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Stress distribution of rockfall events on galleries

Répartition des pressions d'une chute de pierres sur une gallerie

R. Chikatamarla, J. Laue & S.M. Springman
Institute for Geotechnical Engineering, ETH Zurich, Switzerland

ABSTRACT
Rockfall galleries are built to protect local infrastructure and lifelines against rockfall events. They are covered usually with a soil layer, sometimes for aesthetical reasons but also for protection against impact from rockfalls and snow avalanches. The effect of the impact has been quantified in a research project by investigating the properties of the cover (cushion) material. The stress distribution caused by a rockfall event is measured in centrifuge model tests by means of a tactile multipoint pressure transducer on the gallery below the cushion material as well as point load measurements at supports and strain gauges to determine bending of the gallery slab. The technique of measuring stress distribution under a soil layer is adapted from bio-medicine and the car industry to soil mechanics. Features of these pressure sensors will be discussed in relation to the response to a rockfall event and for different types and thicknesses of cushion material. Numerical modelling has also been carried out using LS DYNA. Knowledge gained can be used for formulation of guidelines for the gallery design.

RÉSUMÉ
Des galeries de protection sont construites pour protéger les infrastructure et les voies de ravitaillement contre les chutes de pierres. Elles sont habituellement recouvertes d'une couche de sol, parfois pour des raisons esthétiques mais aussi pour la protection contre les impacts dus aux chutes de pierres et aux avalanches de neige. L'effet de l'impact a été mesuré dans un projet de recherche en étudiant les propriétés du matériau de couverture (coussin). La répartition des pressions dues à une chute de pierres est mesurée dans des essais sur maquette en centrifuge à l'aide d'un capteur de pression multipoint tactile sur la galerie en-dessous du matériau amortisseur ainsi que par des mesures ponctuelles de charge sur les appuis et des capteurs de déformation pour déterminer la flexion du toit de la galerie. La technique de mesure de la répartition des pressions sous une couche de sol a été adaptée de la bio-médecine et de l'industrie automobile à la méchanique des sols. Certaines propriétés de ces capteurs de pression seront discutées par rapport à la réponse à une chute de pierres pour différents types et épaisseur du matériau d'amortissement. Une modélisation numérique a aussi été effectuée en utilisant LS DYNA. Le savoir gagné peut être employé pour l'élaboration de directives pour la conception des galeries.

1 INTRODUCTION

Rockfalls are one of the most prevailing natural hazards in the mountainous regions. Concrete protection galleries are used to safeguard the local infrastructure and life-lines against these potential rock impacts. Protection galleries have to be designed to take the high impact energy of the falling rock boulders, generally in the range of up to million joules (Fig. 1). Cushion materials can be used for effective dissipation of energies, thereby reducing the impact on the protection gallery. The design of the gallery is dependent upon the foreseen impact force and the corresponding penetration depth of the falling rock into the cushion material.

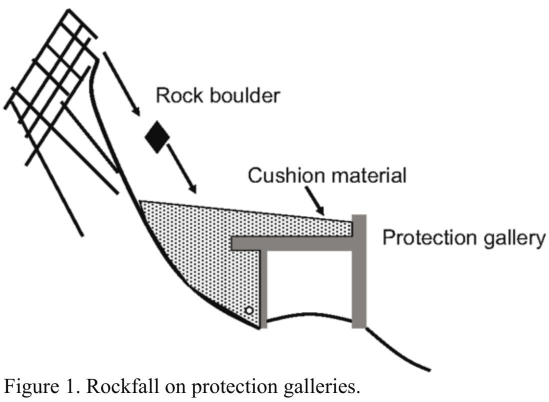


Figure 1. Rockfall on protection galleries.

According to Swiss guidelines for design of protection galleries, the force of impact and the penetration depth is dependent upon the mass and size of the rock, impact velocity, and physical and geotechnical properties of the cushion material (Jacquemoud, 1999).

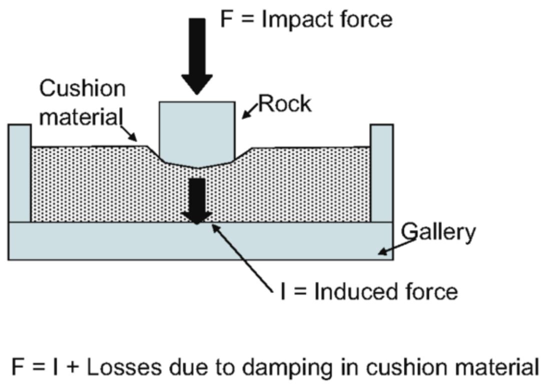


Figure 2. Forces acting on the gallery.

