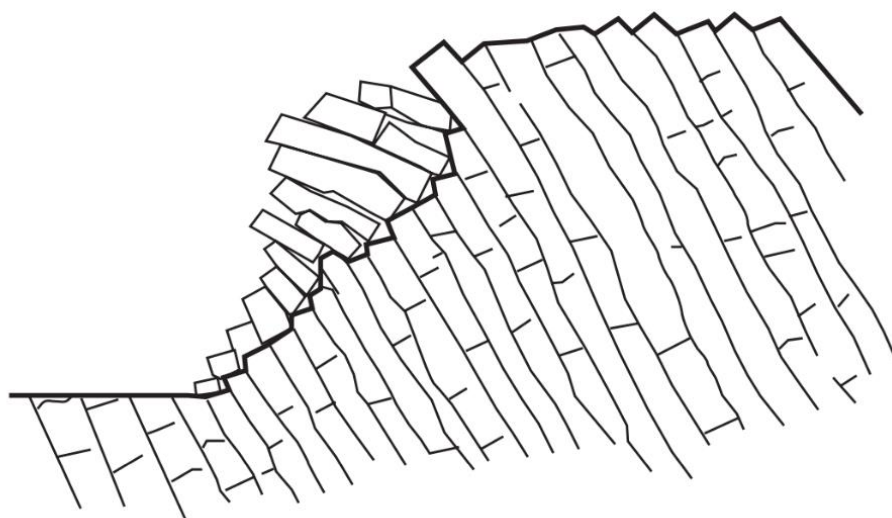


Figure 2.3 Block toppling of columns of rock containing widely spaced orthogonal joints.

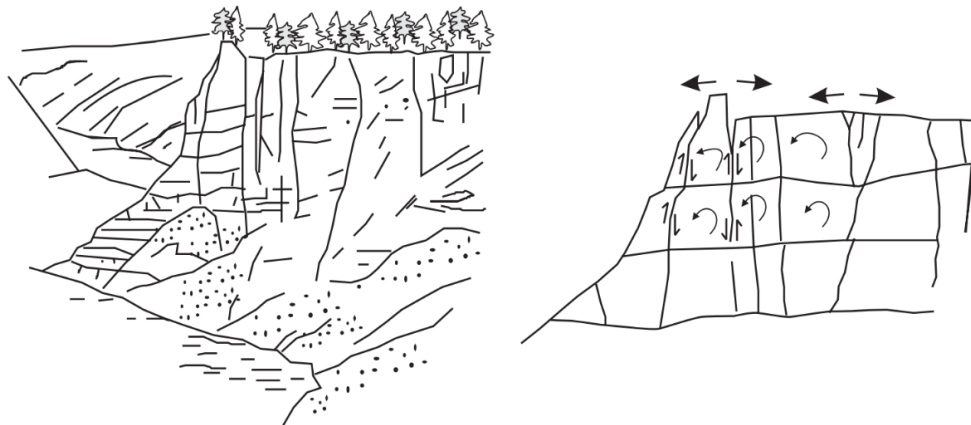


Figure 2.4 Theoretical toppling mechanism for Vaiont's north face (Muller, 1968).

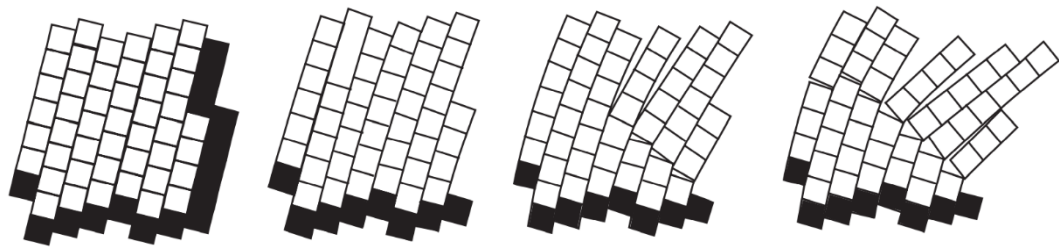


Figure 2.5 Solid blocks are locked in space, whereas open blocks are free to move in this computer-generated model of toppling failure. (Cundall, 1971).

2.2.1.2. Flexural toppling

This is seen in Figure 2.6, which displays continuous rock columns that have been separated by well-developed, steeply dipping discontinuities that have bent forward as they bend. Examples of geological circumstances that might lead to this sort of collapse include thinly bedded shale and slate with poorly developed orthogonal jointing, among other things. It is common for the basal plane of flexural topples to not be as clearly defined as the basal plane of a block topples.

When the slope's toe is slid, dug, or eroded, the toppling process begins, and it advances back into the rock mass, producing deep tension fractures that shrink with depth. It can be difficult to see a toppling collapse from the bottom since the lower half of the slope is covered in unorganized falling bricks. When toppling slopes are examined in-depth, it is discovered that the outward movement of each cantilevered column results in an interlayer slide, which exposes a portion of the upper surface of

each plane in a sequence of rear-facing, or subsequent scarps, such as those depicted in Figure 2.3.

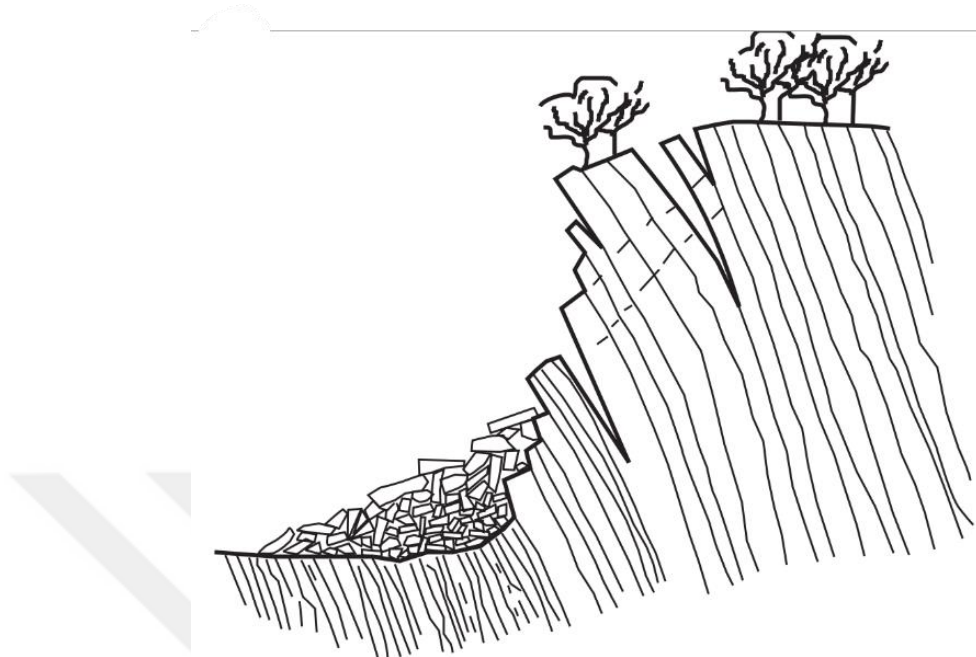


Figure 2.6 Flexural toppling of slabs of rock dipping steeply into face.

2.2.1.3. Block-flexure toppling

The toppling of block-flexure columns is seen in Figure 2.7, and it is characterized by pseudo-continuous flexure and long columns that are interrupted by several cross joints. However, in this situation, rather than flexural toppling caused by a continuous column collapse, the falling of columns is triggered by cumulative displacements on the cross-joints. Because of the huge number of little movements, this kind of toppling produces fewer tension fractures than flexural toppling, as well as fewer edge-to-face contacts and voids than block toppling. This is because of the great number of small motions.

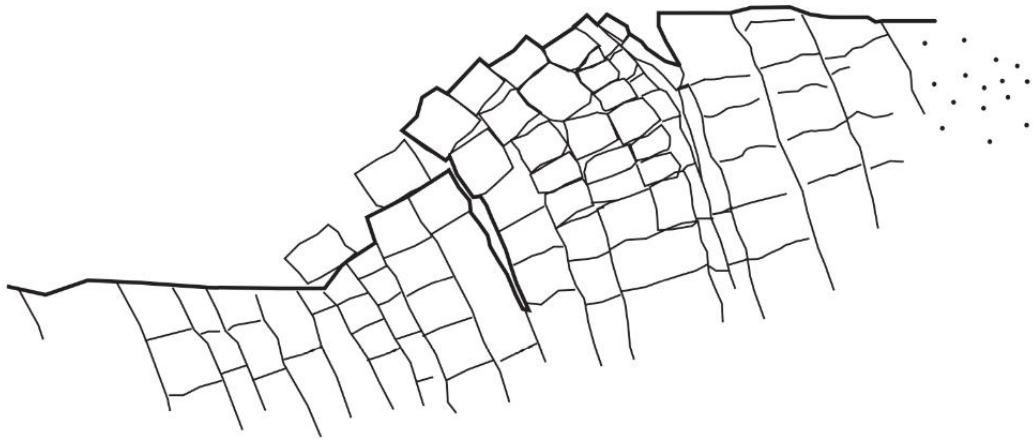


Figure 2.7 Block flexure toppling is defined as the pseudo-continuous flexure of lengthy columns caused by accumulated vibrations at several cross-joints.

2.2.1.4. Secondary toppling modes

Figure 2.8 displays a number of secondary toppling mechanisms hypothesized by Goodman and Bray. The most typical cause of these failures is undercutting of the slope's toe, which can be caused by natural factors like as scour or weathering, or by human activity. All of these failures are primarily the consequence of rock sliding or breakdown of the physical form, and toppling occurs in the upper section of the slope correspondingly to this primary failure (Figures 2.8(a) and (b)). In horizontally bedded sandstone and shale strata, as seen in Figure 2.8, toppling collapse is a common occurrence (c). Shale is often more fragile and more vulnerable to weathering than sandstone, but sandstone is more likely to have vertical stress relief joints. Shale is also less prevalent in natural settings. The shale reduces the sandstone's support, causing the sandstone columns, whose diameters are dictated by vertical joint spacing, to topple off the cliff. In certain locations, overhangs might be as wide as 5 meters, and large-scale rock collapses can occur without warning.

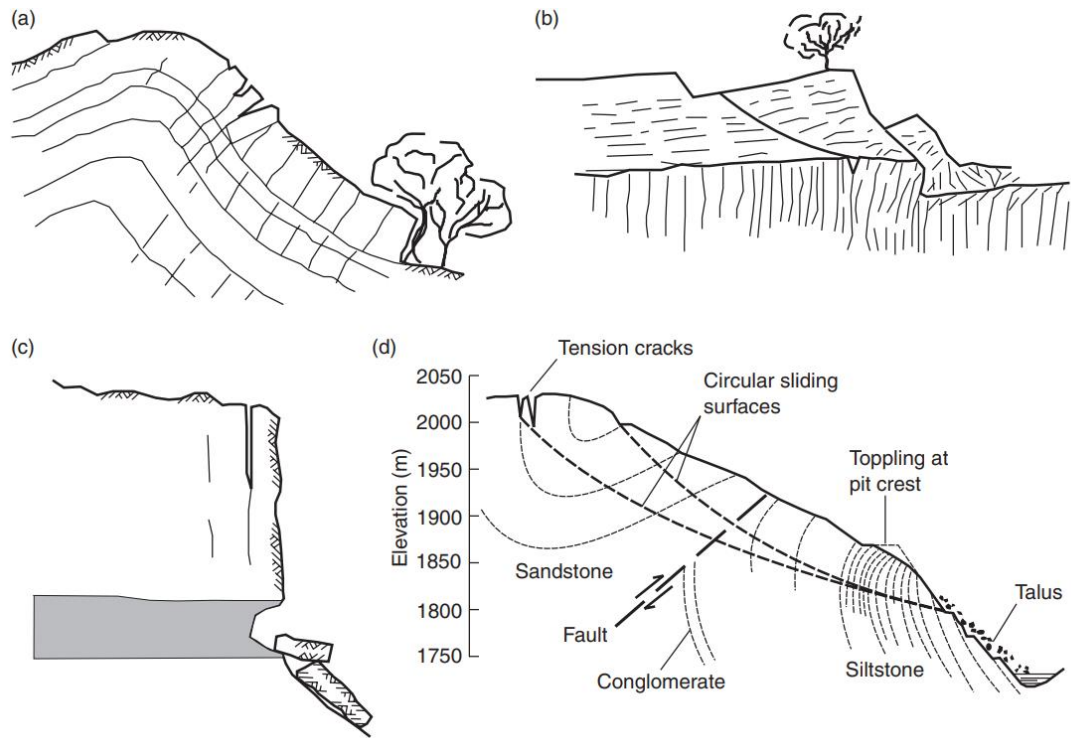


Figure 2.8 Secondary toppling modes: (a) toppling at head of slide; (b) toppling at toe of slide with shear movement of upper slope (Goodman and Bray, 1976); (c) toppling of columns in strong upper material due to weathering of underlying weak material; (d) toppling at pit crest resulting in circular failure of upper slope (Wyllie and Munn, 1978).

