Applied Numerical Modeling in Geomechanics – 2020 – Billaux, Hazzard, Nelson & Schöpfer (eds.) Paper: 14-01

ISBN 978-0-9767577-5-7

Impact on barriers: single rock fall vs. rock mass fall

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1 INTRODUCTION

The estimation of the effects of action as a result of the dynamic impact of rock falls and rock slides is essential for the dimensioning of protective barriers, such as rock fall embankments. In order to realistically calculate impact forces, knowledge of the velocity, the incident angle and the mass of the rock fragment, as well as the interaction between rock fragment and embankment (penetration depths and damping) are of importance. Current approaches providing static equivalent forces are based on empirical relationships (Hofmann & Mölk 2012). Those approaches are limited to the analyses of single block impacts; the dynamic impact of small rock mass falls or rock slides is not considered. In reality, dynamic impact is not always caused by a single block, but often by (sliding or falling) fragmented rock mass.

Until now there is no satisfying reference if and how the impact of rock mass differs from the impact of a single block. Using simple numerical models based on the Distinct Element Method (DEM), the significant differences between the impact of a single block and the impact of fragmented rock mass have been analyzed and evaluated. For this purpose, the programs *UDEC* (Itasca 2011) and *PFC* (Itasca 2014) have been applied.

2 DESIGN AND ANALYSIS

2.1 *Analysis 1: Sliding block vs. Rock slide*

Objective of Analysis 1 was the estimation of the maximum impact force (both, dynamic and static) of a rock slide onto a protective barrier, depending on the number of blocks and their joint spacing. The DEM-codes *UDEC* and *PFC* have been applied using strongly idealized model geometry, as shown in Figure 1. The sliding plane (bedrock) was chosen at a constant angle of 30°. The impact plane (stiff barrier) was defined perpendicular to the sliding plane, at all times (Fig. 1). Comparative calculations have been conducted using rigid blocks. Elastic and plastic deformations are represented by means of contact models.

Elastic deformations were modeled by means of a linear contact model. Plastic deformations were simulated by means of an appropriate damping model. With *PFC*, the viscous damping model was used. With *UDEC*, the Rayleigh damping (proportional to the joint stiffness) was used for the simulation of the plastic deformations. The default local damping, proportional to acceleration, was deactivated for all kinds of block movements. The damping factors used for this comparison have been calibrated equal to a restitution coefficient of 0.45 by means of simulated drop tests.

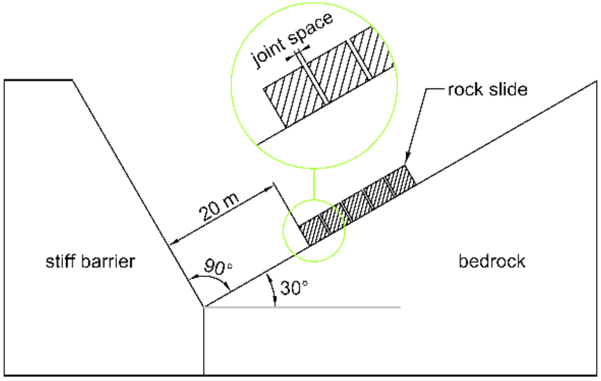

Figure 1. Model used for Analysis 1.

The initial state of the model is shown in Figure 1. A chain of a given number of cubic shaped blocks (in the case of *PFC* spherical blocks) of 1 m³ volume each was released at a constant distance of 20 m from a stiff barrier. The number of modeled blocks was varied between 1 and 30. The joint spacing between the adjoining blocks was varied between 0 and 20 mm. The model parameters used are summarized in Table 1.

Table 1 Parameters used for Analysis 1 and 2.

Model type	Rigid block
Density ρ	2500 kg/m³
Friction coefficient μ	tan 25° = 0.47
Joint stiffness $k_n = k_s$	0.5 GPa/m
PFC Viscous damping: - critical damping ratio $\beta_n = \beta_s$	0.245
UDEC Rayleigh damping (for a block volume of 1 m³): - natural frequency f_{min} - fraction of critical damping ξ_{min}	71.17 Hz (cycles/s) 0.16

2.2 *Analysis 2: Rock fall vs. Rock mass fall*

Objective of Analysis 2 was the investigation of the ratio of the maximum impact force generated by rock mass fall to the maximum impact force generated by comparative single rock fall. The model setup used for the analysis is shown in Figure 2. Both, the geometry and the damping and material parameters (Table 1) are as defined in Analysis 1. An assembly of equally sized discrete blocks was released at varying runout distances of 50 m, 100 m, and 200 m from a stiff barrier. The number of blocks released was kept constant at 1000 blocks. The volume of the equally sized blocks modeled was varied between 0.1 and 10 m³. The black colored block in Figure 2 represents the block position, which was used for the comparative simulations of single rock fall.

