ADVANCED NUMERICAL MODELLING OF GEOGRID-REINFORCED ROCKFALL PROTECTION EMBANKMENTS

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Currently, empirical or simplified analytical methods are used to design such embankments. In order to assess behaviour of rockfall protection embankments in more detail, Opus carried out 3D numerical simulation using the finite element software ABAQUS. In the simulation process rock blocks were thrown onto a geogrid reinforced embankment at different impact angles. The effects of geogrid spacing, the presence of the steel facing mesh and impact angle have been investigated. The numerical simulation procedure can be used to develop and optimise the design of geogrid-reinforced rockfall protection embankments.

Keywords: rockfall protection, embankment, finite element modelling, geogrid.

Introduction

Rockfall can occur from natural sources, such as unmodified hillsides or relict sea cliffs, and man-made features including road cuttings and mines. These rockfalls can be instigated through a wide variety of triggers (e.g. weathering, frost-jacking, seismic activity and blasting). Away from the built environment and its supporting infrastructure, rockfall poses little more than an interesting study of natural process and its risk is generally accepted as part of the natural evolution of the environment. However, the interaction of rockfall with built elements at risk (e.g. residential settlements, businesses, highway infrastructure and rail corridors) frequently causes significant threats, typically in terms of structural damage, loss of life, financial cost and service disruption. As the availability of low-risk sites suitable for development become pressured, areas at greater risk from rockfall are increasingly considered as viable options. Geogrid-reinforced rockfall protection embankments provide effective mitigation against rockfall hazard. However, currently there are no commonly accepted design methods for the rockfall protection embankments. The most advance design technique involves the use of numerical modelling. Opus utilised 3D numerical modelling to investigate the behaviour of the rockfall protection embankments under the impact of rock blocks with high kinetic energies. The design methodology for rockfall protection embankments is described in this paper.

Recent rockfalls in Christchurch

The magnitude 7.1 Darfield Earthquake of 4 September 2010 was centred approximately 40 km west of Christchurch city centre at an approximate depth of 30 km and caused significant structural and land damage. Whilst some rockfalls were recorded as a result of the earthquake, these were generally confined to localised features and areas and their resulting damaging effects were limited, primarily due to the softer ground conditions (typically encountered at the end of the winter) limiting run-out paths. The magnitude 6.3 aftershock of 22 February 2011 generated far greater levels of rockfall. In the Port Hills to the south and east of Christchurch city centre, a total land area of about 65 km^2 was affected by rockfall, stretching from Mount Pleasant in the north, Lyttelton in the south, Godley Head in the east and to Governors Bay in the west. Examples of 22 February 2011 rockfall damage are shown on Fig. 1.

Increased levels of rockfall were largely attributable to the exceptionally high Peak Ground Accelerations (PGAs) in both the horizontal and vertical planes. PGAs of 2.1 g (horizontal) and 2.2 g (vertical) were recorded at Heathcote Valley, the approximate epicentre of the aftershock. In addition to the high PGAs, the dry ground conditions encountered at the time of year (late summer) will have further exacerbated the impact of triggered rockfalls resulting in unusually long run-out distances, especially when compared to those of the initial Darfield earthquake. Damage and disruption caused by the rockfalls was widespread. Transportation infrastructure, businesses and residential dwellings were all affected. For residential dwellings alone over 120 individual dwelling (or ancillary building) rockfall impacts were mapped. Many thousands of individual seismically triggered fallen boulders were mapped across the region, enabling the generation of a unique and comprehensive dataset. Mapped boulder sizes were widely varied. However, the average and the 95th % percentile boulder volume values have been reported as approximately 1.0 m^3 and 3.0 m^3 respectively.

Significant numbers of seismically triggered boulders coupled with their comparatively large volumes, high coefficients of restitution of the dry ground encountered along their run-out paths and mode of travel (significant angular rotation) culminated in a multitude of high total kinetic energy boulders, even over the lower sections of the Port Hills slopes. Resulting levels of damage to the built environment caused by individual rockfall boulders were in many cases localised but considerable.