The collapse of a pit slope in a coal mine, where the beds at the crest of the pit dropped 70 degrees down the face and the strike was parallel with the face of rocks, is represented in Figure 9.4. (d). Toppling collapse occurred at the pinnacle of the pit as a result of 50-degree angle mining, resulting in a circular failure that was located 230 meters upward from the base of the peak. A total movement of around 30 meters was recorded on the slope above the pit, according to thorough monitoring, resulting in fractures forming on the mountain's peak that were several meters broad and up to nine meters deep. Mining was able to continue underneath the sliding slope due to continuous movement monitoring, and the slope was finally stabilized by back-filling the pit (Wyllie and Munn, 1979).

Another example for the toppling process is shown in Figure 2.9 (Sjöberg, 2000). As the sloping depth continually increases, little toppling movement can in the course of

time evolve into a catastrophic failure in open-pit mines. By carefully analyzing movement and recognizing the toppling process, it is able to forecast when hazardous situations are occurring.

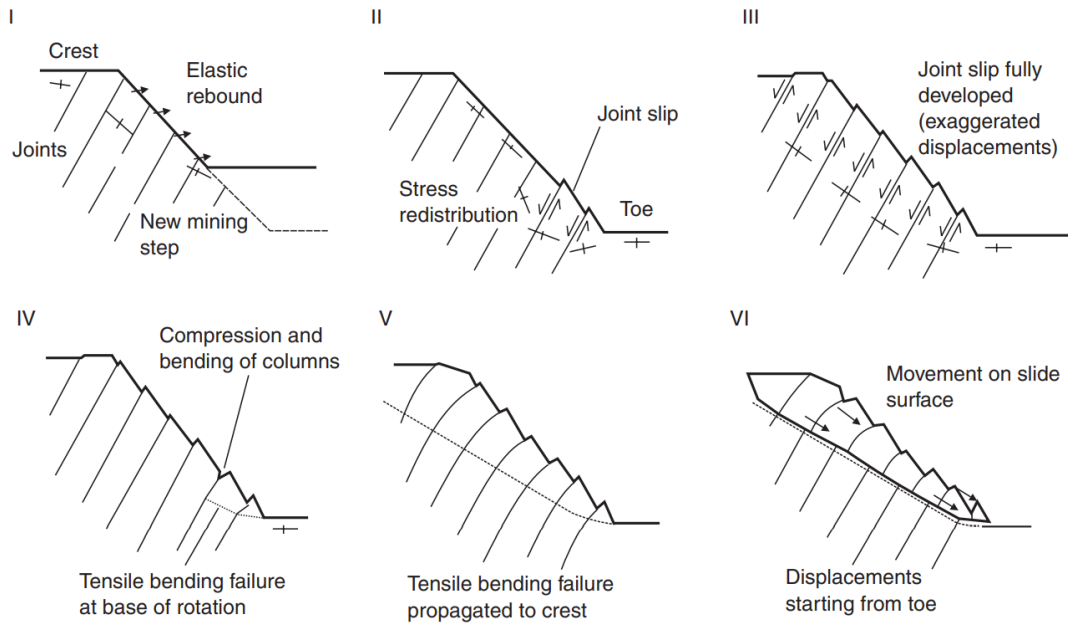


Figure 2.9 Failure stages for large-scale toppling failure in a slope (Sjöberg, 2000).

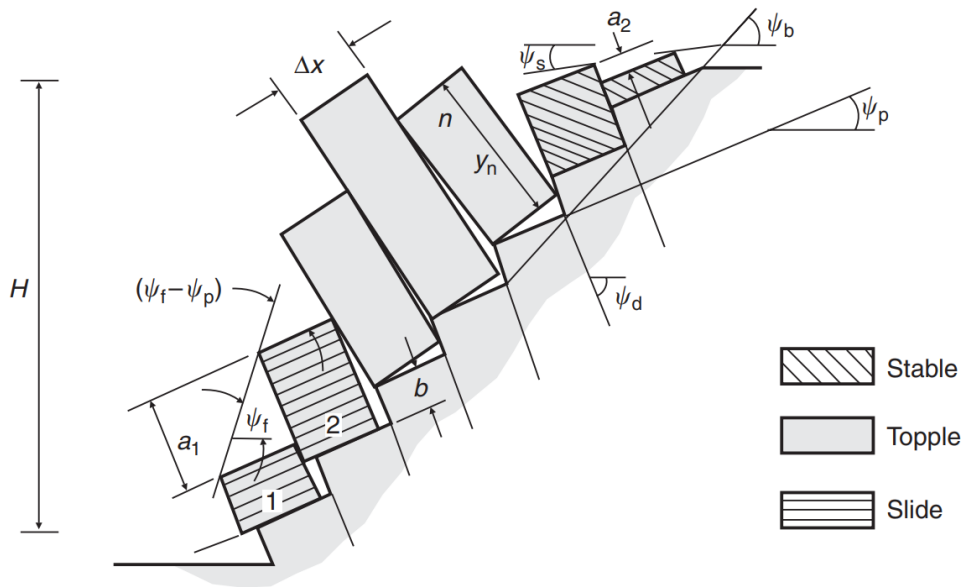


Figure 2.10 Model for limiting equilibrium analysis of toppling on a stepped base

2.4. Other Studies Using Blender Software for Similar Purposes

In 2019, a M.Sc. thesis made by Ahmad G. Khoshnaw called “ROCK-FALL TYPES AND ITS SIMULATION USING BLENDER SOFTWARE” was made and its purpose was to simulate rock fall phenomena using BLENDER computer software and compare with real life laboratory model built during the making of the study.

The procedure was to make a real-life model in the laboratory, use different materials with different shapes to simulate falling rocks, film and record the laboratory test with a high-tech camera and then model the same laboratory test using BLENDER computer software to test its capability to simulate such events.

The materials used to simulate rock were steel in both cubic and spherical shapes and wood also in both cubic and spherical shapes.

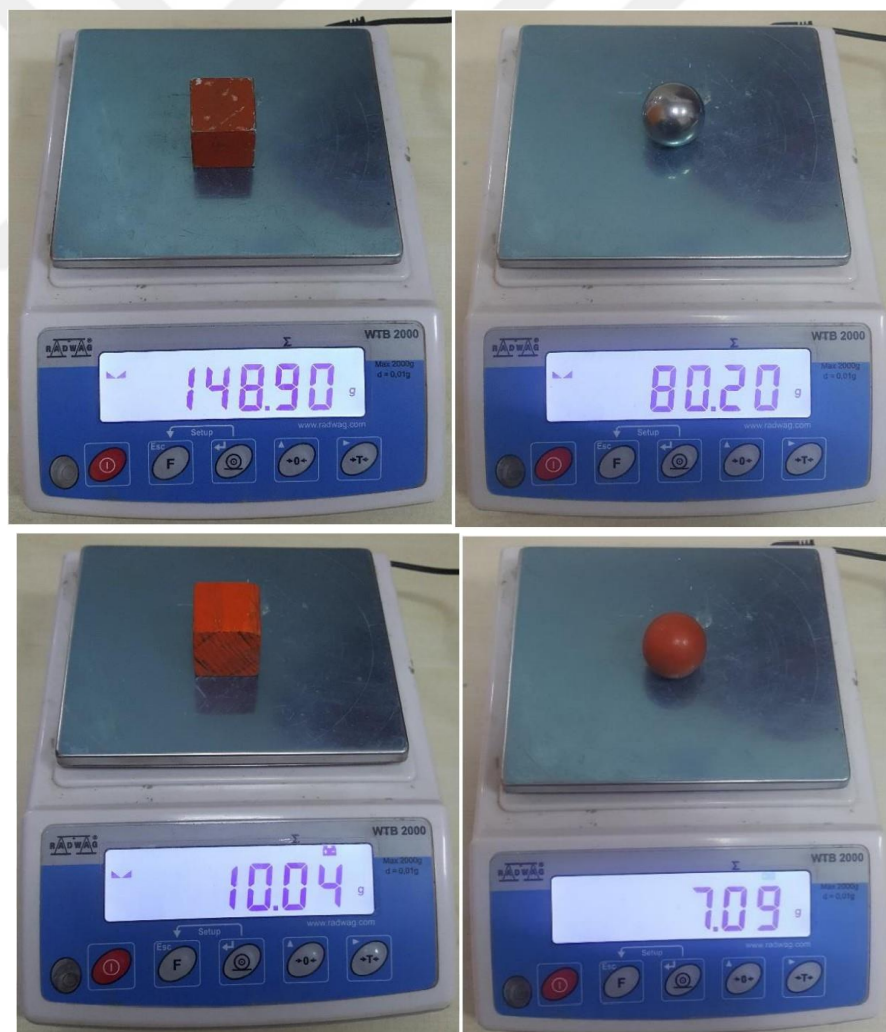


Figure 2.11 Pictures of materials used.

Table 2.1 Physical properties of the materials.

Name		Dimensions (cm)			Mass (g)	Coefficient of Friction	Bounciness
		x	y	z			
Cubic	Steel	2.7	2.7	2.7	148.90	0.31	0.03
	Wood	2.7	2.7	2.7	10.04	0.33	0.04
Spherical	Steel	2.7	2.7	2.7	80.20	0.21	0.35
	Wood	2.7	2.7	2.7	7.09	0.25	0.40



Figure 2.12 The laboratory model

The height of the starting point of the model is 100 cm and this represents the Y direction, the horizontal distance (X) at the bottom is 130 cm, the width of the model is 50 cm, the length of the stage in the middle is 20 cm and the slope of both slides is 45 degrees with a slope of 1% for the stage at the middle.

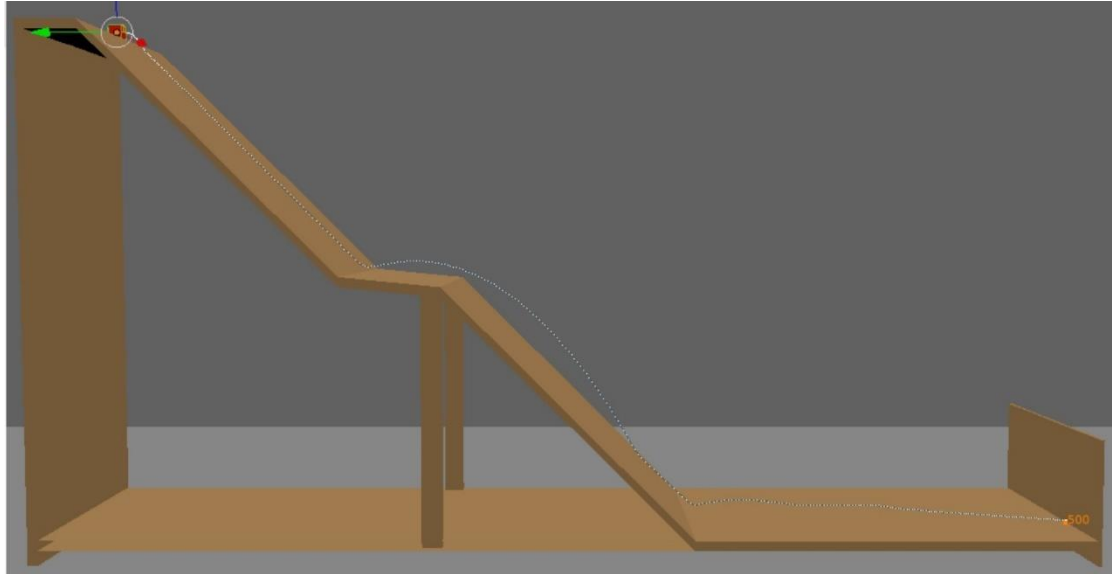


Figure 2.13 The Blender software model

The BLENDER computer software version used in this study is BLENDER 2.78c. The simulation videos were rendered at 25 frames/sec.