3 RESULTS AND DISCUSSION

3.1 *Analysis 1: Sliding block vs. Rock slide*

For the case of directly adjoining blocks (joint spacing of 0 mm), both *PFC* and *UDEC* show an increase of the maximum impact force with an increasing number of blocks (Fig. 3). The increase of the impact force is significantly high between the single block and the five-block-chain. With an increasing number of blocks beyond five, the increase of the impact force is insignificant. For assemblies with a joint spacing greater than zero, the maximum impact force is identical to that of a single block.

UDEC and *PFC* show slightly different results in terms of the amount of the maximum impact force. The reason could be the different damping models used with *PFC* and *UDEC*. Both damping models have been calibrated by means of simulated drop tests. However, this procedure may not be sufficient for the calibration of the Rayleigh damping used with *UDEC*.

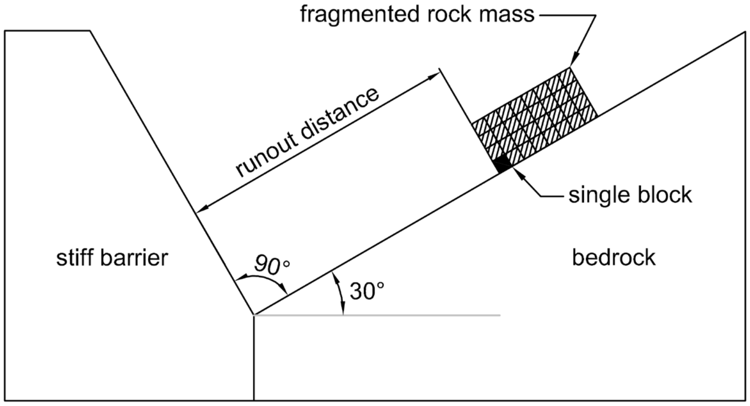

Figure 2. Model used for Analysis 2.

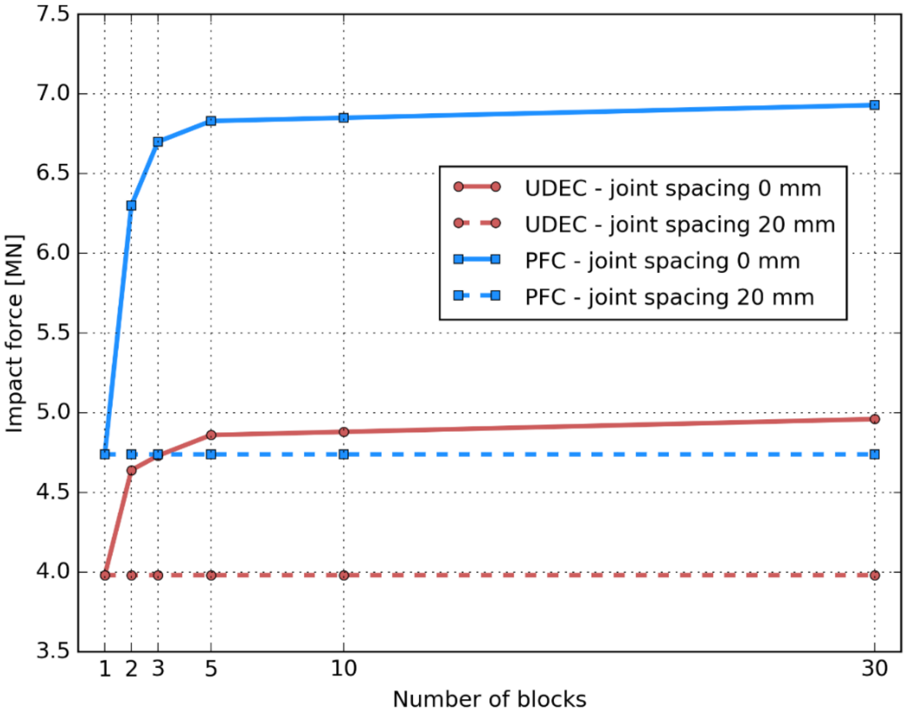

Figure 3. Maximum impact force vs number of blocks.

