An experimental comparison of half-scale rockfall protection sandwich structures

A. Heymann[1, 3], S. Lambert[1], E. Haza-Rozier[2], G. Vinceslas[2] & P. Gotteland[3]
[1]*Cemagref, Grenoble, France*
[2]*CER, Rouen, France*
[3]*L3S-R, Grenoble, France*

Abstract

Protection against falling rocks often requires the building of civil engineering structures such as soil reinforced embankments. A recent development consists of building a sandwich cellular structure for this purpose. Cellular structures are efficient technological solutions widely used in civil engineering for various applications. These structures also appear to be well suited to resist rockfall and to act as protective structures against impacts. This paper investigates the behaviour of three sandwich structures based on half-scale experiments. The 1.5 m high cellular sandwich structures were leaned against a concrete wall with the facing made of geocells filled with a coarse granular material. Three different granular materials were used for the kernel part of the sandwich (between the facing and the wall). The experiments were carried out with dead load "pendular" impacts by a 260 kg spherical boulder with maximal impact energy of 10 kJ. The aim was to evaluate the ability of each kernel material for reducing the stress on the concrete wall.

Keywords: impact, gabion, scrapped tyres.

1 Introduction

Passive structural countermeasures against rockfall consist of structures placed in the vicinity of the elements at risks in order to intercept or deflect the rocks falling from slopes or cliffs. Among the possible structures, some are partly or totally constructed from natural granular materials as for instance galleries covered with cushion layers and embankments, the latter being appropriate for

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medium to high energy impacts (2 to 50 MJ). Even though several experimental campaign and numerical studies were carried out [1–3], the design of rockfall protection embankments suffers from the lack of knowledge concerning the dynamic interaction between the rock and the structure. As a consequence, this design is most often based on empirical approaches. Therefore, research is needed to improve their efficiency and to propose their optimized structures, taking fully into account the dynamics.

For instance, sandwich structures seem to be a promising technical solution. Pioneered in this domain by Yoshida [1], this concept was recently explored using geocells to build the structure [4]. The geocells are metallic wire netting cages. Using different fill materials allows the building of vertical layers to constitute the sandwich. With such a sandwich structure, the aim is to reduce the stresses transmitted within the structure, increasing the diffusion of the stress, as well as the dissipation of the impact energy.

This study is part of a research program dealing with the concept of cellular sandwich protection structures (the Rempare project). This program couples experiments with numerical developments with investigations at the various scales from the constitutive materials to the real-scale structure [4–7].

This paper focuses on half-scale structures with special attention on the transmission of stress within the structure in the impact direction. Three different structures are exposed to dynamic loading with the aim of improving the effectiveness of sandwich structures exposed to rock impacts.

2 Materials and methods

2.1 Impacted structures

The structures consist in two-layered sandwiches, 1.5 m in height, 2.5 m in length and 1 m in thickness (Figs. 1 and 2).

The first layer, or front layer, is made of 15 gabion cages filled with a coarse granular material. These cages are cubic in shape, 500 mm in height and made up

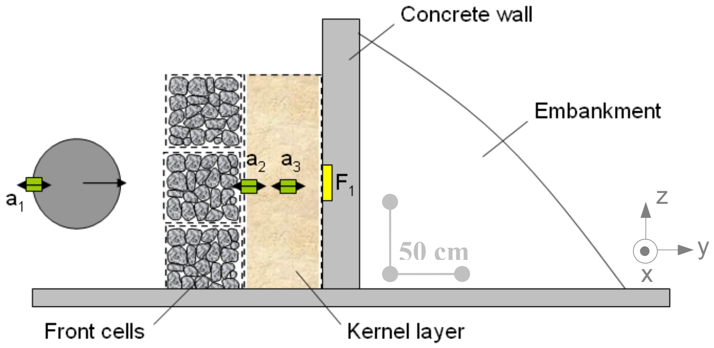

Figure 1: Impacted structure and measurement devices.

Figure 2: A structure before impact.

of a hexagonal wire mesh. The fill material is a crushed quarry limestone, 80 to 150 mm in grain size.

The three structures differ in their kernel fill material (Tab. 1). The sand is a well-graded sand with a 0.2 to 5 mm grain size distribution (Seine sand). Scrapped tyres are 20 to 150 mm in length. The ballast is 30 to 50 mm in grain size distribution. The kernel material is dumped behind the front layer and contained in a geotextile.