The design method on the basis of maximum load of the rock impact results in over-dimensioning of the gallery. This is not realistic and tends to be a conservative method of design and thereby increases the cost of construction. Hence, determination of stresses induced in the gallery is vital in the efficient design of the gallery. This paper focuses on determination of stresses induced in the gallery due to the rock impact investigated in a centrifuge with the help of tactile based pressure sensors.

2 CENTRIFUGE TEST-SETUP

The high rock impact energies are very difficult to achieve in 1g small-scale tests in the laboratory (Montani, 1997), and full-scale field tests are generally very expensive. Higher energies can be achieved at a model scale in the laboratory by rotating the model in a high g field and increasing its unit weight. The protection gallery, with cushion material laid on it, is modelled using a Geotechnical Drum Centrifuge (Springman et al., 2001) together with the rockfall event.

The principle of the centrifuge is to keep the stress levels in the model and prototype equal by reducing the model size by n and increasing the gravity value n times. Appropriate scaling laws (Schofield, 1980) have been extended as needed (Chikatamarla et al., 2005). Modelling the event at high gravity helps in better representation of the impact energy in the determination of the stresses induced in the gallery and in understanding the behaviour of the cushion material. The setup of the centrifuge is shown in Figure 3 for this investigation, with models in two diametrically opposed strong-boxes. These are located inside the rotating drum and mounted on a support plate.

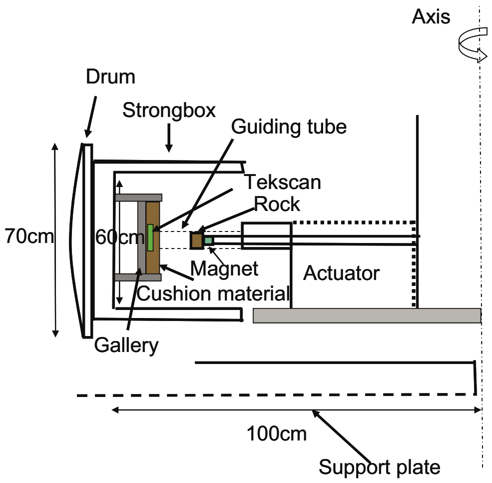


Figure 3. Centrifuge test set-up.

In the centrifuge tests, the steel cylinder will be guided through an aluminium guiding tube to fall onto the cushion material under increased gravity level. A guided tube is used to keep the rock in the g-field. Materials have been chosen to represent the prototype conditions. An aluminium plate is used for modelling the concrete slab by comparing the bending stiffness of the materials using the scaling laws.

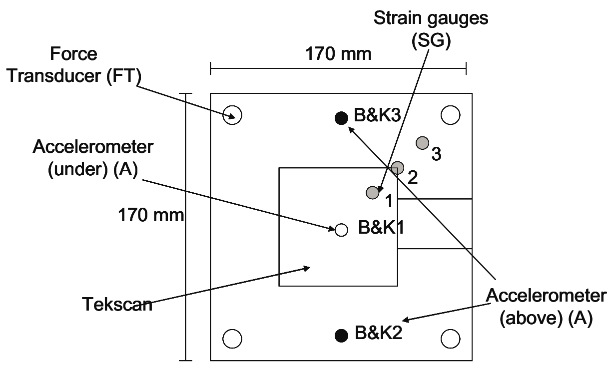


Figure 4. Measuring set-up.

Instrumentation mounted on the aluminium slab is shown in Figure 4. Three accelerometers (A) are placed one below (centre) and two on the top of the slab. The force transducers (FT) placed under the four corners of the slab also act as supports.

The strain gauges (SG) are placed diagonally to get the strain values across the span width. Bending of the aluminium plate is calculated using these strain gauge values, assuming the slab to be a simply supported beam (Birchmeier, 2003). An accelerometer is placed inside the rock to obtain the deceleration record for the rock during the impact. This value is used to calculate the impact force. The first and second integration of the accelerometer values gives the velocity and penetration of the rock into the layer respectively. A Tekscan pressure sensor (pad) (Tekscan 1992; Springman et al., 2002) is placed between the aluminium plate and cushioning soil layer. The Tekscan sensor records the impact distribution of the load and also the path traced by the rock on the cushion material after the impact.