Fig. 1. Seismically triggered) rockfall boulder resting on a block wall having passed dwelling, Morgans Valley, 22 February 2011, Christchurch (left); Impact damage to a house due to seismically triggered rockfall boulder, Morgans Valley, Christchurch (right)

Methods of mitigating rockfall

Physical options for mitigation of rockfall can be broadly broken down into passive and active systems, both with an element of at-source treatment (scaling). Active systems generally require retention of the unstable rockmass at source by mechanical means. Such systems often include combinations of rock bolts, high strength steel mesh, cables and concrete. With active systems, successful mitigation relies upon all potential sources being treated. Quite often this treatment needs to be carried out in hazardous construction conditions. In many cases maintenance and long-term durability issues make this option less attractive compared to passive systems. Passive systems rely upon the optimal placement of a downslope system that arrests the rockfall before impacting the element at risk. To effectively select, correctly size and place passive systems a careful blend of assessment, analysis and judgement is required. Typical examples of passive rockfall mitigation systems include dynamic and non-dynamic catch fences, attenuators, catch ditches, rock sheds and embankments (or bunds). Ultimately the selection of passive systems is governed by a number of factors that include the available construction envelope, site access, hill-slope geometrics, maintenance requirements, long-term durability and anticipated design loading (total kinetic energy and number of rockfall impacts).

For the majority of the Port Hills, the rockfall threat (based upon the observed occurrences during the 22 February 2011 aftershock) is primarily from seismic events triggering widespread releases, resulting in multiple boulders travelling down-slope with large total kinetic energies.

Passive systems in the form of Mechanically Stabilised Earth (MSE) embankments have been used in New Zealand and elsewhere to mitigate the rockfall hazard in environments similar to Port Hills. MSE embankments (including geogrid-reinforced fill embankments) are able to withstand multiple impacts of rockfalls with high total kinetic energies and can be relatively easily repaired.

MSE rockfall protection systems are cost-effective and have a considerable design life. A substantial disadvantage of this rockfall protection system is the need to have an appropriate stable site for the construction of the rockfall protection embankments.

Rockfall protection embankments

For sites where multiple impacts of rockfall with high kinetic energy levels are expected, MSE rockfall protection embankments present a reliable cost-effective method of mitigating rockfall hazard. Examples of such structures are shown on Fig. 2.

Geogrid-reinforced embankments are widely used for mitigating rockfall hazards. Methods used for the design of the geogrid-reinforced rockfall protection embankments vary from country to country.

Available design methods have been summarised by Lambert &Bourrier, (2013) and include:

- A simplified design method based on consideration of the mass of the embankment and its ability to withstand the impact;
- A simplified method based on consideration of penetration of the rock block into the embankment and assigning the minimum thickness of the embankment that will provide appropriate safety margin;
- Pseudo-static design approach that considers a load that is statically equivalent to the dynamic impact load, where the embankment's static stability is checked using commonly accepted design methods;
- Analytical design methods based on the comparison of the incident translational kinetic energy of the block with the energy dissipated within the embankment during the impact; and,
- Design methods based on numerical modelling to model the impact and assess the

Fig. 2. Rockfall protection embankments in Europe: 12 m high rockfall protection embankment, Italian Alps (left); end section of a rockfall protection embankment near Mont Blanc Tunnel (right)

deformation of the embankment using either finite element method or discrete element methods.

In most of countries currently there are no recommendations or guidelines for the design of rockfall protection embankments. In Italy and Austria design standards have recently been developed and published (UNI, 2012; ONR, 2012). While simplified methods are being widely used in the current design practice, numerical modelling based on non-linear soil models and consideration of dynamic effects provides a more advanced design tool capable of detailed analysis of the stress-strain condition of the embankment, energy dissipation mechanisms and optimisation of the design of rockfall protection embankments. Currently design methods based on numerical modelling are becoming more attractive to the geotechnical designers as a large number of finite element software products are available on the market.

Numerical modelling of geogrid-reinforced rockfall protection embankments has been used for the analysis of the full scale tests data in Italy (Peila et al., 2007) and Japan (Maegawa & Van, 2011), and the numerical modelling method has been calibrated against the field test data and adopted soil models and design assumptions have been verified. In both cases (Peila et al., 2007; Maegawa & Van, 2011) the modelled behaviour of the embankments under the impact of a rock block matched the field test data reasonably well, indicating that numerical modelling provides an effective design tool that can be used in practical engineering.