This structure is leaned on a reinforced concrete wall, with a ground compacted backfill. This latter is assumed to be rigid compared to the sandwich.

The sandwich structure aims at reducing the force applied to the wall.

Table 1: Kernel fill material.

Structure ref.	Kernel fill material
S1-sand	Seine sand, 0.2-5 mm in grain size distribution
S2-mixture	Mixture : 70% Sand - 30 % scrapped tyres (in mass)
S3-ballast	Ballast

2.2 Experiments

Experiments consisted of pendular impacts by a projectile on the structure. The projectile is made of a 54 cm in diameter steel spherical shell, filled with concrete and having a mass of 260 kg [4].

The pendulum system consists of two metallic beams, 7 m high, connected by a cross beam on which are fixed two metal chains that support the sphere (Fig. 3). The projectile can be lifted up to a maximal height of 4 m using a hand cable winch. The maximal impact energy that can be developed is 10 kJ.

The continuous measurements during these tests are:

- The acceleration of the projectile: a piezoresistive accelerometer is mounted on the shell opposite the impact point (sensor a_1, Fig. 1).

- The acceleration of different points within the structure. These points are mainly in the impact direction, at the interface between the front layer and the kernel layer and in the middle of the kernel (sensors a_2 and a_3 respectively). These piezoresistive uni-axial accelerometers are The force transmitted to the concrete wall at various points, and notably along the impact direction (sensor F_1 on Fig. 1). The sensitive surface of the sensor is 0.1 m². The stress transmitted to the wall, σ_{trans}, is deduced from this measurement.

Sensors a_2, a_3 and F_1 are placed along the impact axis, that is to say at the same height as the impact point (mid-height of the structure). The sample rate is 40 kHz. In order to minimize the noise due to high frequency phenomena, signals are submitted to a low-pass Butterworth filter with a cut frequency of 1 kHz.

All the signals are submitted to the same filter to avoid any time lag bias resulting from this treatment.

Curves plotted give the variation of the signal during the impact.

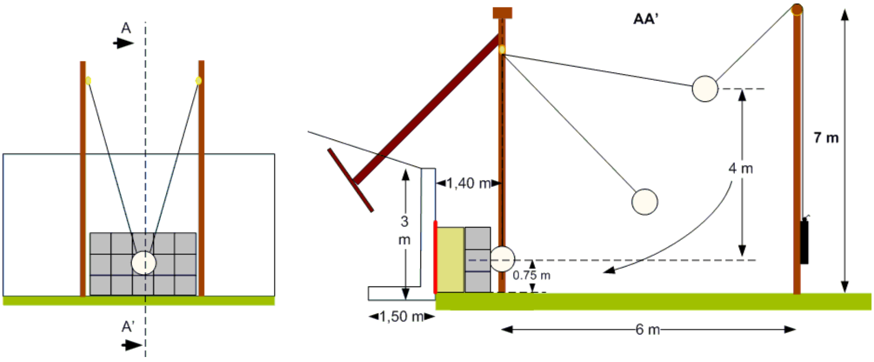

Figure 3: Sketch of the experimental device.

Figure 4: Accelerometer: a_1 (left) and a_2 (right).

Four successive tests with increasing energy (2, 4, 8 and 10 kJ) were carried out on the same structure, without repairing. The 10 kJ impact was repeated once.

3 Results

As the structure is expected to reduce the load on the concrete wall, the assessment of the response of the different structures is primarily based on the forces (or stress) transmitted to this wall. The other data are intended to characterize the impact and also to understand the phenomena explaining the responses of the three structures. It is expected that these data will give evidence of the influence of energy dissipation and of stress spreading on the concrete wall.

3.1 Stress on the concrete wall

The sensor along the impact axis (F_1) is considered first as it is presumed to be exposed to the higher load. Figure 5 illustrates the time evolution of the stress in the case of the 4 kJ impacts on the three structures. The curves are plotted so that the signal starts changing at t=0, without any consideration for the impact time as determined from accelerometer a_1.

The stress curve shape and stress amplitude are different from one structure to the other. The lower stress is obtained for structure S1-sand whose kernel is composed of sand. By contrast, the higher stress is obtained for structure S3-ballast, whose kernel material is ballast. The ratio between these extremes is of about 2. Concerning the shape of the curves, the main conclusion drawn is that the maximum is reached later in the case of structure S2-mixture. Moreover, for this structure the load increase rate before reaching the peak is lower than for the other structures.

