Summary of World Wide Rockfall Tests

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There are two principal methods of analyzing and evaluating rockfall. One method is to perform field tests that involve the initiation of controlled rockfall events. The second employs mathematical models to produce computer simulations that represent the mechanics and outcomes of the rockfall processes. The value of predictions produced by these programs depends significantly on their calibration to observed responses of falling rocks under well-defined, real-world conditions. Therefore, the ultimate success of both methods depends greatly on the accuracy of data gathered during actual field rock-rolling trials. Since the 1960s there have been over 15,500 rocks rolled. Many of these rock-rolling tests occurred in Canada, France, Italy, Japan, Peru, Switzerland, Taiwan and the USA (Arizona, California, Colorado, North Carolina, Oregon). These field-trial tests collected different data; some to calibrate computer models or to determine the degree of hazard associated with rockfall and others to test the capacity or utility of specific rockfall protection measures. In many cases, field-test experiments were conducted with multiple objectives. This paper attempts to summarize rockfall testing where rocks were rolled down a slope, tumbling, falling and spinning.

1 INTRODUCTION

There are two principal methods of analyzing and evaluating rockfall. One method is to perform field tests that involve the initiation of controlled rockfall events and then to observe and document the behavior of the falling rocks. A series of field-test experiments at different locations permits the assessment of responses of falling blocks to varying slope characteristics. The second method employs mathematical models to simulate the mechanics of the rockfall processes. The value of predictions produced by these programs depends significantly on their calibration to observed responses of falling rocks under defined real-world conditions. Therefore, the ultimate success of both methods depends greatly on actual field rock-rolling trials. Many variables may be evaluated during a field trial, but the significance of several variables depends upon the primary purpose of the evaluation. The field-trial procedures may collect different data if the purpose is to calibrate computer models, or if the purpose is to specify proposed rockfall protection measures. In many cases, field-test experiments are conducted with multiple objectives. To date over 15,550 rocks have been rolled and analyzed (Fig. 1). This paper attempts to summarize rockfall testing where rocks were rolled down a slope, tumbling, falling and spinning.

2 HISTORY

Prior to the 1960s there is no record of rock rolling testing. Avalanche protection can be dated as far back as 1518 but the development of rockfall protection presumably developed from about 1834, i.e. the beginning of railway construction. Although many geotechnical issues were studied rockfall was not singled out and not recognized as a discipline for study. Instead up until the 50s rockfall protection relied primarily on railway specific measures as precaution against rockfalls (Spang & Bolliger 01).

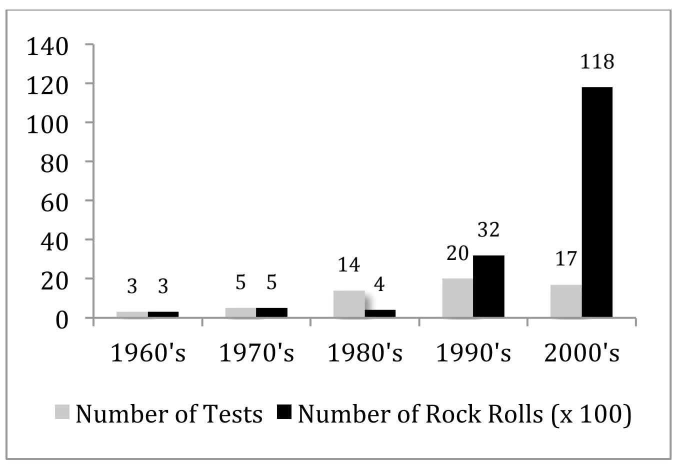

Figure 1: Number of rock rolling tests and number of rock rolls over the last 50 years.

3 THE SIXTIES

Beginning in the 1960s comprehensive rock-rolling testing was born. While the exact numbers are lost in time it is estimated that well over three hundred rocks were rolled and studied during the 60s.

In the early 1960s Arthur M. Ritche of Washington State Department of Transportation performed one of the first comprehensive tests where rocks were rolled, filmed, and analyzed (Ritche 1963). The tests were primarily aimed at evaluating catchment width criteria but many rocks were rolled into barriers for evaluation. During this landmark study Ritchie rolled hundreds of rocks on various highway and quarry slopes. The empirical rockfall trajectory charts and tables developed by Ritchie enabled designers for the first time to select the appropriate depths and widths of catchment ditches in combination with fences relative to the actual slope inclination and height. Although there have been subsequent studies on the subject, the Ritche Criteria is still used today around the world.

Concurrently in Japan rock rolling experiments were performed at the Iwanaicho Thunder Cape test site in 1961 and at the Kobe test site in 1968 (Usiro et al. 2003). The purpose of these tests was to study rockfall trajectories.