Principles of numerical modelling of rockfall protection embankments

In our analysis we modelled rockfall events using ABAQUS software. ABAQUS is a general purpose highly sophisticated finite element (FE) computer program that can be used to solve a variety of engineering and research problems. It is especially suited for nonlinear finite element analysis and is widely used in engineering and academic environments. ABAQUS enables modelling of static and dynamic problems with a high level of detail. Numerical simulation of the free fall of a rock block in ABAQUS can be carried out using two different methods:

- the rock block can be modelled at its initial drop height and ABAQUS can calculate the full motion of the block under the influence of gravity, or alternatively,
- the rock block can be modelled at a position near or very close to the soil surface with a certain mass and predefined initial impact velocity to simulate the impact.

The first option is less practical because of the large number of time increments required to complete the free fall analysis. We utilised the latter method to model the impact of the rock block on the embankment. In our analysis we used *RocFall* software to determine the striking speed, the direction of the rock block movement and the location of the impact. *RocFall* is a statistical analysis program designed to assist with assessment of slopes exposed to risk of rockfalls. Energy, velocity and “bounce height” envelopes for the entire slope are determined by *RocFall*, as well as the location of the impact. Distributions of energy, velocity and bounce-height are also calculated along the slope profile. Distributions can be graphed and comprehensive statistics are automatically calculated. Slope geometry and ground conditions that govern the coefficient of restitution should be defined to assess the direction and kinetic energy of the rock block.

Deformation of the embankment upon impact of a rock block depends on many variables. Some play a major role, while others have a minor effect. For example, the coefficient of friction between the embankment surface and the block, the Poisson’s ratio of the soil, and the mechanical properties of the rock are considered to have negligible effect. On the contrary, dimensions of the rock, impacting velocity of the rock, deformation and strength properties of the soil, friction between the geogrid and the soil and the size of the embankment play a major role in its response. In our analysis we did not consider the rotational kinetic energy of the rock block as it is generally less than 10–15 % of the total block energy (Chau et al., 2002). However, the rotational effects can be modelled in ABAQUS if required.

The ABAQUS modelling process involves building a model, defining material properties, introducing the finite element mesh, applying loads and boundary conditions, and running the analysis. Similar to Peila et al. (2007), our numerical algorithm was based on an explicit time integration known as “centred difference method”. The simulation computation was divided into up to 40 time steps, and foreach step, the instant displacement, speed and acceleration of each element of the FE mesh were evaluated. The ground was modelled using three-dimensional cubic shaped blocks with eight integration nodes.

Material properties were assigned using the ABAQUS property module. The soil embankment, the geogrids and the welded facing steel mesh were modelled as deformable materials. The rock block was modelled as rigid body. The geogrid and the facing steel mesh were modelled as elastic shell layers. The embankment material was modelled using elasto-plastic Mohr-Coulomb model. The soil, geogrid, rock block and steel mesh parameters used in the numerical simulation are given in Table 1. The size of the rock block in our analysis was chosen to approximately represent the 95th % percentile boulder volume value during the 22 February 2011 Christchurch earthquake. Also, we adopted a rock block speed representing a possible rock block speed in accordance with *RocFall* analysis for 22 February 2011 Christchurch earthquake.

The geometry of the analysed embankment and the rock block, as well finite element mesh and a typical image of the crater created by the rock block are shown on Fig. 3. The length of the analysed section of the embankment was chosen based on a number of initial numerical simulations that identified the minimum distance to the edge boundaries where the boundary conditions had minor effect on the stress-strain state at the impact location. The adopted crest width of the embankment was 1 m, and the adopted angle of the batter slopes to the horizontal was 60°. The geogrid layer spacings of 0.5 m and 1 m were analysed. Effect of the presence of the facing steel mesh was also analysed.

For the analysis of a typical impact, the rock block was thrown into the middle section of the modelled embankment (Fig. 3, left). For the analysis of the effect of the impact’s proximity to the end of the embankment, the rock block can be thrown at the edge of the embankment (Fig. 3, right).