Comparison based on the maximum value of the transmitted stress shows the same trends for all the impact energies (Fig. 6). Ballast as kernel material leads

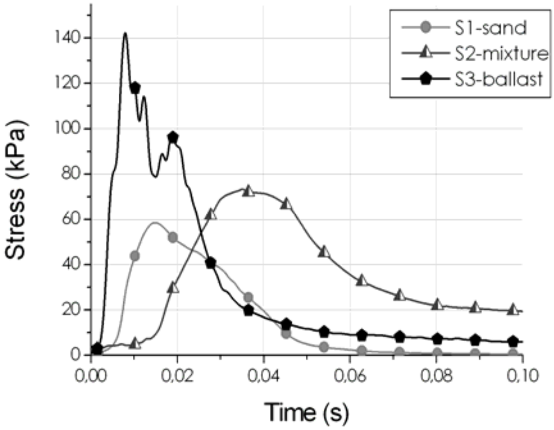

Figure 5: Time evolution of the stress on the wall during the 4 kJ impact (sensor F_1).

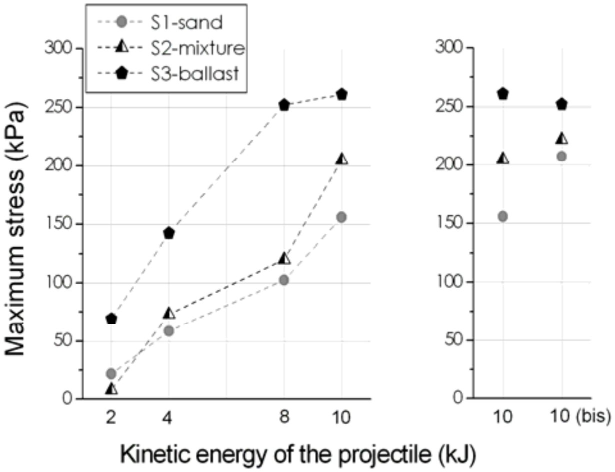

Figure 6: Stress on the concrete wall (sensor F_1) - all the tests.

to the higher stress while the lower stress is obtained for sand as kernel material. Values obtained with the sand-tyre mixture are slightly higher than those obtained with sand. In addition, in the case of ballast as kernel material, the maximum stress seems to reach a threshold value from the 8 kJ impact at a stress of about 250 kPa, even for the second 10 kJ impact. For the others kernel materials, the maximum stress increases almost linearly, without reaching this threshold value.

In order to explain these differences the other measurements will be analysed in the following. The first step consists in assessing the diffusion within the structure. Indeed, the diffusion within the structure may be affected by the characteristics of the different materials.

3.2 Diffusion

During the impact, the stress propagates with time from the contact area to the wall with a spreading. In soils, it is generally assumed that the stress diffuses

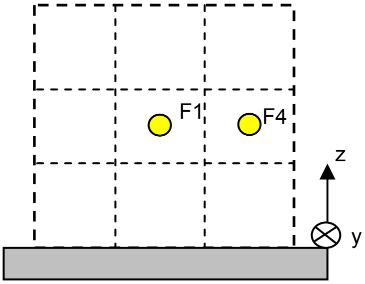

Figure 7: View of the position of stress sensors F_1 and F_4.

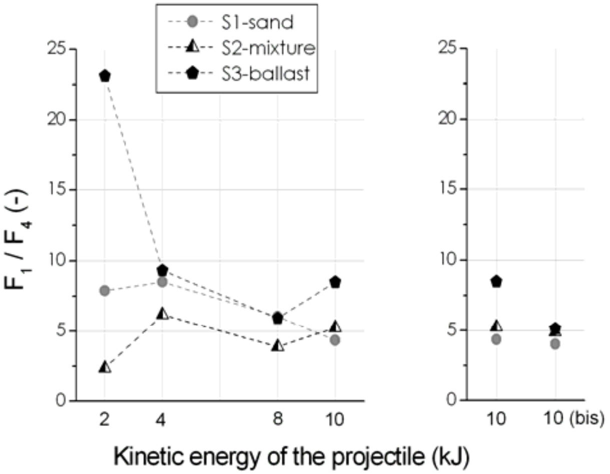

Figure 8: Illustration of the diffusion effects: ratio F_1 to F_4 - all the tests.

within a cone. As a consequence, the loading on the wall is not concentrated along the impact axis but also concerns points apart from this axis. To explore the consequence of the diffusion mechanisms a force sensor is placed on the concrete wall 50 cm aside the impact vertical plane on the same horizontal plan (F_4 on Figure 7).