3 PRESSURE SENSORS

The "pads" consist of a matrix based tactile sensor with a thickness of 0.1 mm. A sensing cell area of approximately 0.76 mm x 0.76 mm at about 1.58 mm centre to centre was chosen for these tests. In total a chosen pad consists of 1936 sensels. The maximum appropriate normal stress or pressure range (the highest being 175 MPa) must be selected to achieve optimum resolution. This range is divided into 256 compartments, and reported on a scale of 0-255.

3.1 *Calibration*

The goal is to be able to create known normal stress conditions at each sensing cell location to calibrate the system. This is quite a challenge because of the irregular boundary conditions created in granular media. Response under a combination of normal and shear stress must be investigated to ensure that the measurement of normal stress remains unchanged.

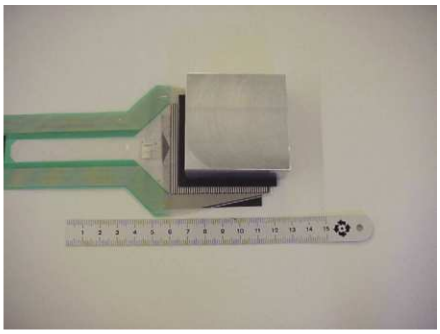


Figure 5. Calibration set-up for the Tekscan sensor system.

The calibration is conducted with a simple load system that contains two 56 mm x 56 mm x 20 mm polished aluminium plates and two rubber pads (0.1 mm thick). The size of all these elements represents the area of the sensor exactly, which is placed between the aluminium plates and loaded with weights or a press. The rubber pads are intended to provide an even pressure distribution and ensure every sensor cell will be loaded to the same degree.

Laboratory and centrifuge calibration tests were carried out to confirm repeatability in the short and long terms and as a function of loading rate and steady state load applied. The influence of temperature is also investigated to understand the affect on the conductive properties of this transducer.

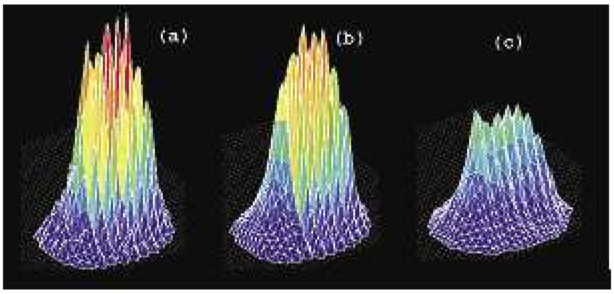


Figure 6. Results processed by an averaging function. (a) Peak impact distribution, (b) averaged impact distribution 1, (c) averaged impact distribution 2.

Figure 6 shows the same hammer test but with an area processed 3D plot to cut off the singularities. The software provided by the manufacturers offers two different methods of averaging. Paikowsky & Hajduk also found that, after due consideration of all of these effects, the errors for pressures < 15% of maximum range were greater than ±10%. The errors fell within ±10% for pressures greater than this percentage of maximum

3.2 *Measurements from pressure sensors*

Rockfall tests were done for different g-levels and falling heights. Results are shown in Figure 7 for the case of 60g, 80 mm fall height (1.25 MJ) with three different thicknesses of sand layer as a cushion material.

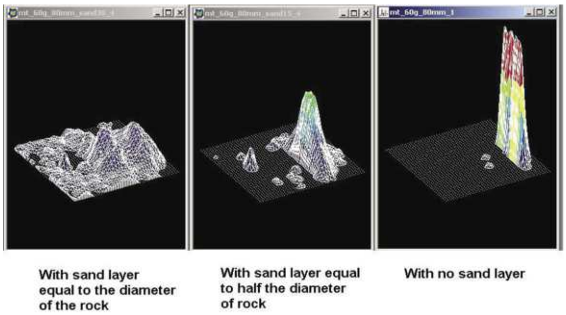
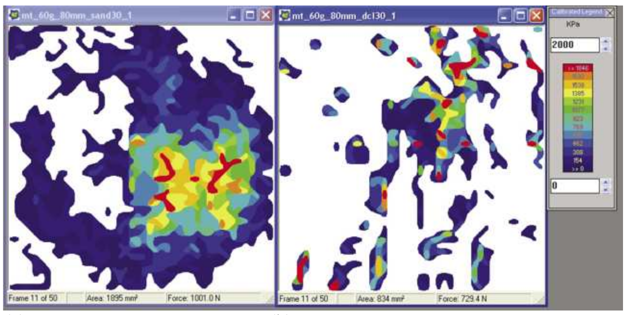


Figure 7. Tekscan picture for three different thicknesses of sand for the case of 60g and 80 mm fall height (1.25 MJ).