For both the real-life laboratory video and the BLENDER rendered video, the program tracker video analysis was used. The program allows users to construct particle model simulations based on Newton's laws by tracking selected objects movements. The program provides users with data for the selected objects.

The results taken from tracker video analysis from both the real-life model video and the rendered video from blender were then compared using the program SPSS. To compare the reality between the actual representing laboratory and the Blender software simulation, statistical tests were performed to find the degree of R, R square, significance rate P-value, Standard Deviation, degree of freedom, and correlation by using the T Test and regression analyses in statistical software SPSS. The version used in this study is IBM SPSS Statistics 23.

The results of the study showed very close results between the two models and some of those results are given in figure below.

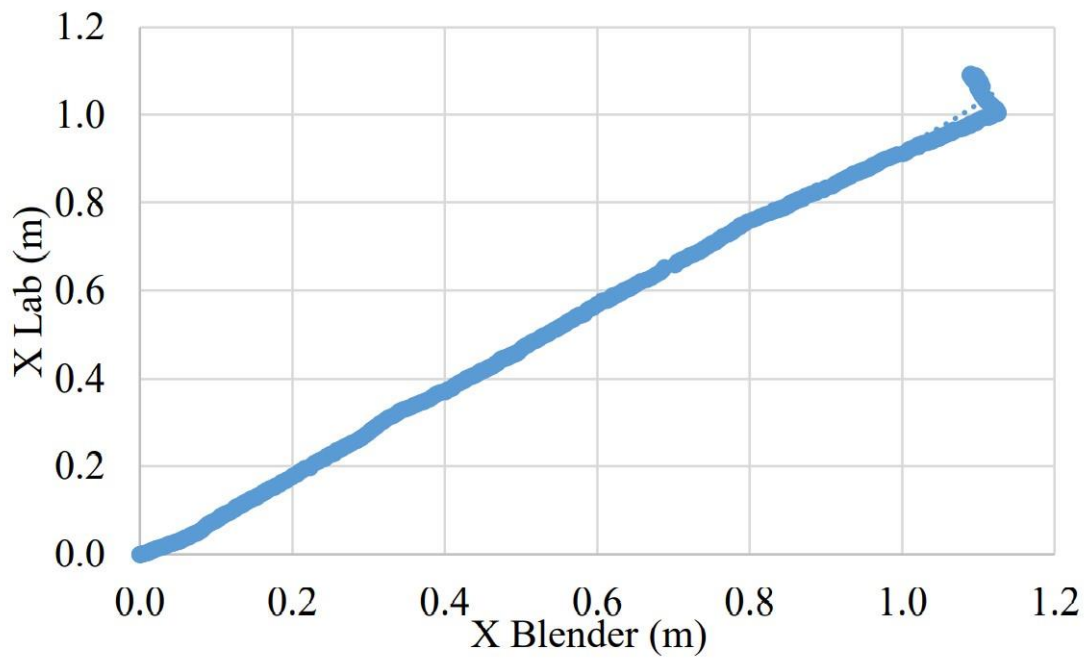
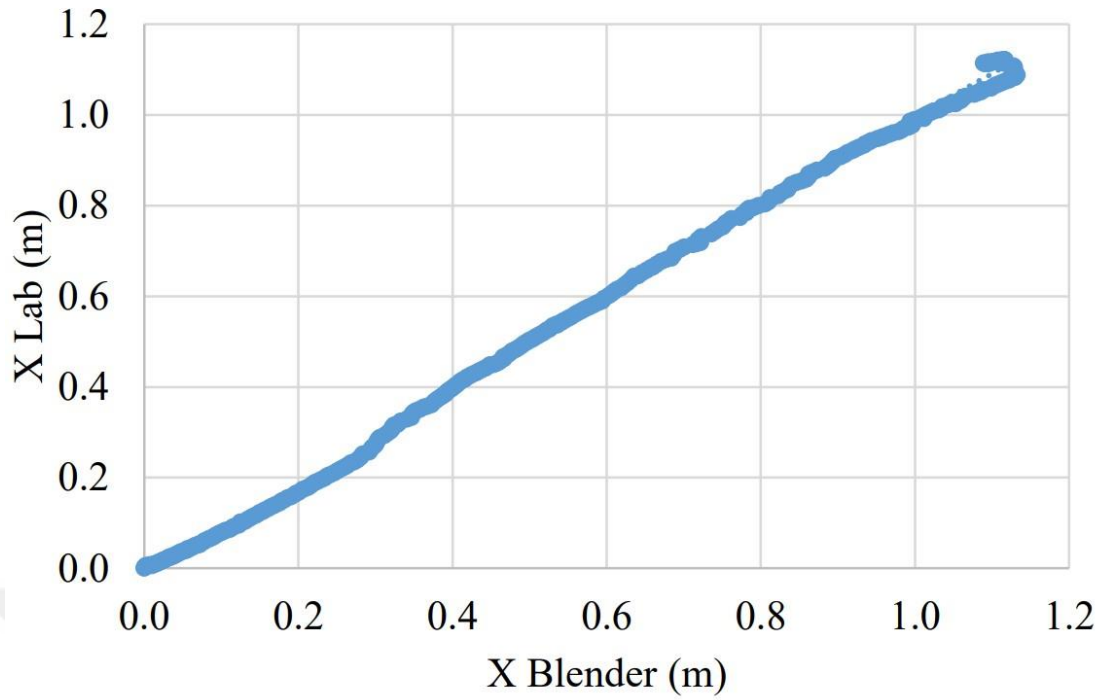


Figure 2.14 The relation between the laboratory and BLENDER results in terms of displacement (X) for wood and steel cubic samples respectively.

2.4. Simulation Through Software Applications

Physical modeling is one of the standard approaches for examining the mechanism of instability in geomaterials. A tilting table, a base friction table, and a centrifuge are examples of common geotechnical engineering physical modeling instruments. (Amini et al., 2017) used a tilting table apparatus to conduct a series of slide-toe-toppling physical model tests, as illustrated in figure 2.15.

As seen in figure 2.16, they constructed three models of secondary toppling to test their theories. A sequence of artificial cross-joints was constructed on the base of the blocks to simulate the block toppling mode. The overall failure plane had an angle of 14 to the floor of the table to achieve this result. It was necessary to employ continuous blocks in order to imitate the flexural toppling mode; nevertheless, the blocks were broken at their bases as a consequence of the bending caused by the bending. Finally, to replicate the block-flexural mode, half of the blocks were continuous and the other half had cross-joints. As the model was tilted, the stress fractures number and depth rose, and bricks began to collapse. Following processes may result in bending deflection of the blocks. The chunks ultimately toppled, forcing the earth mass to glide in a semi-circular pattern (Amini et al., 2017). The amount of model tests done is displayed in Table 2.2.

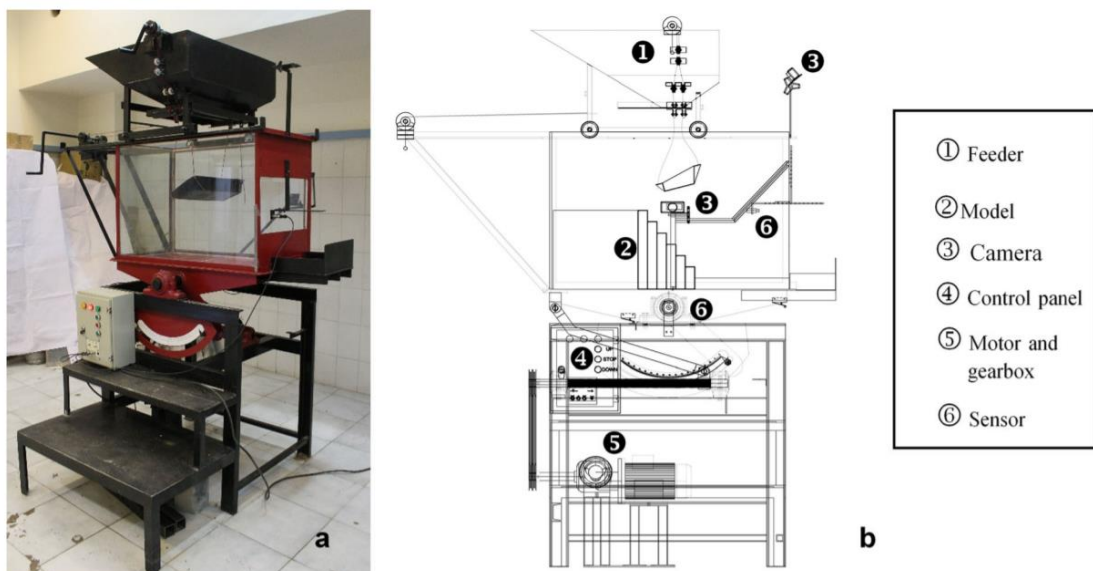


Figure 2.15 The tilting table apparatus used for physical modelling, (a) is a real-life picture, (b) is the schematic diagram (Amini et al., 2017).

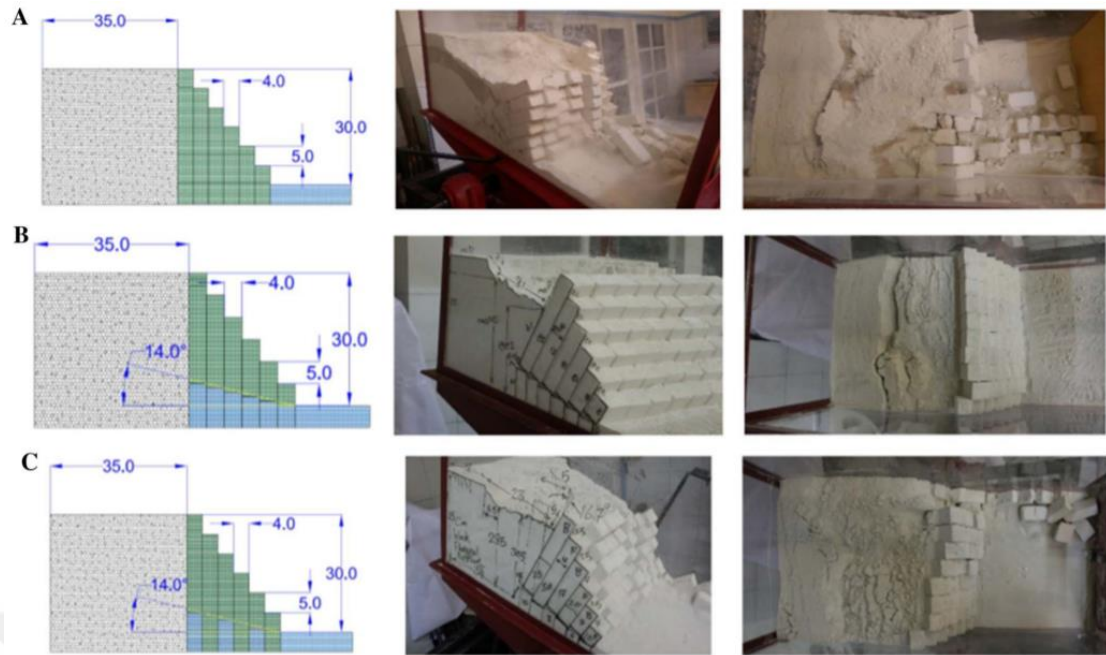


Figure 2.16 Slide-toe-toppling models with a height of 30 cm, with schematic designs and photographs. (a) flexural toppling, (b) blocky toppling, (c) block-flexural toppling (Amini et al., 2017).

Table 2.2 The slide-toe-toppling physical model tests (Amini et al., 2017).