The ratio of the maximum values of F_1 to those of F_4 is plotted in Figure 8. A high ratio value reveals a stress concentration in the impact axis. Figure 8 shows that for the first impact, there is a great variability among the three structures.

Ballast leads to an important load concentration in the impact axis. From the second impact the values rapidly converge on 5 for all the structures.

Based on this maximum stress criterion there is thus no significant difference in terms of diffusion. Diffusion mechanisms do not explain the differences in stress value in the impact axis from one structure to the other.

3.3 Projectile acceleration

Another way to analyse the structures response is to investigate the projectile acceleration (sensor a_1, Fig. 1). Figure 9 shows that the maximum projectile acceleration is four time higher with sand as kernel material than with ballast. The acceleration in the case of the sand-tyre mixture as kernel material is slightly higher than that with ballast. This is exactly the opposite of what is observed on the transmitted stress. While the ballast structure presents the higher transmitted stress, the projectile acceleration is the lower.

In addition, in both cases the maximum acceleration seems to reach a plateau from the third impact (8 kJ) while in the case of mixture as kernel material it increases, even for the second 10 kJ impact.

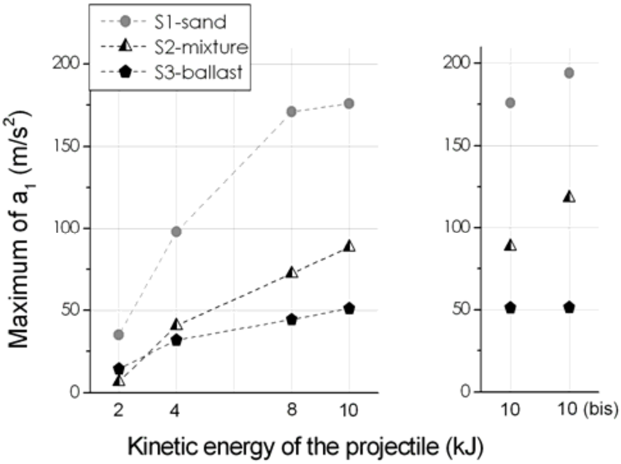

Figure 9: Projectile acceleration (a_1) - all the tests.

3.4 Acceleration within the structure

In order to understand the energy transfer inside the kernel layer, the acceleration measured by the accelerometer a_2 is analysed. The a_2 accelerometer is positioned at the interface between the front and the kernel layers (Fig. 1). The maximum acceleration value is presented in Figure 10. Previous analysis has shown that this peak was not affected by reflection of the compression wave on the concrete wall [7].

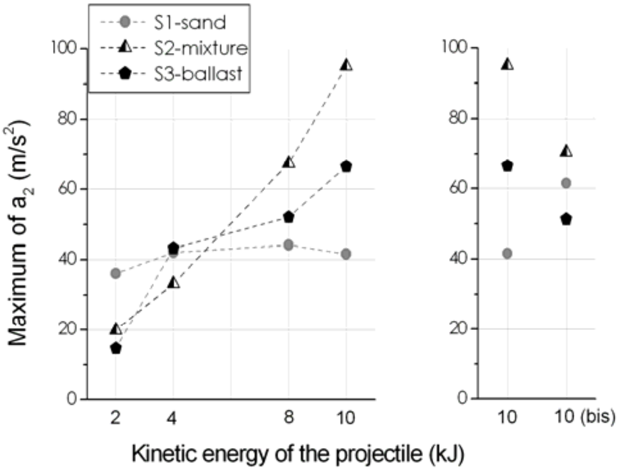

Figure 10: Acceleration at the interface between the front and kernel layers - all the tests.

Trends are different compared to results presented in Figure 9. In the case of sand-tyre mixture or ballast as kernel material, the acceleration increases almost linearly up to the 10 kJ impact. The increase is higher with the mixture. With sand, the acceleration is almost constant from the 2 kJ impact to the 10 kJ impact (40 +/- 5 m^2/s). For the third impact (10 kJ) a ratio of two is obtained between the maximum acceleration, obtained with the mixture and the minimum obtained with sand. With the mixture or the ballast, the acceleration measured during the second 10 kJ impact is lower than during the first one.

4 Discussion

4.1 General comments

The response of the three structures appears to be very complex to understand (Tab. 2). No simple analysis allows interpreting the stress values based on the other measurements.