In 1968 the BLS Railway Company together with Brugg Cable Company performed flexible barrier tests in Lotschberg, Switzerland, measuring a 10-kilojoule impact. This was the first time on record a rockfall impact in a barrier was measured (Spang & Bolliger 01).

4 THE SEVENTIES

The 70s enjoyed some very ambitious rock rolling tests performed with the purpose of analyzing large rock trajectories, verifying particles in motion for computer modeling, and evaluating the effectiveness of mitigation measures. Over 500 rocks were rolled and analyzed with an increased effort in measuring velocity and energy.

Broili (1973) studied the trajectory of a 10 m^3 rock with an estimated weight of 26,308 kg. The rocks, dislodged from a bluff on Mount St Martino near Lecco, Italy, were studied to aid in the design of rockfall protection measures. One important observation and measurement made during these tests was the significant loss of energy as the rocks hit the ground (Spang & Bolliger 01).

Across the Pacific in Japan tests were ongoing at the Asari and Iwadono test sites in 1972, and the Aigi and Sonohara test sites in 1973. The purpose of these tests was to study rockfall trajectories. The results from these tests were used to develop tables defining the inter-relations between slope geometry, rock size, velocity and energy (Usiro et al. 2003).

Meanwhile in the USA D'Appolinia Consulting Engineers in 1978, under contract with the North Carolina Department of Transportation, conducted rock rolling tests used to design rockfall mitigation measures for the Beaucatcher Mountain Highway project (Evans 1989). One hundred and forty six rocks were rolled to develop a computer model.

In Canada the Ministry of Highways and Public Works conducted rock-rolling tests along the Trans Canada Highway to support a slope stabilization project near the Ferrabee Tunnel. (Elstron et al. 1973). The purpose was to test the effectiveness of a proposed wall and ditch. Observations were made on the behavior of 350 individual rockfalls. One notable conclusion was that due to the unpredictable behavior of the rocks after ground impact the full range of velocity and trajectory for this site was not covered by the tests.

5 THE EIGHTIES

During the 80s significant advancements in the science of rockfall were developing. Somewhat fewer rocks were rolled and analyzed (an estimated 434) but significantly more trajectory details were measured and many more protective measures were studied. By the end of the 80s several rockfall computer models (CRSP, Rockfall, RocFall, etc.) were developed and were receiving widespread acceptance. During this time increased effort was given to the mechanics of rockfall and for the first time comprehensive tests were performed where rocks were rolled down a slope into flexible barriers and studied in detail.

In Japan extensive testing was underway. Seven tests were performed at seven different test sites from 1980 through 1988 (Usiro et al. 2003). The purpose of these tests was to study rockfall trajectories and build upon testing from the 60s and 70s to further develop the tables on the inter-relations between slope geometry, rock size, velocity and energy.

Back in North America many studies were performed. The Canadian Railways rolled rocks into a cable net attenuator system constructed in Kicking Horse River Canyon near Golden, B.C., Canada (Wyllie, 1986). Approximately 60 rocks were rolled. The governing criteria for performance were rock size and velocity. In California, USA, as part of a rockfall mitigation study, the California Department of Transportation rolled 223 rocks into catchment ditches and catchment fences on numerous road cuts around California (McCauley et al. 1985). The purpose of these tests was to study the effectiveness of protective measures that were already in place along the state's highways. This work concentrated on slope angle and slope height and attempted to calculate velocities and bounce heights. In 1987 the California Department of Transportation rolled twelve rocks as part of the Gaviota Pass rockfall project near Santa Barbara, California, USA. The purpose was to evaluate catchment ditch effectiveness, establish modeling parameters, and design catchment ditches with flexible rockfall fences and draperies.

(Duffy 1987). A few years later the California Department of Transportation began a research project to test and evaluate manufactured flexible rockfall barriers used in Europe (Smith & Duffy 1989). The purpose of this research was to construct, test, and evaluate the effectiveness of flexible rockall fences. Seventy-six rocks were rolled in a series of three tests. Translational and rotational velocities were measured.

Nearby the Colorado Department of Transportation began a series of tests, near Rifle, Colorado, USA, on flexible barriers designed to attenuate the impact energy. This particular design was constructed of railroad ties and used tires (Barrett & Pfeiffer 1989). The tests also provided needed data for validation of the rockfall model CRSP developed by the Colorado School of Mines. Thirteen rocks were rolled. To the south CALMAT Surface Mine in Rillito, Arizona, USA rolled 52 rocks testing three bench geometries (Evans 1989). These tests were also used to determine the accuracy of the Ritche empirical model and the available rockfall computer models (ROCKSIM, Hoeks, CRSP). Additionally the study developed a rational process to the design of catch bench geometry. Ultimately the author wrote a computer program that combined the aspects of the tests and the models.