Model test no. ^a	B20	B25	B30	BF20	BF25	BF30	F20	F25	F30
Toppling mode	<i>Blocky</i>	<i>Blocky</i>	<i>Blocky</i>	<i>Block-flexural</i>	<i>Block-flexural</i>	<i>Block-flexural</i>	<i>Flexural</i>	<i>Flexural</i>	<i>Flexural</i>
Table Inclination at failure (°)	13	9.5	7.7	26.5	20	13	31	23	17

^aThe number in front of B (Blocky), BF (Blocky-flexural), and F (Flexural) indicates the height of the model

Numerical methods are frequently employed as tools for solving a variety of rock engineering problems, as well as for project design and stability control. The failure behavior of rock structures can be better understood by observing them both within and outside. A continuous model is one in which elements are connected to each other, while a discrete model is one in which elements are divided by a discontinuity. The discrete models allow for the creation of slide and separation models. Continuous, discrete, hybrid, or a combination of numerical methods are the most prevalent numerical methods in rock mechanics (Khosravi et al. 2017).

To simulate the consequences of the physical models in this inquiry, the numerical tools UDEC (Universal Distinct Element Code) and Phase2 are employed. The finite element-based Phase2 program is a useful tool for studying soil and rock slopes, and it has been successfully used to examine pure circular and toppling failures. The accuracy and usability of finite element technique findings in continuous model investigation and appraisal were already demonstrated (Amini and Ardestani 2019). As a consequence, this approach may be used for the purpose of investigating the circular zone of slide-to-toppling failures. The use of the finite element approach in the examination of discontinuous models has risen as a result of the inclusion of joint elements to the technique. For the assessment of the joints, the Goodman joint element is implemented in the Phase2 program. This aspect can be used to mimic the separation of two slipping layers of a joint. To put it another way, the Goodman joint element is utilized to evaluate joints because it allows the system to compensate for joint surface separation and also sliding over one another. As a result of this feature, it is possible to represent toppling failure in this manner. As a result, this program might be used to mimic toppling failures. The Universal Distinct Element Code (UDEC) is a two-dimensional numerical software that is the core of the specific element technique for discontinuum media in static and dynamic scenarios, such as rock slopes, toppling failure, and fracture propagation. The Lagrangian computational approach, which is excellent for modeling block scheme movement and distortion, is used in this software. Discontinuities are represented as block boundary conditions, and they, like block discontinuities and rotations, are permitted substantial movement (ITASCA Cons. 2014). Despite the fact that the blocks are discontinuous, they may be emulated in Phase2 software using joint components, as explained earlier. Phase2 may be utilized to describe this failure since the slidetoetoppling failure is simulated in this study and the toppling of the blocks is induced by the constant media weight that lies behind the blocks. Significant mobility between components is simpler to mimic using DEM than with the Finite Element Method (FEM). Furthermore, UDEC software was used to simulate the aforementioned failure in order to compare it to experimental testing and analytical solutions in order to determine whether numerical technique for slide-toe-toppling failure is more accurate.

The stability of a slope may be determined by calculating the safety factor. The safety factor is determined in terms of shear failure as indicated in Eq (1):

$$FOS = \frac{\tau}{\tau_s} \quad (1)$$

where, s and ss are the shear strength and shear stress on the slip surface, respectively.

According to Eq. (2), the shear strength is determined in accordance with the Mohr-Coulomb criteria as follows:

$$\tau = s_0 + \sigma_n \tan \phi \quad (2)$$

The cohesion and normal stress on the slip surface are s_0 and σ_n , respectively, and the friction angle is ϕ . The parameters of cohesiveness and friction angle are progressively lowered to the failure threshold in this procedure.

The stress reduction factor is abbreviated as SRF. Eqs. (3) and (4) yield the decreased resistance parameters S_c and ϕ_c , respectively.

$$S_c = \frac{s}{SRF} \quad (3)$$

$$\phi_c = \tan^{-1} \left(\frac{\tan \phi}{SRF} \right) \quad (4)$$

Physical and mechanical characteristics of the materials should be provided in order to do numerical modeling. Table 2.3 contains a list of the characteristics of the block and powder. Table 2.4 also includes information on the qualities of the joints that connect the blocks. For numerical modeling was based on the Mohr- Coulomb friction law was. When the program failed, the first geometry of every model was created. After that, the model was put through a shear strength reduction study.

Table 2.3 The slide-toe-toppling physical model tests (Amini et al., 2017).

Element	Unit weight (kN/m ³)	Modulus of elasticity (MPa)	Poisson ratio	Tensile strength (kPa)	Friction angle (peak) (°)	Friction angle (residual) (°)	Cohesion (peak) (kPa)	Cohesion (residual) (kPa)
Solid block	21.1	10	0.25	14	35	25	100	0
Powder	14	3	0.3	0	20	15	0.35	0.15

Table 2.4 The slide-toe-toppling physical model tests (Amini et al., 2017).

Normal stiffness (MPa/m)	Shear stiffness (MPa/m)	Peak cohesion (kPa)	Residual cohesion (kPa)	Peak friction angle (°)	Residual friction angle (°)
100	1	0	0	32	25

Result of Numerical Modelling

The mechanism of slide-toe-toppling failure was investigated using numerical modeling centered on the kind of failure in the toe region of the slope (in three sections of flexural, blocky and block-flexural). The numerical modeling results are presented in the following sections.

Flexural Toppling Failure

In a kind of instability like this, solid blocks near the slope's toe were completely continuous and were able to tolerate tensile forces. Theoretical analyses and physical analyses demonstrate that in a kind of failure like this, the homogenous soil mass near the slope's toe suffers circular sliding, pushing the rock blocks closer to the slope's toe. As a result of the bending-induced tensile stress, the rock blocks may collapse and tumble. The results of the physical model displayed in figure 2.16 are provided here for comparison because the numerical model findings were almost identical. The difficulties that will be discussed for this model will also be applied to other models with the possibility for flexural toppling in the toe.

Figures 2.17 and 2.18 show the numerical analysis of the model stated in figure 2.11 a. The model's stress reduction factor was calculated to be 0.9785 and 0.9605, respectively, in UDEC and Phase2 programs. The cross (*) and purple (O) symbols in figure 2.16 represent the yield and tensile points, respectively. These figures show that the top half of the slope (uniform mass of soil) has suffered circular sliding, while the bottom half (rock blocks) has failed due to tensile stress. In toppling collapses, particularly flexural failures, determining the whole failure plane in the rock mass is difficult. But this plane is typically higher than the plane normal to dominating discontinuities. Theoretic and practical research have projected the angle inbetween

the two planes (the overall plane failure and the plane corresponding to main discontinuities) has been calculated to be between 5 and 15 degrees.

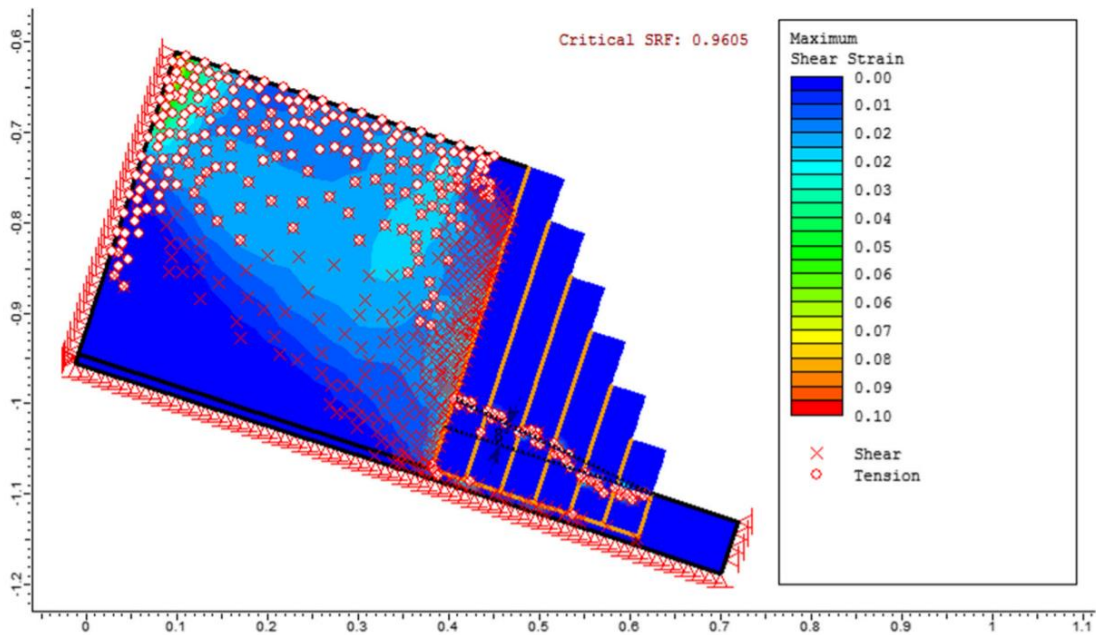


Figure 2.17 The result of numerical modelling in the model F30 with Phase2 software.

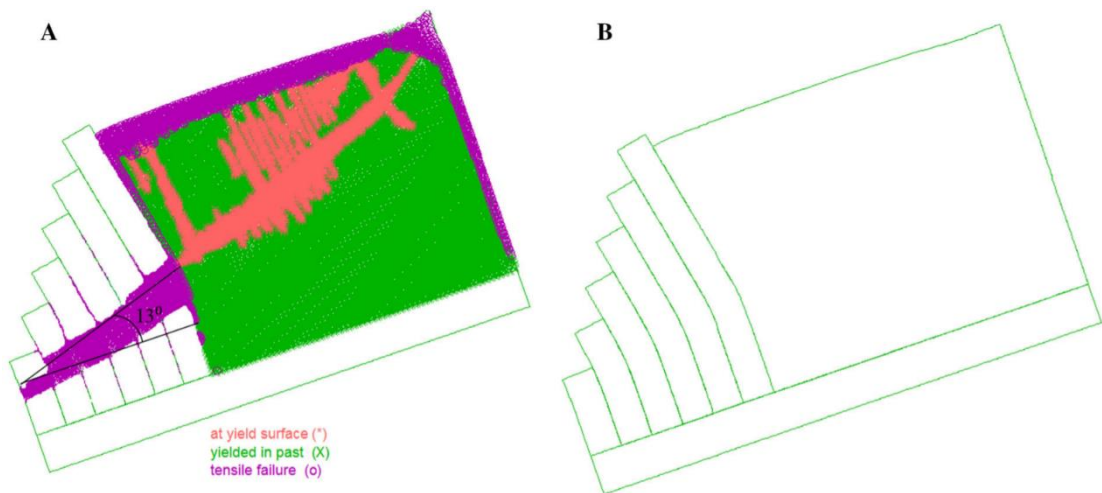


Figure 2.18 result of numerical modelling in the model F30 with UDEC software, (a) is the plastic plot, (b) is the block plot after deformation.

As stated by these numbers, the angle between the normal to discontinuities and the complete toppling failure plane is between 10 and 11.31 degrees (Amini et al., 2017). To confirm the conclusions of numerical modeling, the values of this angle in the

produced models were decided. According to the data, this model's angle in UDEC program is 13 and in the Phase2 program is 8, which falls within a reasonable array of values.

Block Toppling Failure

The presence of cross-joints limits the capacity of blocks to bear tensile stresses in this form of instability, leading them to slide or topple under the pressure imposed by sliding soil mass at the slope's upper half. The results of numerical analysis of the physical model using the Phase2 program and the UDEC program are shown in Figures 2.15 and 2.16, respectively. Figure 2.16 depicts the positioning of tension fractures, the circular failure path, and the shearing between joints. The right sides of the cross-joints at the base of the blocks are stable, but the left sides have succumbed, suggesting that they have all toppled and experienced pure toppling. In figure 2.15, the path of cyclic failure can also be shown. The bricks have also tumbled around their base, signifying a total toppling. In the models described, the toppling potential of the blocks could be differentiated from the sliding potential of the blocks. The stress reduction factor in UDEC and Phase2 software is 0.986 and 0.79, respectively.