Table 2: Trends from the measurements along the impact direction.

Measurement	**Ranking based on the maximum value**
Projectile acceleration	Ballast < Mixture < Sand
Front/kernel acceleration	Mixture < Ballast < Sand
Stress on the wall	Sand ≤ Mixture < Ballast

Comparison of observed trends must account for the fact that the test consisted of successive impacts on two-layered structures involving granular materials. In this context, phenomenon such as compaction and particles crushing are expected, inducing changes in the mechanical and geometrical characteristics of both the kernel and the front layers, at least in the impacted area.

Moreover, as the compression wave propagates through the structure, a temporal analysis would be necessary for interpreting the data from the different sensors. For instance, in the case of sand in the kernel and a 8kJ impact, it takes 2.5 ms and 10 ms for the compression wave to reach accelerometer a_2 and sensor F_1 respectively [7]. These values decrease with the increase of number of impacts and similar values are obtained with the other kernel materials.

4.2 On the influence of the kernel material characteristics

Before the first impact, the kernel material is rather loose. In the case of sand and ballast the successive impacts leads to particle rearrangement and compaction. In the case of ballast the rapid change of the ratio F1/F4 is assumed to be due to stones rearrangement. In a loose particles assembly, diffusion is less important than in a dense one.

In the case of sand, the limited changes observed on the acceleration at the interface between the front and kernel layers are due to compaction. The kernel rigidity increases with successive impacts resulting in a decrease in the acceleration at this interface, compensating the boulder acceleration increase. This is confirmed by the increase in stress on the wall from the first to the second 10 kJ impact.

By contrast, the successive impacts have a different influence on the sand-tyre mixture. With this material, the maximum values of the different measurements along the impact axis increase almost linearly during the test series. This is to be associated with the elasticity of this material. The compression wave induces minor changes in the characteristics of this material.

With increasing impact energy, coarse particle crushing is expected to occur. Actually, this phenomenon has been observed in both the front layer and the kernel layer composed of ballast. With the other kernel materials, crushing concerns the only front layer. Crushing may explain the plateau observed on the stress curve in the case of ballast. Indeed, crushing tends to restrict the amplitude of the stress transmitted to the load [4]. This phenomenon is associated to the amplitude of the force transiting through force chains in the coarse material. The stress on the wall is not really appropriate for this purpose at it gives an average calculated on a large surface compared to the particles size.

By extrapolation the stress on the wall would still be 250 kPa for higher energy impacts, as long as there are particles to crush between the projectile and the wall.

4.3 Practical implications

The first practical conclusion is that sand is the most efficient as kernel material for reducing the load to the concrete wall resulting from the impact by the projectile. The difference with the sand-tyre mixture is little. This is consistent with previously published results concerning singles geo-cells [4].

The second practical implication concerns the design of rockfall protection embankments: neither the kinetic energy of the projectile nor its acceleration are appropriate for assessing the response of the structure. For a same kinetic energy very different structure behaviours are observed and a high projectile deceleration does not lead to a high stress within the structure. This conclusion should be considered as the current design of classical rock fall protection embankments is generally based on one of these two data.

4.4 Perspectives

In order to better understand the behaviour of the three structures, complementary analyses are necessary.

For this purpose, the data from the other sensors placed in the structure will be analysed. Actually, three other force sensors and six other acceleration sensors were positioned outside the impact axis. Deformations of the front face of the structure are also measured after each impact. This analysis will account for temporal effects.

In addition this data will allow validate the numerical modelling tools that are being developed [6, 8]. In return these models will help providing simple physical models for understanding the response of these structures.

5 Conclusion

This paper presented the very first results and analysis from impact tests on two-layered half-scale rockfall protection structures.

The experiments have shown that the most efficient material to be used as kernel fill material to reduce the stress on the concrete wall was sand: its efficiency is up to twice that of ballast. The efficiency of the sand-tyre mixture is intermediate. Particle crushing and compaction appears to explain the difference of behaviours observed. These two phenomenons do not affect the three different fill materials in the same way.

This paper provided a large number of data related to the dynamical response of these structures. Nevertheless, these data do not allow interpretation directly on the observed responses. A comprehensive understanding and assessment of the mechanisms at work in the structure is however necessary for optimising the design of such structures. With this aim, the next step will consist of processing all of the measurements, taking into account the temporal effect, and using numerical tools.

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