Across the Atlantic at the Bekenried test site in Switzerland some 16 rocks were rolled into a flexible barrier. Although the tests were primarily for testing the barrier rock roll trajectories were also studied (Gerber et al. 1988).

6 THE NINETIES

It is probably fair to say that around the world an explosion of rock rolling occurred during the 1990s. The majority of the tests were performed to evaluate the effectiveness of various barriers but the majority of the rock rolls were rolled to evaluate catchment ditch effectives, develop design criteria and to study rockfall trajectories. These worldwide tests collectively measured rockfalls, impacting the various barriers, with energies ranging between 20 and 2700 kilo joules. All the tests were performed in a similar manner; the slopes were prepared with a grid, rocks were weighed with load cells, cameras (high speed, video, film) were set up at three or more viewing locations and rocks were rolled down the slope either by high scalers, heavy equipment or cable systems. Energies were analyzed using both translational and rotational velocity or in some cases only translational velocity. Much of this work, although initially for the purpose of barrier testing, included the filming of the rock rolls for use in trajectory analysis providing an abundance of trajectory data on some 369 rock rolls on hard rock slopes, colluvial slopes and mixed colluvial and rock slopes. In total it is estimated that over 3200 rocks were rolled and studied in the 1990s.

In Japan two tests were performed at the Yaka and Otaru test sites in 1994 adding additional trajectory data to the already abundant Japanese data collected in the 60s, 70s and the 80s (Usiro et al. 2003). Nearby in the Maeda Kosen Quarry 9 rocks were rolled into a reinforced earthen berm (Geo-Rock Wall with Cushion Cags) designed to stop large impact energies (Yoshida & Momura 98). In Shayupin, Taiwan flexible fence barriers were studied to evaluate performance and collect data on rockfall trajectories (Hwu & Spang1997).

In the United States a large number of tests were performed testing a variety of barriers. Hearn (1991 & 1992) was testing the Flex-Post fence (an experimental infrastructure with a double twisted wire mesh panel) in Colorado at the Rifle test site. The California Department of Transportation (Duffy & Hoon 1993, 1996, 1998) tested flexible rockfall fences with different meshes (rectangular and diagonal cable meshes, surplus anti-attack submarine nets and 6-gage chain link mesh) and infrastructure configurations (post dimensioning, energy absorbing devices type and positioning) at the Shale Point test site in California, USA. Kane & Duffy (1993) performed a low energy flexible barrier test at the Shale Point test site in California (24 rock rolls). Andrew et al. (1998) performed tests at the Rifle test site of a recently developed flexible cable net fence (31 rock rolls). Duffy & Hoon (1996) were testing concrete barriers (k-rail/jersey barriers at the Shale Point test site (10 rock rolls). Beck (1995) was testing catchment ditch effectiveness at the Anderson Grade truck climbing lane project. Beck rolled some 15 rocks measuring impact locations and roll out distance. Colorado DOT (Parsons et al. 1992) was testing reinforced earthen berms designed to stop large impact energies (9 rock rolls). In Oregon, the Oregon Department of Transportation was pioneering a new rockfall fallout design criteria for 4:1 (V:H) slopes (Pierson et al. 1994). An impressive 2800 rocks were rolled off several 4:1 slopes into three differently shaped ditch to develop design charts for fallout areas.

In Europe extensive testing was also underway. Additional tests at the Bekenried test site in Switzerland were performed where rocks were rolled into a flexible barrier. Barrier performance and rock roll trajectories were studied (Gerber et al. 1998). A comprehensive testing program in Oberbuchsiten, Switzerland (Duffy & Haller 1993) was completed on steep hard rock slopes. Finally very high energies were obtained not by increasing mass but by increasing velocity (a very important step). Kurz (1993) with the Railway Department in Stuttgart, Germany was testing rail and tie walls commonly used on the

German railways at the Oberbachsiten, Switzerland test site (8 rock rolls). In Switzerland, Bozzolo et al. (1998), while developing a computer model, rolled rocks at the Bedrina test site near St Gottard, Ticino, Switzerland, to assist in the calibration of the model. In Italy extensive studies into the mechanics of rockfalls were performed. Azzoni & de Freitas (1995) describes the data gathered from several in situ rockfall tests carried out at a quarry at Strozza, near Bergamo, Italy. Some 60 individual rock-rolling tests were performed. Through the measurement of the slope geometry, the rock characteristics and the rockfall trajectory several parameters were examined; the restitution and friction coefficients, dispersion of trajectories effect of block geometry, and the efficiency of the catchment ditch.