3.2 *Analysis 2: Rock fall vs. Rock mass fall*

Figure 4 shows the impact force ratio (ratio of the maximum impact force generated by rock mass fall to the maximum impact force generated by single rock fall) as a function of the block volume. Two extreme scenarios have been investigated in terms of rotational velocity, fixed spin and free spin. The analysis shows a dependency of the calculated impact force ratio on the block volume and on the rotational damping (fixed spin and free spin, Fig. 4). The impact force ratio is generally higher with fixed spin. The reason could be in the course of impact force. Figure 5 shows the course of the impact force (left) and the accumulated material at the barrier (right). The runout distance is 50 m. The single block volume is 1 m³ (Fig. 3).

With fixed rotational velocity (Fig. 5A), the block assembly of 1000 blocks moves more or less as a coherent mass. As a result, many blocks hit the barrier simultaneously, creating a higher impact force, abruptly. With free rotational velocity, the moving block assembly behaves like a dry sand-flow. The flow front of the block assembly is becoming thinner with increasing runout. Single blocks are hitting the barrier, successively.

Compared to block volume and rotational spin, the runout distance has minor influence on the impact force ratio. However, Figure 4 shows that the free spin regression line with 50 m runout distance shows a higher impact force ratio than the free spin regression line with 200 m runout distance. Vice versa, the fixed spin regression line with 50 m runout distance shows a lower impact force ratio than the fixed spin regression line with 200 m runout distance. With longer runout distance, velocity and kinetic energy increase, one the one hand. On the other hand, the front of the moving mass thins out and the mass interacting with the barrier is reduced. This thinning-out effect is much higher with free spin.

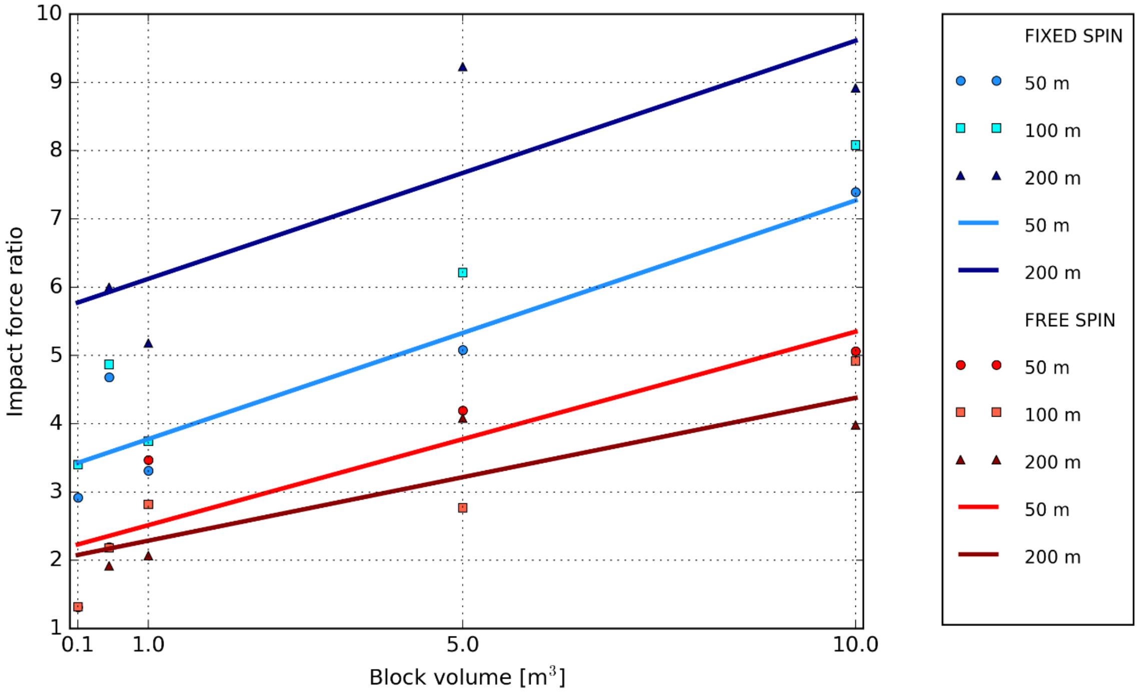

Figure 4. Ratio of the maximum impact force generated by single rock fall and rock mass fall (impact force ratio) for single block volumes of 0.1, 0.5, 1.0, 5.0 and 10.0 m³. The lines for 50 m and 200 m runout distances are regression lines.