The peak values of cell pressure decrease and the distribution becomes more spread as the thickness of the cushion material is increased. Hence the stresses induced in the gallery and supports are significantly lower.

Tekscan pressure sensors also help in understanding the contact stresses between the cushion material and the gallery. Figure 8 shows sand (d_{50} = 0.1 mm) and clay lumps (d_{50} = 7 mm) as cushion materials for the case of 60g and 80 mm fall height.



(a) (b)

Figure 8. The contact points of materials (a) sand and (b) clay lumps on the pressure sensors for the case of 60g and 80 mm fall height (1.25 MJ).

It is clearly seen that the contact is evenly distributed in case of sand as compared to the clay lumps. The total distributed load is also higher in case of sand as compared to the clay lumps due to the higher energy dissipation time of the clay lumps. An attempt was made to use a lightweight, industrial waste material as a cushion material on the protection gallery. A sand-rubber (SR) mixture and a sand-sawdust (SS) mixture, with 80%-20% weight ratios have been chosen. The use of the lightweight mixtures also reduces the dead weight of the material on the gallery significantly. The weight of SS mix used was only 10% as that of pure sand (S), which is one of the most widely used fill materials. Figure 9 shows the impact distribution of rock on sand (S), SS mix and SR mix for the case of 60g and 80 mm fall height (1.25 MJ).

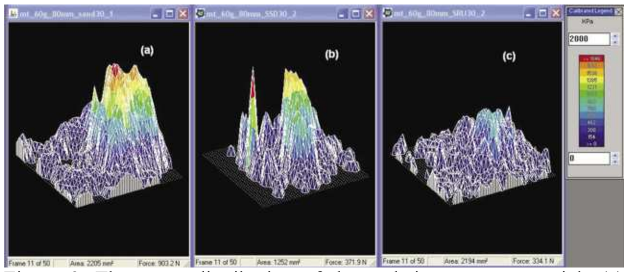


Figure 9. The stress distribution of the rock impact on materials (a) sand, (b) sand 70% - sawdust 30% and (c) sand 70% - rubber 30% for the case of 60g and 80 mm fall height (1.25 MJ).

The path of the rock after the impact can be traced with the movement of the centre of gravity of the rock in contact with the cushion material can be recorded. This feature helps to understand the bouncing of the rock and the response of the gallery to the rock impact. Figure 10 shows the path traced by the rock on rubber, sand and sawdust for the case of 20g and 20 mm fall height. Movement of the rock after impact was least in case of the sand as it is less elastic than the other two materials.

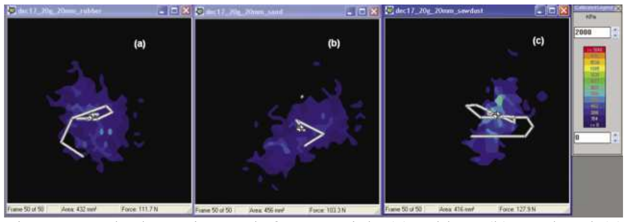


Figure 10. The bouncing path for materials (a) rubber, (b) sand and (c) sawdust for the case of 20g and 20 mm fall height.

4 NUMERICAL MODELLING

Numerical modelling was done using the FE program LS-DYNA (LS-DYNA, 2003). LS-DYNA is a general-purpose FE code for analyzing the large deformation dynamic response of structures, including structures coupled to fluids. The main solution methodology is based on explicit time integration.