Modelling results

Numerical simulation was carried out for striking angles of –30°, 0° and +30° (positive angles correspond to the downward movement of the rock block). The total displacement contours within body of the

Table 1

Soil, geogrid and rock block parameters

Geotechnical parameters	Soil	Geogrid	Rock Block	Steel Mesh
Unit Weight, kN/m^3	19	0.0042 (kN/m^2)	24	78.5
Young’s Modulus, MPa	120	200	Rigid body	200×10^3
Poisson’s Ratio	0.3	0.3	Rigid Body	0.3
Friction Angle, degrees	32	2/3 (tan ϕ) (geogrid-soil contact)	As for the soil (block – soil contact)	2/3 (tan ϕ) (geogrid-soil contact)
Cohesion, kPa	2	0 (geogrid-soil contact)	0 (block – soil contact)	0
Striking speed, m/s			28	
Size, m			1.5×1.5×1.5	

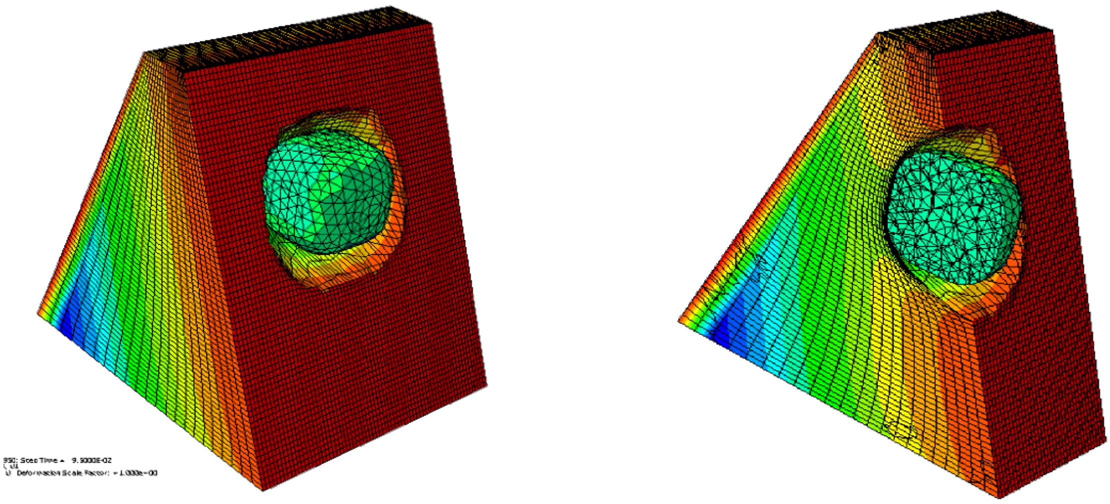

Fig. 3. Analysed rockfall protection embankment (image from ABAQUS): typical impact (left); impact at the end of the embankment (right)

embankment from ABAQUS outputs are shown in Fig. 4. It can be seen that the depth of crater and the displacements depend on the striking angle of the rock block and reach their maximum values at the striking angle of 30°. This is explained by the fact that the proportion of the frictional dissipation energy is substantially higher for the striking angle of –30°, compared to the case with the striking angles of 0° and + 30° where plastic deformation penetrates substantially deeper into the body of the embankment (Fig. 4).

The effect of the spacing of the geogrid layers on the behaviour of the embankment have been also investigated (Fig. 5). Numerical simulations were carried out for the striking angle of +30°. The modelling data indicated that the strengthening effect of closer spaced geogrid layers can be adequately modelled by ABAQUS enabling the designer to optimise the design of the geogrid-reinforced soil embankment and to achieve cost savings on the imported fill and amount of geogrid.

Our analysis of the embankment with and without the facing steel mesh (Fig. 6) indicated that while the shapes of the crater created by the rock block for the two cases are substantially different, the effect of the presence of the steel mesh on the overall performance of the embankment is relatively minor, which agrees well with the test data published by Peila et al. (2002).

ABAQUS also enables the designer to predict the single impact energy and the number of lower energy impacts that will cause the failure of the embankment.

Conclusions

Rockfalls pose a major hazard to infrastructure, commercial buildings and residential dwellings in hilly and mountainous regions throughout New Zealand. The magnitude 6.3 Christchurch earthquake of 22 February 2011 generated substantial levels of rockfall and resulted in damage to infrastructure and residential dwellings. For sites where multiple impacts of rockfall with high kinetic energy levels are