7 THE NEW MILLENNIA

By now, with the increasing demand for rockfall fences, the industry together with academia and governmental agencies developed a standard test for fences. The new test protocols required the rocks be dropped directly into the test fence without any ground contact and subsequently without any rotation. These new standards decreased the number of rock rolling tests performed. Fortunately with the increasing demand for methods to predict rockfall, rock rolling tests continued largely for the purpose of studying rockfall trajectories and calibrating and developing computer models. In fact it is estimated that a remarkable 11,800 rocks were rolled and studied since 2000.

In Japan rock-rolling tests continued at the Kochi site (Ushiro & Tsutsui 2000) where 69 rocks were rolled for rockfall trajectory studies. This was followed by tests performed at the Ehime Prefecture Uma-gun Doi-cho, (Ehime Macadam Industry, Ltd.) where 40 rocks were rolled for trajectory analysis and simulation modeling. An unprecedented 14 cameras were used to study the rock rolls (Usiro et al. 2003).

In the United States the California Department of Transportation was testing a temporary flexible rockfall barrier for use during construction (Duffy & Jones 2000). Twenty-five rocks were rolled into the barrier. Rockfall trajectory studies were performed by the California Department of Transportation at the Devils Slide project near San Francisco (Whitman & Duffy 2006) and the Highway 39 project near Los Angeles (Salisbury & Duffy 2011). Over 140 rocks were rolled in two separate site investigations. In Colorado, USA, at the Georgetown Incline site four tests were performed, from 2004 to 2009, to validate the rock rolling models used by CRSP 4.0 and testing a rockfall attenuator system (Arndt et al. 2009). Seven rocks were rolled. Again in Oregon, the Oregon Department of Transportation, as part of a National Pooled Fund Study to advance catchment width design, performed an extensive research project consisting of rolling approximately 11,250 rocks off vertical, 4:1, 2:1, 1.5:1, and 1:1 slopes of three different heights (12, 18, and 24 meters) into three differently inclined catchment areas (flat, 1/6:1, 1/4:1). The data has been used to develop design charts for dimensioning rockfall catchment areas (Pierson et al. 2001).

In Europe experimental rockfalls were carried out on the slopes near Val d'Ega in the Val d'Ega Valley, South Trypol, Italy (Schweigl et al. 2003). Nineteen rocks were rolled to verify computer modeling and back analyze restitution coefficients. Two tests were performed at the Apennines test site near Parma, Italy where 43 rocks were rolled and the Leopontine test site in northern Italy where 40 rocks were rolled (Giani et al. 2004). These tests were performed to study trajectory analysis, the suitability of existing barriers and the need for new barriers.

In Italy the University Degli Studi Di Trieste tested a hybrid fence commonly referred to as an attenuator (Badger et al. 2008). The tests were performed at the test facility near Meano, Italy. Four rocks were rolled to evaluate system performance.

In France Dorren et al. (2006) performed extensive rock rolling tests to study the protective effects of forests. One hundred rocks were rolled at a non-forested site and 102 rocks were rolled at a forested site. Trajectories were studied in depth.

In South America at the Yanacocha Mine, in northeastern Peru near Minera Yanacocha 46 boulders were rolled in a quarry to test mine bench effectiveness and calibrate and confirm the results from Colorado Rockfall Simulation Program (CRSP) analysis (Dessenberger & Skurski 2006).

8 SUMMARY

The importance of rock rolling studies has been clearly demonstrated and acknowledged worldwide as an important task in rockfall science. Practitioners for more than 50 years have been testing barriers, developing models, and creating design guidelines nearly all of which are based on actual rock rolling events. Over 15,500 rocks have been rolled and analyzed to various degrees. In the 1960s three tests were performed, one each in the USA, Japan and Switzerland. Over 300 rocks were rolled. During the 1970s five tests were performed, one in Italy, two in Japan, one in the USA and one in Canada. Over 500 rocks were rolled. Testing increased considerably in the 1980s with fourteen tests, seven in Japan, one in Canada, five in the USA, and one in Switzerland. Over 400 rocks were rolled. Testing increased further in the 1990s with twenty tests, three in Japan, one in Taiwan, eleven in the USA, four in Switzerland, and one in Italy. Over 3200 rocks were rolled with 2800 rolled in one test alone. Testing decreased slightly in the new millennia but the rock roll numbers were higher than ever. Over 11,880 rocks were rolled with 11,250 rolled in one study alone. Collectively there were seventeen tests, two in Japan, eight in the US, four in Italy, two in France, and one in Peru. Rock rolling tests have been used to study catchment design and effectiveness, barrier performance, site investigations, and for computer model development and verification. Nothing can replace the value of witnessing a rolling rock impact a barrier and seeing the impact forces and subsequent response of the barrier. Nor is there any replacement to watching a rock roll and bound down a slope, without regard to the constraints of a computer model, and as if in protest do the unexpected. Experience has proven that rolling tests have provided otherwise unknown insights into rockfall behavior.

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