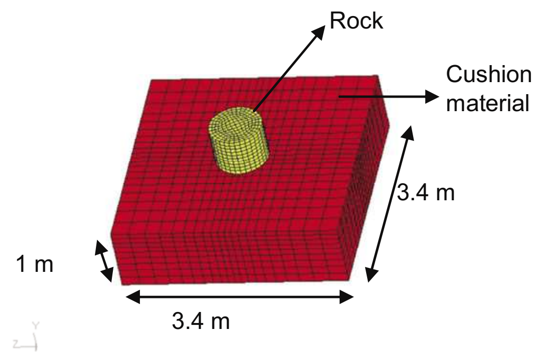


Figure 11. Numerical test set-up.

The model set-up in the pre-processing unit is shown in Figure 11. The basic 3D model consists of a rock and sand layer with appropriate boundary conditions. The sand layer is fixed on four sides with one degree of freedom in the vertical direction, and at the bottom it is fixed in all directions. The soil layer is modelled as linear-elastic / perfectly plastic using the material model “MAT_SOIL _AND_FOAM” (MSF), and “MAT_RIGID” is used for the rock as it is considered to behave as a rigid material. MSF has a perfectly plastic yield surfaces, and no strain hardening (LS-DYNA, 2003). The results shown are for sand. The values of the materials parameters are taken from laboratory tests carried out by Frey (2003).

5 RESULTS AND COMPARISON

Figure 12 shows the comparison of stress distribution values using Tekscan and LS-DYNA. Similar input conditions were used for the numerical calculations as in the centrifuge test. LS-DYNA allows only the stress distribution of each element and not a spatial distribution of the stress over the entire gallery. An element directly under the rock impact influence area has been considered for the comparison. The Tekscan “screen grab” shows the stress distribution for the case of 40g and 80 mm fall height. The average value of the stress is about 0.1 MPa under the rock impact area. For the same input conditions the numerical calculation results in the value of 0.17 MPa.

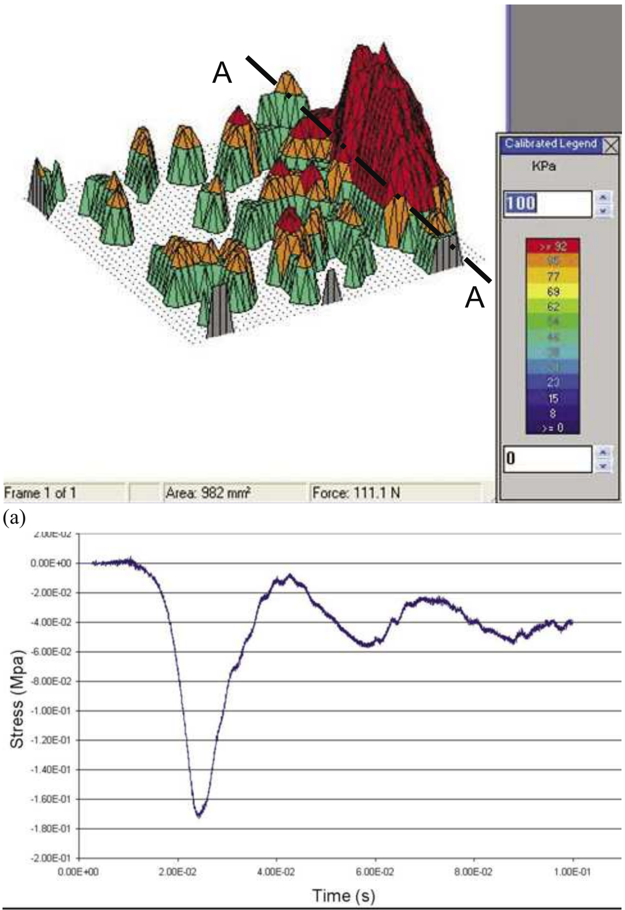


Figure 12. Comparison of stress distribution of rockfall for the case of 40g and 80 mm fall height for using (a) Tekscan and (b) LS-DYNA (section A-A).

The difference in the values can be attributed to the lower sample rate of the tekscan measurements and the stiffer boundary conditions of the numerical model.

6 CONCLUSIONS

The use of flexible tactile pressure sensors is an exciting and promising measurement technique for a wide range of geotechnical investigations in the laboratory. Special challenges relate to calibration of the base stress level and the interface conditions. Load rate, load holding, creep and hysteresis effects may be problematic under high g levels in the centrifuge. Results presented in this paper show the potential of these transducers for measuring normal stress distributions. The comparison between the Tekscan and numerical results are positive.

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