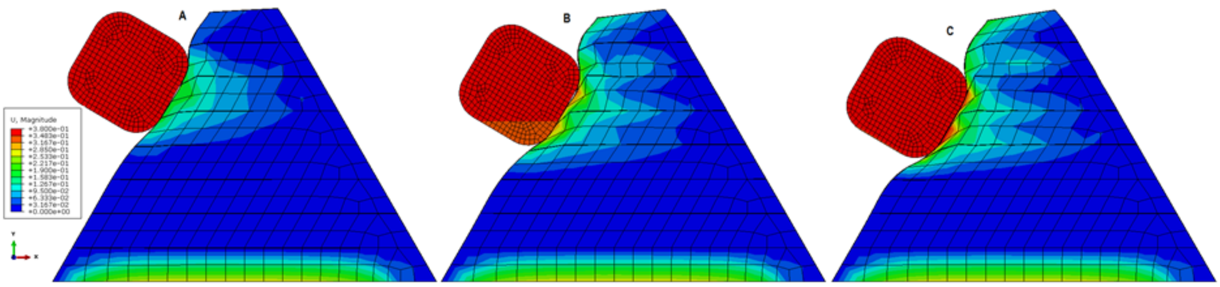

Fig. 4. Total displacement for striking angles of –30° (A), 0° (B), and +30° (C)

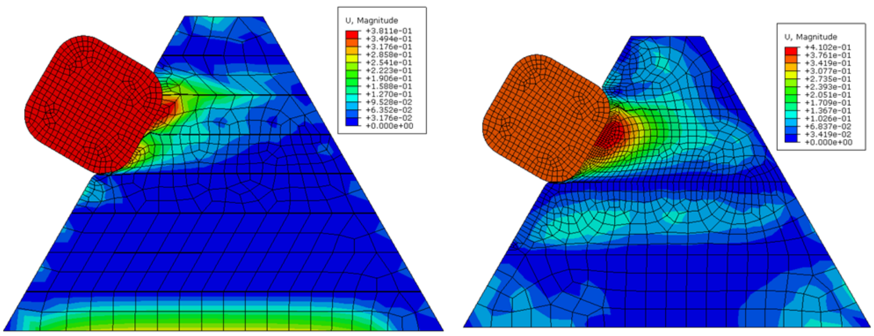

Fig. 5. Total displacements from ABAQUS outputs for geogrid spacing of 0.5 m (left) and 1 m (right)

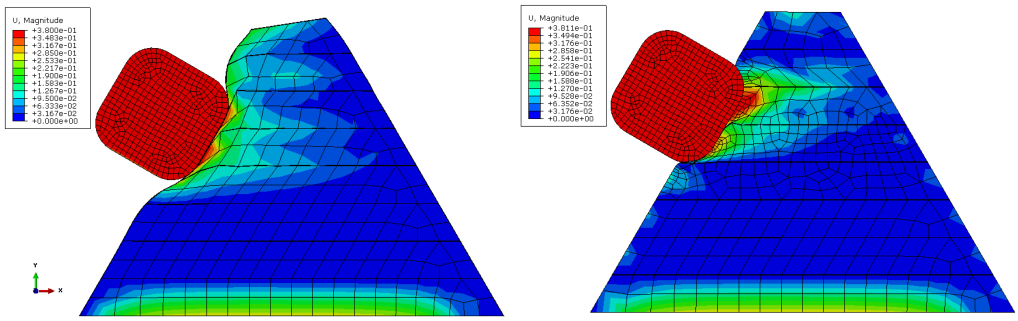

Fig. 6. Total displacements from ABAQUS outputs for the embankment with the facing steel mesh (left) and without the facing steel mesh (right)

expected, geogrid-reinforced rockfall protection embankments present a reliable cost-effective method of mitigating rockfall hazard. While a number of simplified design methods for rockfall protection embankments are available, advanced numerical modelling gives the designer an opportunity to analyse various load cases, to optimise the design and achieve cost savings where possible.

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СОВРЕМЕННОЕ ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ДАМБЫ, УКРЕПЛЕННОЙ ГЕОРЕШЁТКОЙ, ДЛЯ ЗАЩИТЫ ОТ КАМНЕПАДА

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В настоящее время для проектирования подобных дамб применяют эмпирические или упрощенные аналитические методы. Компания Opus осуществила трехмерное численное моделирование с помощью программного метода конечных элементов ABAQUS с целью детального изучения принципа работы защитных дамб. В процессе моделирования на дамбу, укрепленную георешёткой, сбрасывали каменные блоки под разным углом падения. В статье было проанализировано влияние шага георешётки, наличие ячеек со стальной поверхностью и угол падения. Метод численного моделирования может быть использован для разработки и оптимизации проектирования защитных дамб, укрепленных георешёткой.

Ключевые слова: защита от камнепада, дамба, моделирование с применением метода конечных элементов, георешётка.

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