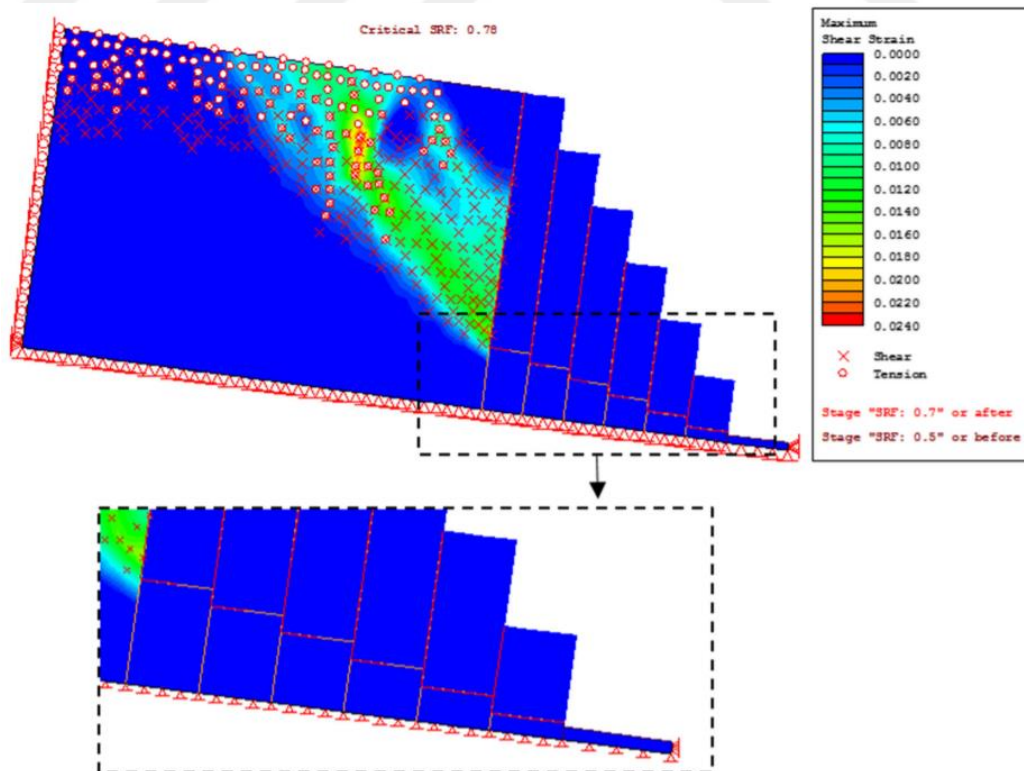


Figure 2.19 The result of numerical modelling in the model B30 with Phase2 software.

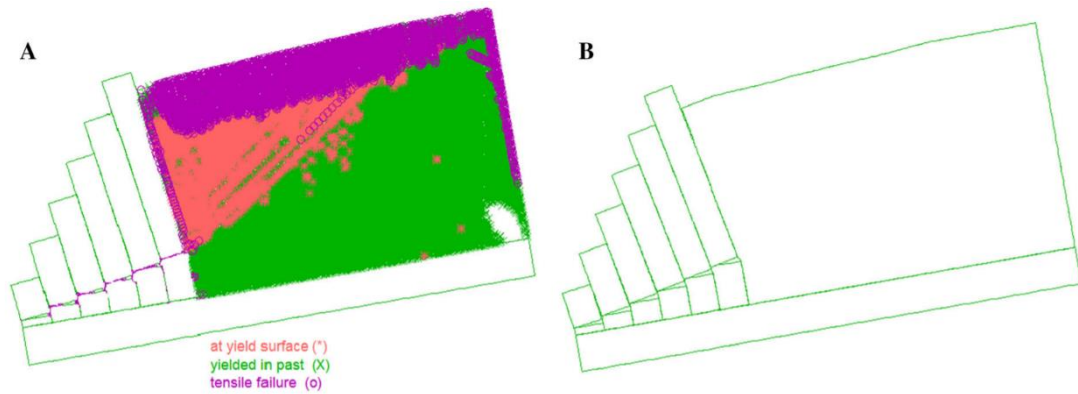


Figure 2.20 The result of numerical modelling in the model B30 with UDEC software, (a) is the plastic plot, (b) is the block plot after deformation

Block-Flexural Toppling Failure

As a result of the circular sliding pressure, some of the blocks twisted and broke under tensile pressures, while others were split at the cross-joints and finally all tumbled together. The outcomes of this numerical study on the physical model are displayed in Figures 2.19 and 2.20, with stress reduction factors of 0.959 and 1.037 in the Phase2 program and the UDEC program, respectively. Figure 2.19 shows how the failure surface traveled through the cross joints. Figure 2.20 similarly shows the plastic locations that have yielded as a result of the influence of normal and shear stresses. As may be observed, the failure surface created by the mixture of flexural and blocky toppling failures crosses the location of cross-joints in the discontinuous mass.

Results and Discussions

In this part, the outcomes of numerical modeling with the UDEC program and the Phase2 program are compared to the comparable physical modeling to confirm the numerical simulation's correctness. The numerical analysis yields a variety of diagrams and numbers, and the outcomes of numerical and physical modeling are compared. To put it another way, while comparing various models, the important stress reduction factor is a suitable statistic to utilize. In numerical techniques, this amount may be believed to be comparable to the factor of safety (Amini and Ardestani 2019; Zienkiewicz et al., 1975). Because the critical stress factor of reduction of all numerical models should be 1, because the safety factor of physical models was 1 at

the moment of failure. The stress factor of reduction of numerical models is compared to the factor of safety (FOS) of equivalent physical models in Table 2.5 reveals that in numerical modeling using Phase2, the discrepancy between experimental and numerical findings is less than 11%, with the exception of model B30. Furthermore, as indicated in this table, the UDEC program's maximum error is 9%, which is suitable considering the failure mechanism's complexity. The average inaccuracy of the UDEC program and the Phase2 program, according to this table, is 3.39 and 8.21%, respectively, demonstrating that the UDEC program findings are more consistent than the Phase2 program results.

Comparing the table incline at the instant of failure is another approach to evaluate the conclusions of numerical and physical models. In numerical simulations, the line that is perpendicular to the discontinuities of rock mass corresponds with the table incline. The max table incline recorded in numerical models is compared to the values expected by the analytical result of (Amini et al., 2017) in figure 2.19. The numerical and analytical results are in good agreement, as seen in this graph. This graph shows the average relative error among the analytical approach and numerical modeling, which is 7.37% for the UDEC program and 11.93% for the Phase2 program. As a result, the UDEC findings are more reliable than the Phase 2 findings.

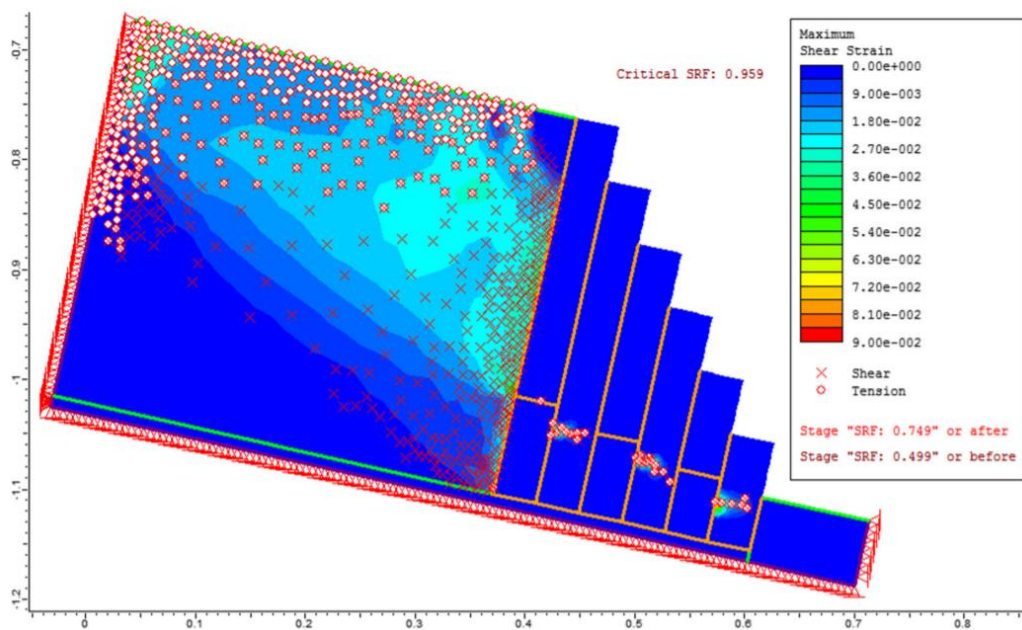


Figure 2.21 The result of numerical modelling in the model BF30 with Phase2 software

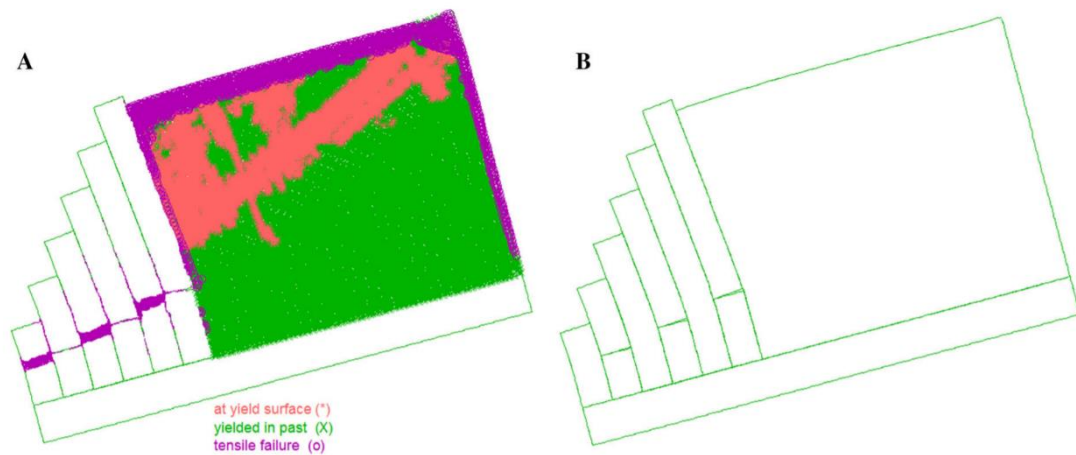


Figure 2.22 The result of numerical modelling in the model BF30 with UDEC software, (a) is the plastic plot, (b) is the block plot after deformation.

The numerical modeling outcomes are also compared to both the physical modeling findings and the analytical expectations, as illustrated in figure 2.22. In Phase2 software, the tilt of the prediction table is usually always smaller than the value computed in physical models. The underestimation of the Phase2 program models might be due to the inadequacy of FEM algorithms to simulate separation and displacement along discontinuities. The UDEC software's prediction table inclination is in good agreement with their respective experimental and analytical models, as shown in figure 2.22.

Table 2.5 Comparison of numerical modeling results with corresponding physical models.

Models	B20	B25	B30	BF20	BF25	BF30	F20	F25	F30
FS in physical modeling	1	1	1	1	1	1	1	1	1
SRF in UDEC software	1.08	1.09	0.986	0.998	0.998	1.037	0.986	0.956	0.978
SRF in Phase2 software	0.9	0.89	0.78	0.944	0.936	0.959	0.927	0.965	0.96
Error of UDEC software (%)	8	9	1.4	0.2	0.2	3.7	1.4	4.4	2.2
Error of Phase2 software (%)	10	11	22	5.6	6.4	4.1	7.3	3.5	4

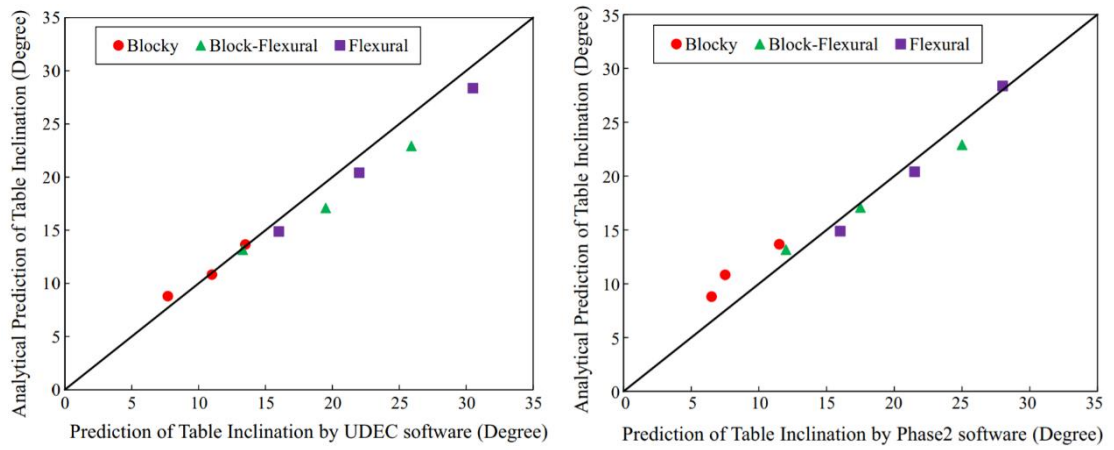


Figure 2.23 Comparison of numerical modelling results with analytical predictions.