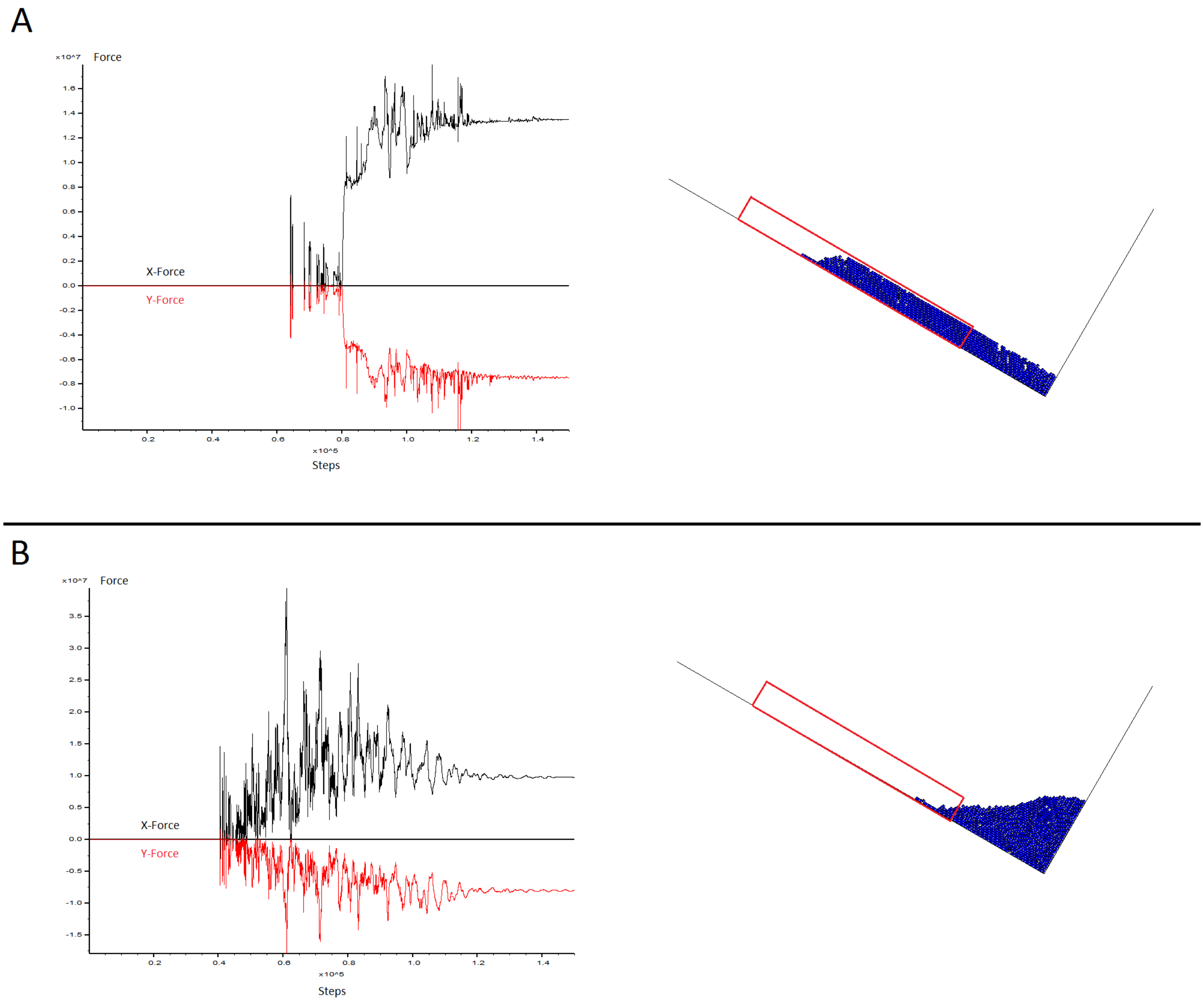

Figure 5. Impact force vs. calculation steps (left) and end position of the released blocks (right) for a runout distance of 50 m and a block volume of 1 m³. The red rectangle indicates the release position of the simulated 1000 rock blocks: A) fixed rotational velocity; B) free rotational velocity.

4 CONCLUSIONS

This study provides the first results of an extensive study with regards to the dynamic interaction of a rock slide and rock fall onto protective barriers.

The results of Analysis 1 indicate that the front part (i.e. the first five blocks) of a rock slide generates 90-98% of the maximum impact force. The effect of the following sliding blocks (beyond five) is negligible. An explanation could be that the first few blocks, after their impact, are acting as a barrier themselves. They take up most impact force of the following blocks.

The results of Analysis 2 indicate that there is a relationship between single rock fall and rock mass fall. It predominantly depends on block volume and rotational damping. Runout distance has a higher effect on the impact force ratio with fixed spin than with free spin.

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