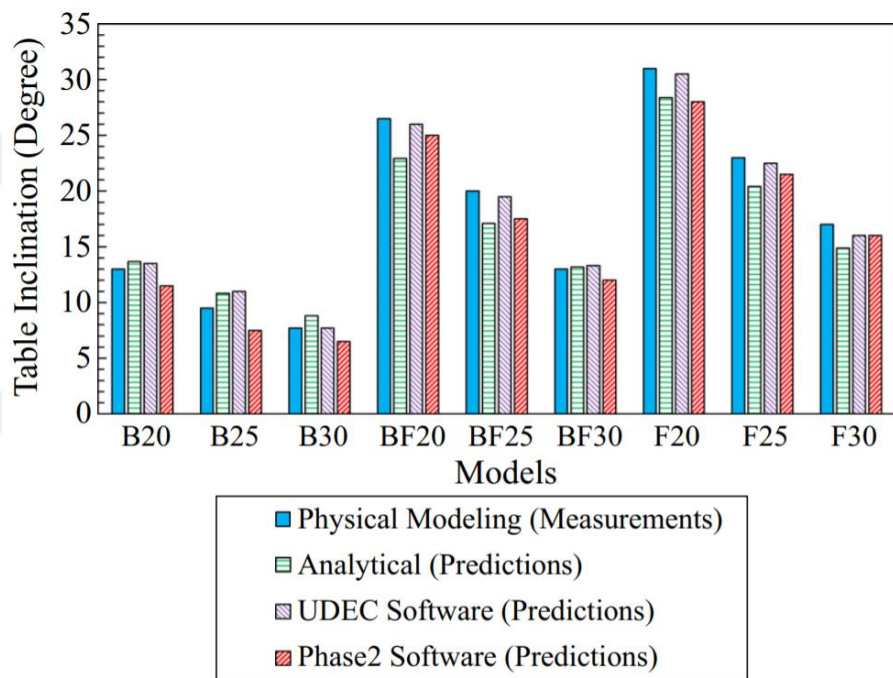


Figure 2.24 Comparison between physical, analytical and numerical results.

CHAPTER III

METHODOLOGY

3.1. The Examined Studies

The aim of all the studies examined in this paper, is to try to identify the behavior of each rock block on the slope. The studies classified the behaviors into three types; stable, where the rock block does not change its position or rotation, sliding, where the rock block slides to change its position while maintaining its rotation, and toppling, where the rock block changes both its position and its rotation.

A more detailed look is going to be made to each study to get more details about the slope geometries in each study.

3.1.1. Wyllie and Mah Study

This study is a practice of the Goodman and Bray limit equilibrium analysis. The aim is to find the behavior of each rock block as mentioned earlier and finding the FS (factor of safety) by finding $\phi_{required}$, then finding the ratio of $\frac{\tan\phi_{available}}{\tan\phi_{required}}$, where

$\phi_{available}$ is the angle of friction on the faces and bases of the blocks.

The slope geometry is shown in figure 3.1 and its details are shown in table 3.1. The width of each block is 10 m

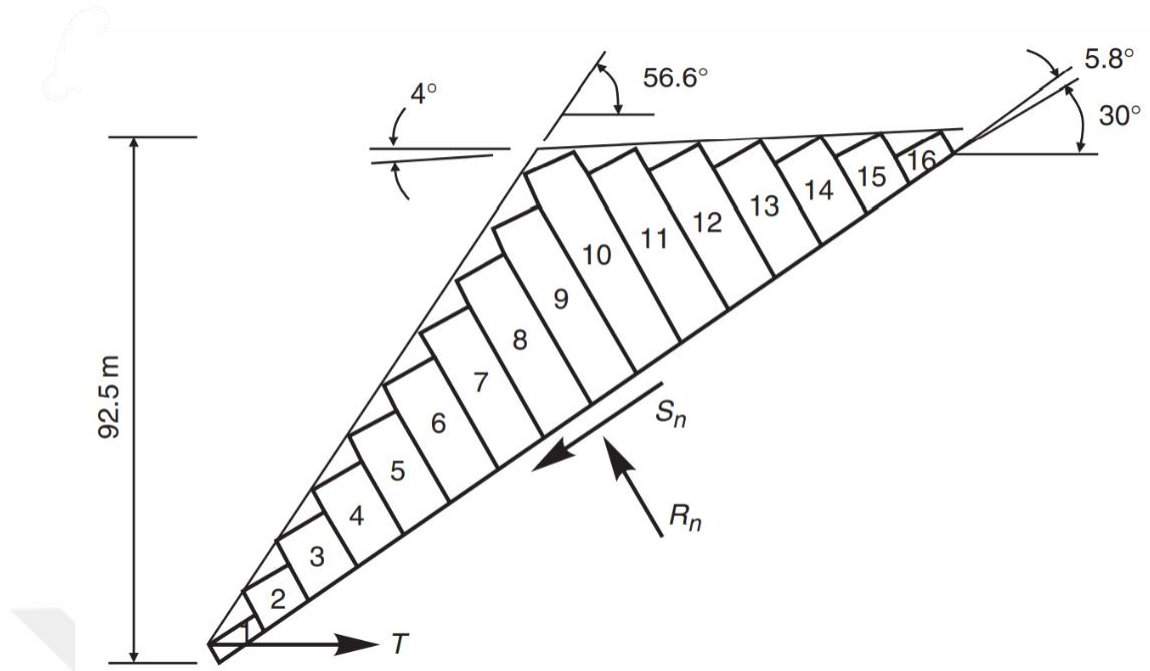


Figure 3.1 Slope geometry

The slope geometry shows the height of the slope, the angle of the surface and the angle of the block on the surface.

In table 3.1, the value n refers to the number of the rock block and the value y_n refers to the height of each rock block. The values are in meters. The angles of friction on the faces and bases of the blocks ($\phi_{available}$) are the value of 38.15°.

Table 3.1 Listing block dimensions and stability mod

n	y_n	Mode
16	4.0	
15	10.0	STABLE
14	16.0	—————
13	22.0	
12	28.0	T
11	34.0	O
10	40.0	P
9	36.0	P
8	32.0	L
7	28.0	I
6	24.0	N
5	20.0	G
4	16.0	
3	12.0	—————
2	8.0	SLIDING
1	4.0	

3.1.2. Guo et al., Study

This study conducted an experiment using the shake table in the institute of Engineering Mechanics China Earthquake Administration (Guo et al., 2017). There are 26 blocks in total. The size of the model box is $3.6 \text{ m} \times 1.6 \text{ m} \times 1.8 \text{ m}$. The details of the slope geometry are shown in figure 3.2. The internal angle of friction θ_b is 36.2° . The angle of friction of block side joints and block base joints equals 30° .

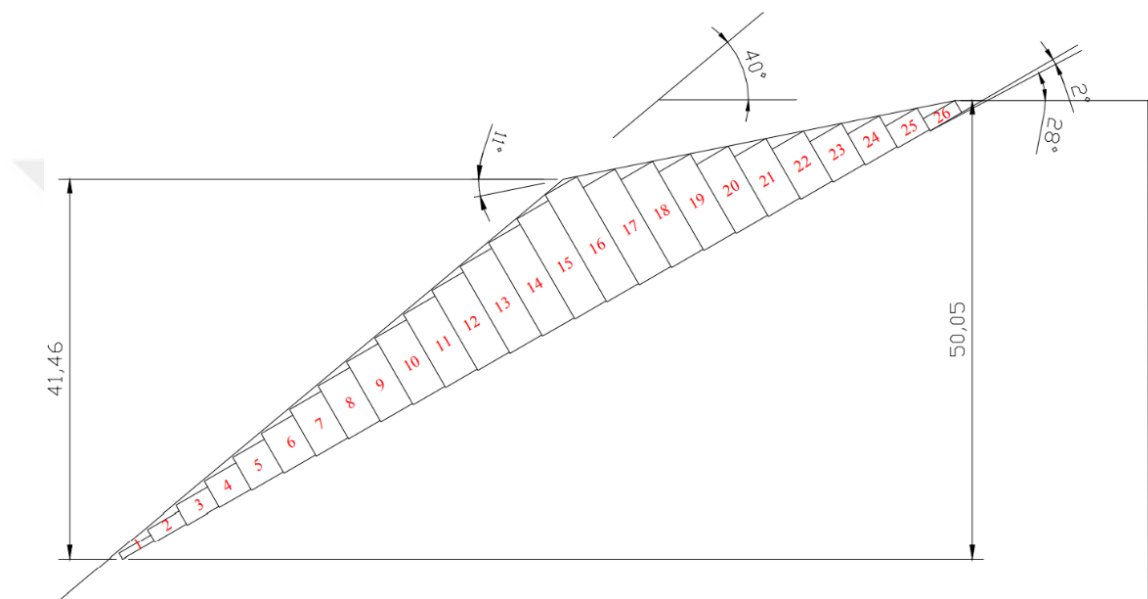


Figure 3.2 The limit equilibrium model for physical model on the shake table test

The slope geometry shows the height of the slope, the angle of the surface and the angle of the block on the surface.

In the table 3.2, the value n refers to the number of the rock block and the value y_n refers to the height of each rock block. The values are in meters.

Table 3.2 The sheet from limit equilibrium analysis of slopes under static state

1	2	9
<i>n</i>	<i>y_n</i> (cm)	MODE
26	1.5	
25	2.7	
24	3.9	
23	5.1	
22	6.3	
21	7.5	
20	8.7	
19	9.9	
18	11.1	
17	12.3	
16	13.5	
15	12.7	
14	11.8	
13	11.0	stable
12	10.1	
11	9.3	
10	8.4	
9	7.6	
8	6.7	
7	5.9	
6	5.0	
5	4.2	
4	3.3	
3	2.5	
2	1.6	
1	0.8	

3.2 Modeling in BLENDER software

BLENDER software is an increasingly more popular program in the animation and 3D modeling industry. It's a free and open-source software that's getting better and more advanced every day. In this study, was used to simulate rock toppling failure, the version used in this study is BLENDER 3.0. The frame rate for rendered videos was 30 frames/sec. The process followed in BLENDER software is shown in figure 3.3, and the figures 3.4 and 3.5 show the models created in BLENDER from the camera view for the book study, internet study and program study respectively.

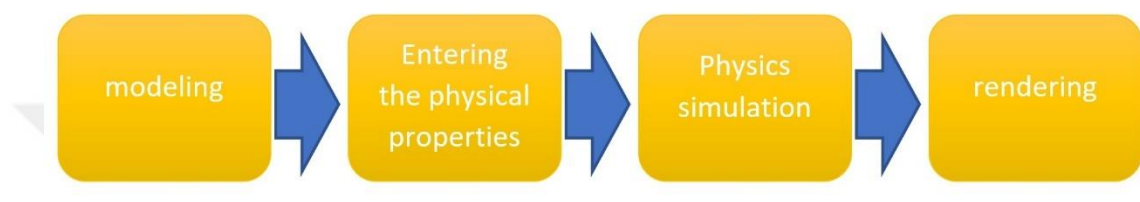


Figure 3.3 The process in BLENDER software.

The first step is to model slope geometries in BLENDER software, to get a meaningful simulation result, all the geometrical details such as the width and height of each rock block, the slope of the surface and the slope of the rock blocks of that surface are modeled exactly like they are mentioned in the study.

Then entering the physical properties like the mass, the method which BLENDER calculates the geometry of the existing objects and the friction. Values such as bounciness, damping translation and rotation are also changeable variables, but in this study, they were left as the default values. The way the mass was calculate is by using the BLENDER software feature “calculate mass” from the rigid body properties. The process followed in this feature is the user is able to choose a material type such as brick, gold, glass, limestone, marble and many more, then the software will calculate the mass based on the volume of the object. In this study, for all simulations, limestone was chosen. The method which BLENDER calculates the geometry of the existing objects was chosen to be “Convex Hull”, which means the software will take every detail on the object into account during the simulation, with the expense of computing power. Because of the geometry of the rock blocks, other options like “Box” could have been chosen, but since the model is not complicated choosing “Convex Hull” would give more accurate results with a negligible downside.

The friction in BLENDER software is a value changeable between 0 and 1. The friction value is selected differently in each model.

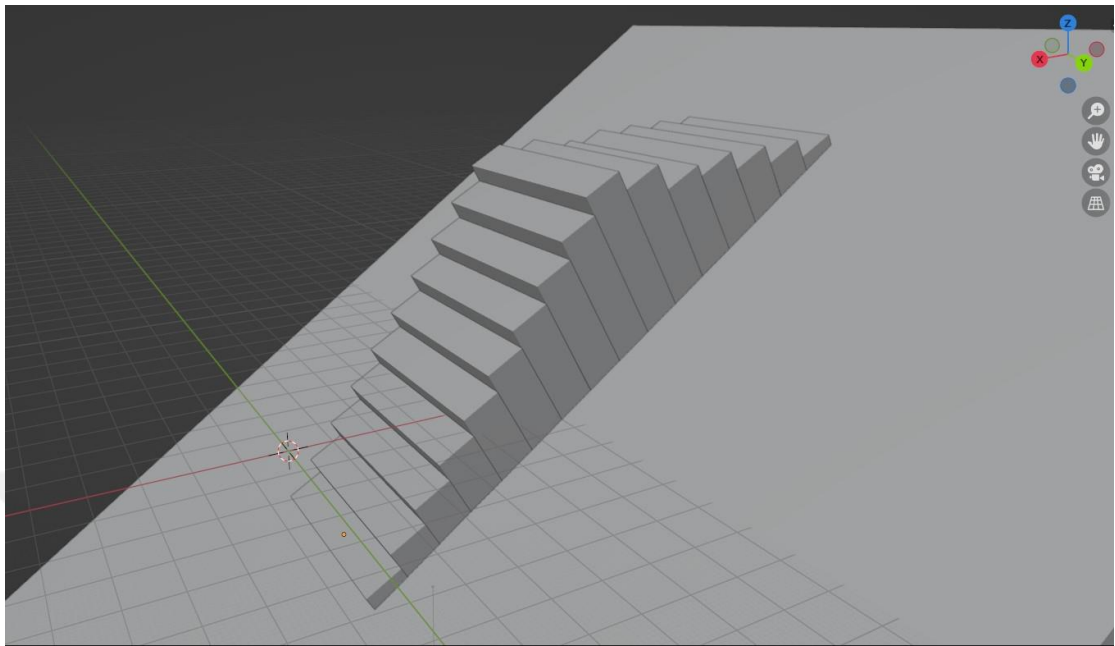


Figure 3.4 BLENDER model for the Wyllie and Mah study. (3D view)

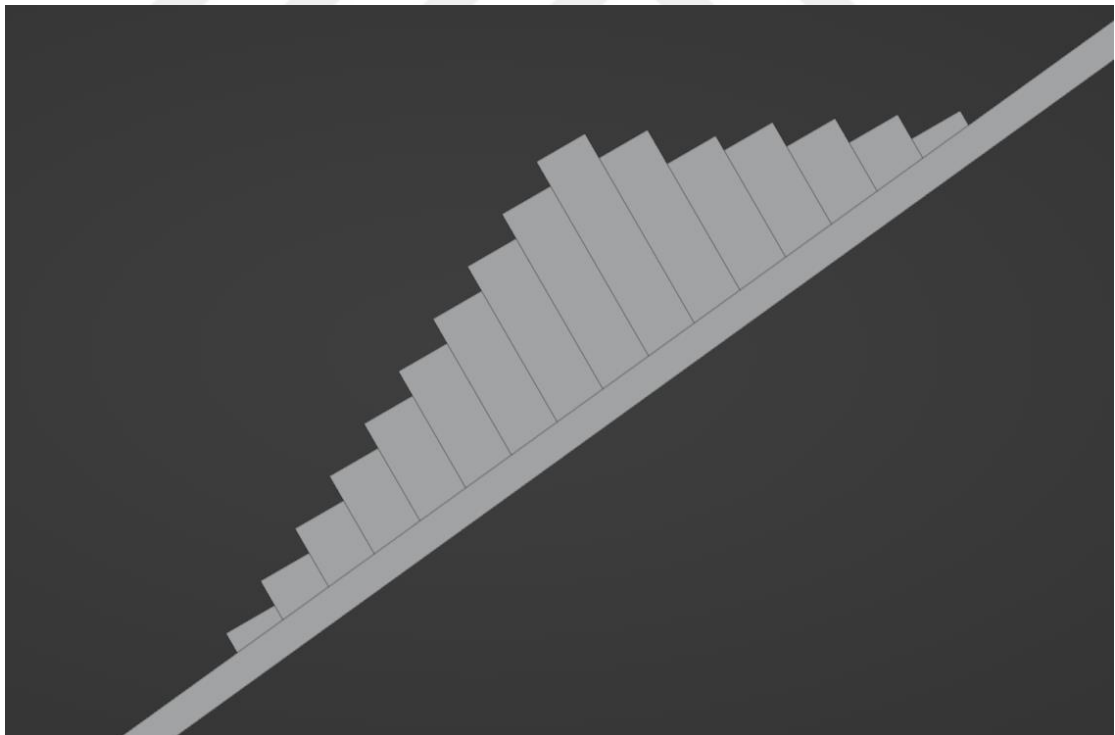


Figure 3.5 BLENDER model for the Wyllie and Mah study.

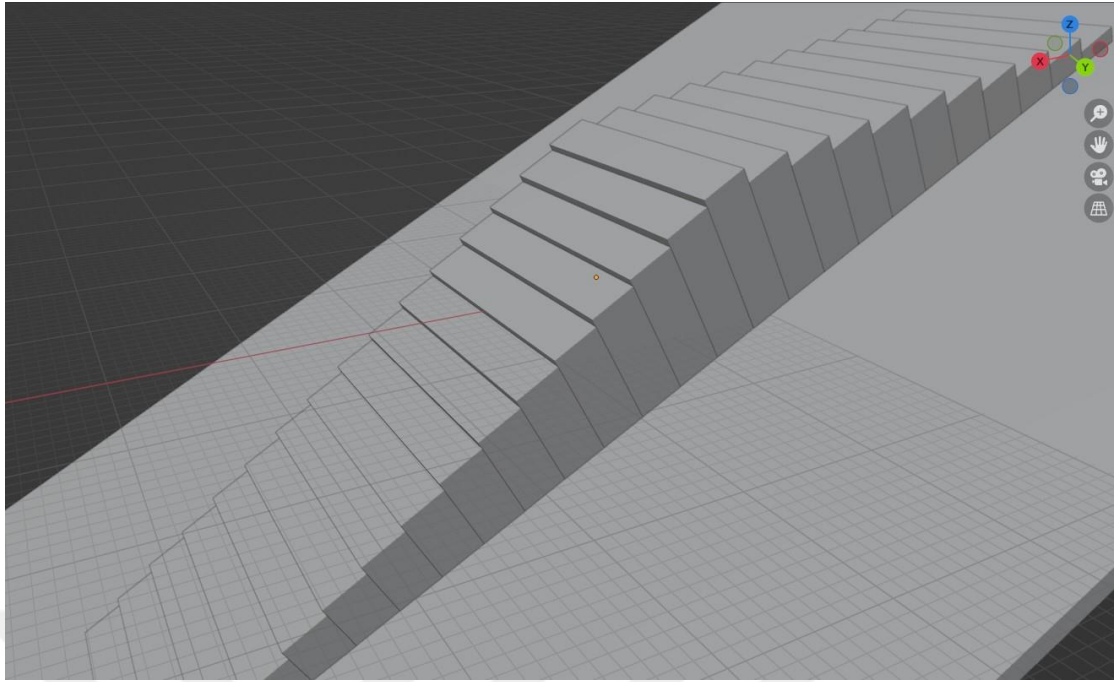


Figure 3.6 BLENDER model for the Guo et al., study. (3D view)

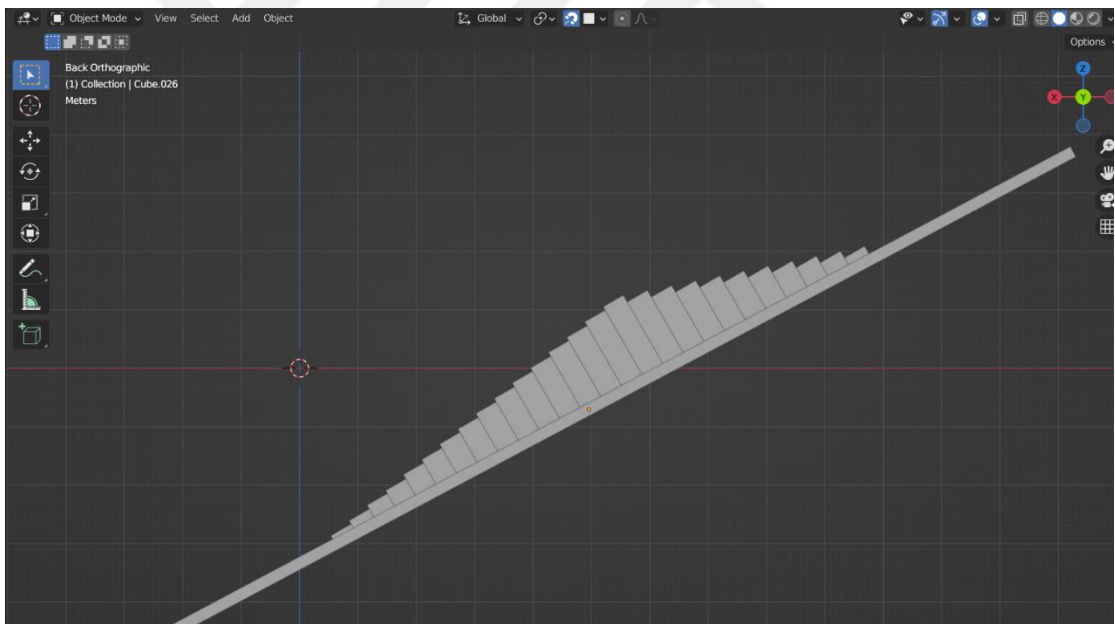


Figure 3.7 BLENDER model for the Guo et al., study.

For the results to be accurate, a lot of attention must be given to designing and modeling the slope. That's why the part that will take the most amount of time is modeling the slope geometry. Parameters like the width and height of the blocks, the angle of the surface and the angle of the block with the surface all have to be carefully modeled in detail

CHAPTER IV

RESULTS AND DISCUSSION

In this section, the result of each BLENDER simulation and its comparison with its respective study are being discussed.

The results will be shown in tables for easier understanding.

4.1 Wyllie and Mah study

The result of the physics simulation for the book study is shown in figure 4.1.

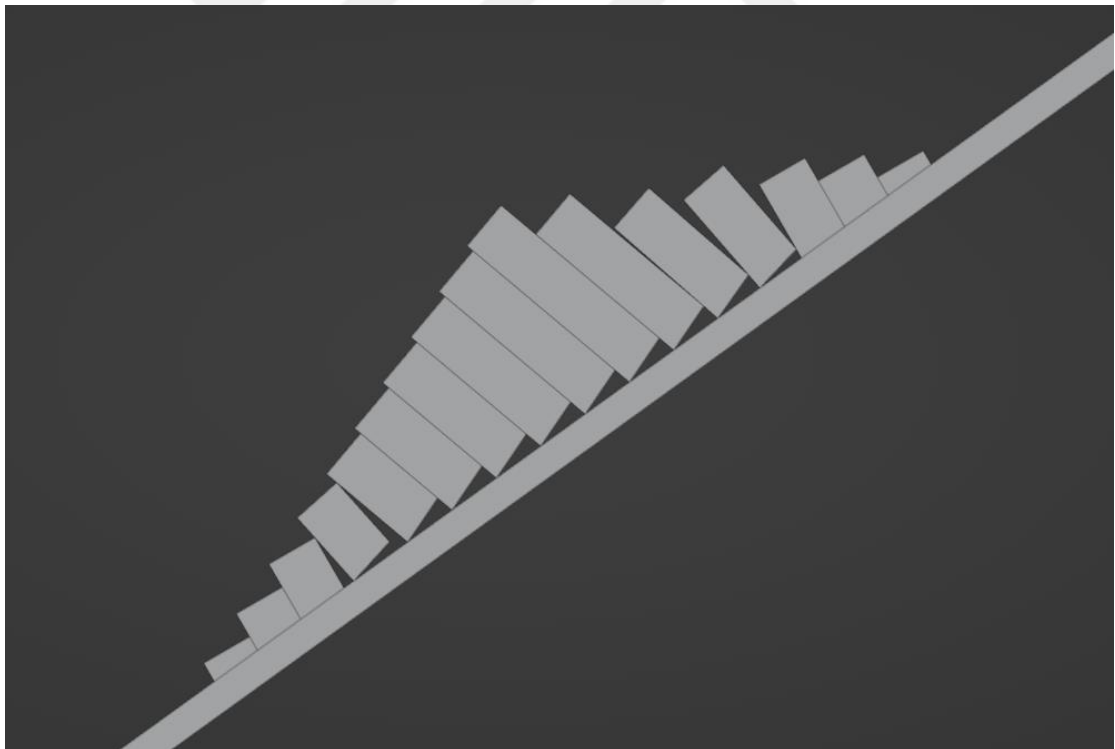


Figure 4.1 Result of the BLENDER model for the Wyllie and Mah study (while falling).

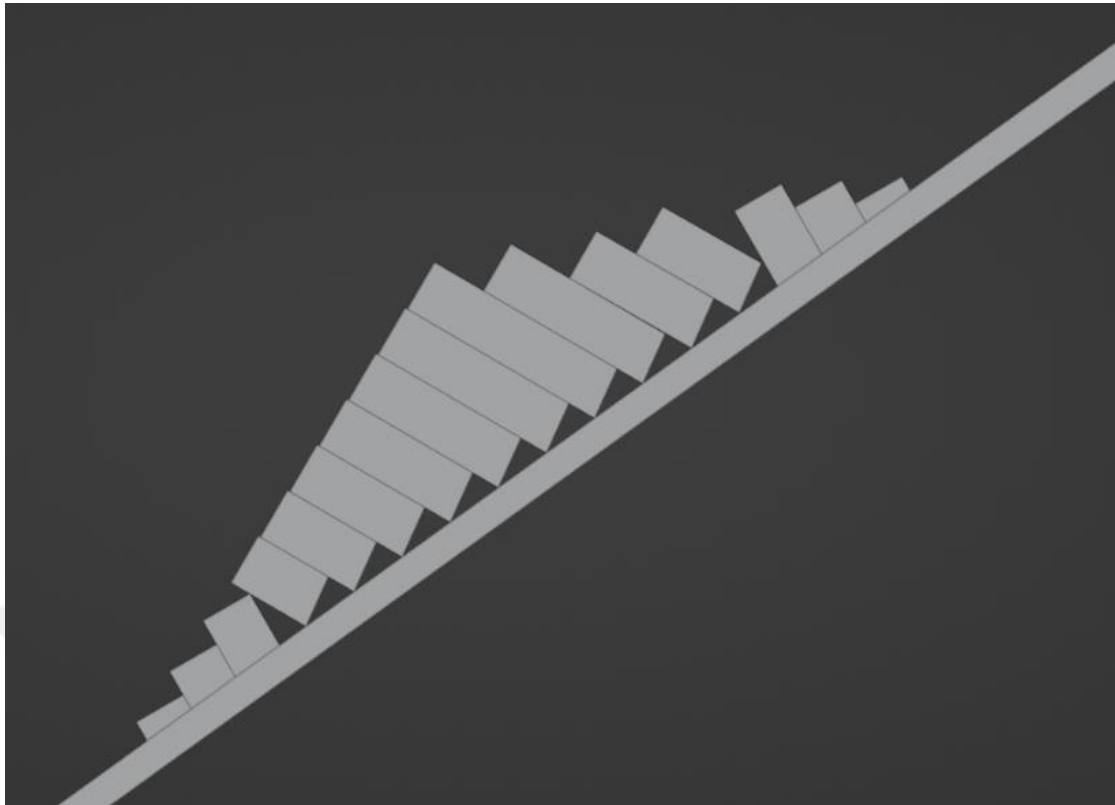


Figure 4.2 Result of the BLENDER model for the Wyllie and Mah study.

Table 4.1 Listing block dimensions and stability mods

n	y_n	Mode
16	4.0	STABLE
15	10.0	
14	16.0	
13	22.0	T O P P L I N G
12	28.0	
11	34.0	
10	40.0	
9	36.0	
8	32.0	
7	28.0	
6	24.0	
5	20.0	
4	16.0	
3	12.0	SLIDING
2	8.0	
1	4.0	

As seen in the table 4.1 and figures 4.1 and 4.2, the result of the BLENDER simulation and the book study are identical. Where in both, the first three block are sliding, the blocks 4-13 are toppling and the last three block (14, 15 and 16) are stable.

4.2 Guo et al., study

The result of the physics simulation for the internet study is shown in figure 4.2.

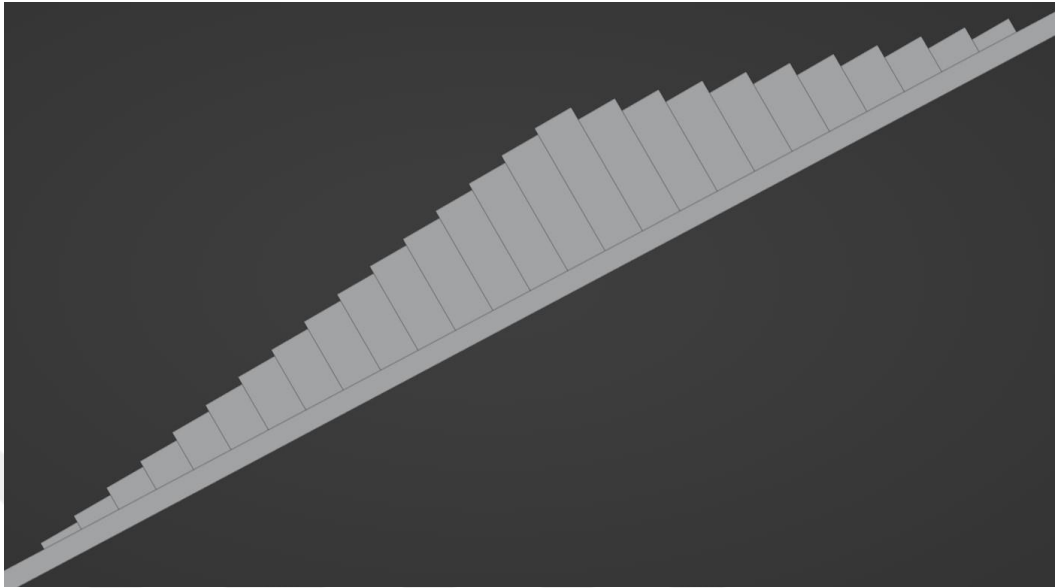


Figure 4.3 Result of the BLENDER model for the Guo et al., study.

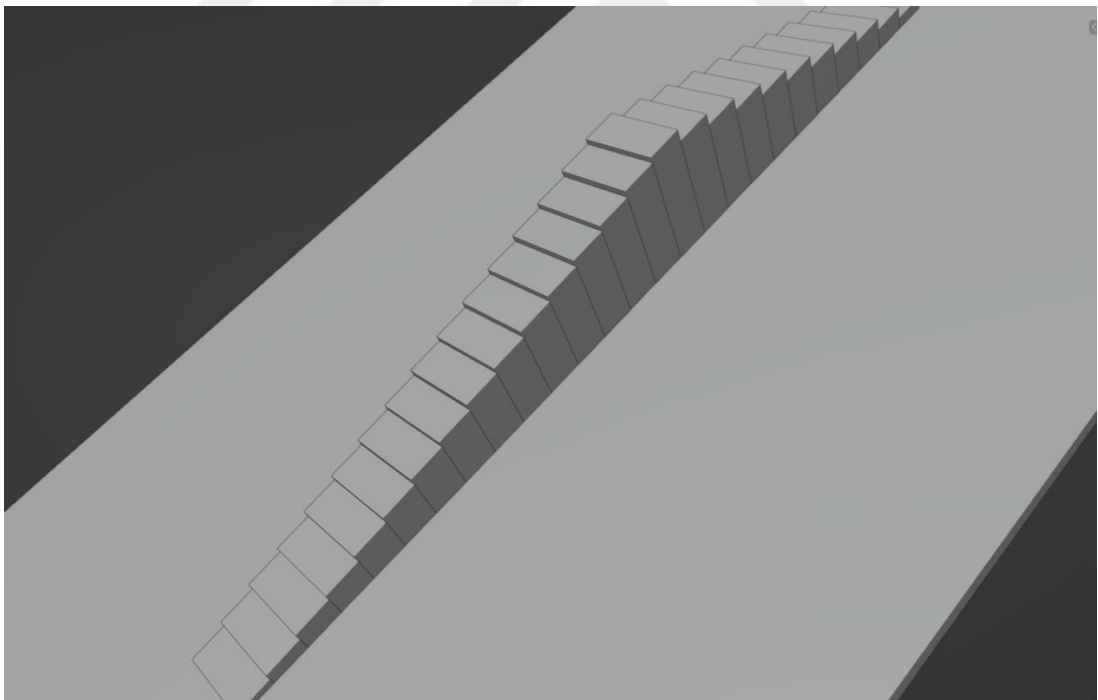


Figure 4.4 Result of the BLENDER model for the Guo et al., study (3D view).

Table 4.2 The sheet from limit equilibrium analysis of slopes under static state

1 <i>n</i>	2 <i>y_n</i> (cm)	9 MODE
26	1.5	
25	2.7	
24	3.9	
23	5.1	
22	6.3	
21	7.5	
20	8.7	
19	9.9	
18	11.1	
17	12.3	
16	13.5	
15	12.7	
14	11.8	
13	11.0	stable
12	10.1	
11	9.3	
10	8.4	
9	7.6	
8	6.7	
7	5.9	
6	5.0	
5	4.2	
4	3.3	
3	2.5	
2	1.6	
1	0.8	

Just like in the previous simulation and as seen in the table 4.2 and figure 4.2, the result of the BLENDER simulation and the book study are identical. Where in both, all the blocks are stable.

The results of both studies show that the potential of the computer software BLENDER. When used correctly and models and properties were designed and entered carefully and in detail, the computer software BLENDER can give us very accurate results when simulating geological phenomenas like rock toppling failure.

The results of the study made by (G. KHOSHNAW 2019) also proves the capability of BLENDER computer software to simulate events related with civil engineers.

But, one downside of the computer software BLENDER is that it does not give results as data or as measurable parameters by default. The fact of it being open source can be used and programing the software BLENDER to give results in a different way is possible. Or other programs can be used to extract the data in different ways.

Table 4.3 A comparison between Wyllie and Mah study and BLENDER model respectively.

<i>n</i>	Mode	<i>n</i>	Mode
16	STABLE	16	STABLE
15		15	
14		14	
13	T O P P L I N G	13	T O P P L I N G
12		12	
11		11	
10		10	
9		9	
8	SLIDING	8	SLIDING
7		7	
6		6	
5	SLIDING	5	SLIDING
4		4	
3		3	
2		2	
1		1	

Table 4.4 A comparison between Guo et al., study and BLENDER model respectively.

1 <i>n</i>	9 MODE	1 <i>n</i>	9 MODE
26		26	
25		25	
24		24	
23		23	
22		22	
21		21	
20		20	
19		19	
18		18	
17		17	
16		16	
15		15	
14	stable	14	stable
13		13	
12		12	
11		11	
10		10	
9		9	
8		8	
7		7	
6		6	
5		5	
4		4	
3		3	
2		2	
1		1	

CHAPTER V

CONCLUSION

5.1. Conclusions

The results obtained from this study show the capability of BLENDER Software to be used in simulating the toppling failure phenomena in nature especially in highways, the following notes were obtained:

- BLENDER Software can be used to simulate the rock toppling failure phenomena due to high positive results obtained from the study.
- While the testing process founded that BLENDER Software is to practice software in this direction of simulating works. It covers all major variables and parameters simply.
- Materials Mass has no significant effects on the results from BLENDER Software and this issue can be controlled easily.
- BLENDER Software is an open-source program and can be obtained easily (Free of Charge).

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