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Oltion Korini, Marion Bost, Jean-Pierre Rajot, Yb Braouli, N Freitag. Experimental study of reinforced soil bunds subjected to horizontal impact. 14th International Congress of Rock Mechanics and Rock Engineering, Sep 2019, FOZ DO IGUACU, France. 8p. hal-02461202

HAL Id: hal-02461202

<https://hal.science/hal-02461202v1>

Submitted on 30 Jan 2020

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Experimental study of reinforced soil bunds subjected to horizontal impact

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ABSTRACT: Rockfall phenomenon is a common event in mountainous areas and presents a serious risk to the nearby buildings or infrastructure. Different protection measures may be taken depending on the site conditions. A reinforced soil bund can be effective in stopping blocks with relatively high speed and kinetic energy. This article presents the response of three reinforced soil bunds subjected to horizontal impacts. The tests are dimensioned in a reduced scale with a factor of 1/3 by following specific similarity rules and assumptions. A rectangular shape with ratio height/width equal to 2 is chosen aiming to have a lower footprint than the dominating trapezoidal shape of existing soil bunds. In order to find the most efficient design, different reinforcement patterns are installed in each bund. The failure mechanisms and the role of the reinforcements are observed with several instrumentations.

1 INTRODUCTION

1.1 *Background*

Reinforced soil bunds have been for decades constructed close to mountainous slopes to protect the nearby habitations, roads and railways. The plastic behavior of the soil makes these structures very efficient in stopping falling rocks. They are recommended over other protections when dealing with blocks that attain a high kinetic energy in the range of 5-30MJ (Descoeurdes, 1997). Due to their generally simple composition of soil and geosynthetic reinforcement, these barriers are easier to construct and to maintain compared to other solutions such as steel fences. Also it is claimed that they are more cost efficient than other solutions for design energies higher than 3MJ (Brunet et al., 2009).

Many configurations are possible for the bunds consisting of reinforced soil. This is because of the different types of geosynthetic reinforcement and different ways of placement inside the bund. Experiments on real scale with different types of reinforced soil bund showed that whatever the solution, there is a significant damage and plastification close to the impact position and a lower deformation far from it (Burroughs et al., 1993; Peila et al., 2007). For this reason, lately there has been a lot of research on these types of structures with a special concern on the facing. Different designs were considered in order to reduce the damage to the bund by confined soil (Yoshida, 1999), or localize it using easy reparable and separate elements like gabions or geocells (Heymann et al., 2010; Maegawa et al., 2011).

The available design procedures for reinforced soil bunds are mainly empirical and a general methodology is not yet available (Lambert and Bourrier, 2013; Ronco et al., 2009). Usually the bunds tested by researchers have trapezoidal shape with horizontal layers of geosynthetics inside (Fig. 1), while the faces are held by light welded steel meshes (Maegawa et al., 2011; Peila et al., 2007; Yoshida, 1999). There have been some attempts to model numerically the reinforced soil bunds, by using finite elements (Murashev et al., 2013; Ronco et al., 2009) or discrete elements (Plassiard et al., 2005). Nevertheless, these approaches have not been generalized

for use in all cases and the constitutive laws for soil and reinforcement behavior are simple and do not consider the possible dynamic dependence of the material strength.

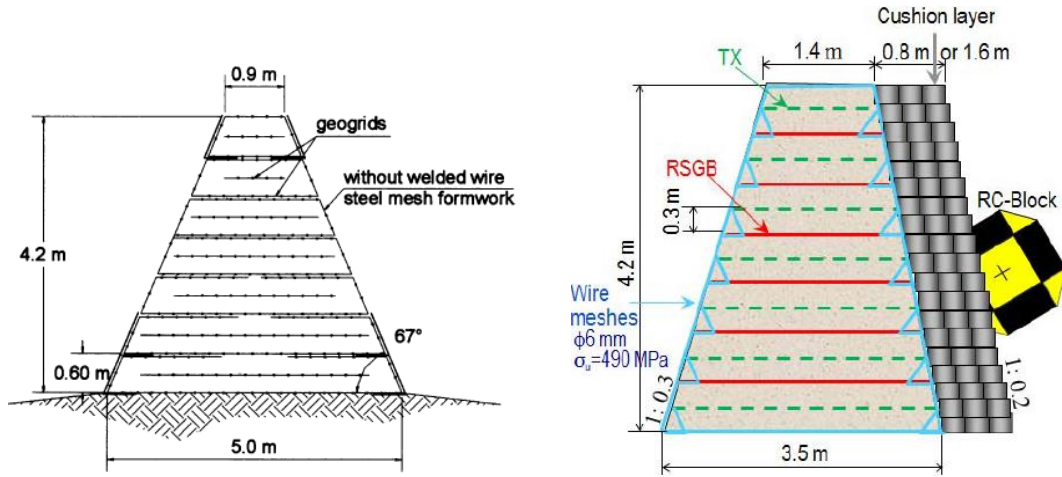


Figure 1. Reinforced soil bunds tested by Peila. et. al., 2007 (left) and Maegawa et. al., 2011 (right).

1.2 Objective

The reinforced soil bunds are generally designed to be robust in terms of shape and geometry. The role of the reinforcement during the impact is either neglected or not well defined. This research project aims to optimize the bund shape and in the same time, to find the most efficient reinforcement design that would suit to this shape.

This article presents the response of three reinforced soil bunds subjected to horizontal impacts. A slender bund shape with vertical upstream and downstream faces is proposed, aiming to lower the footprint of the barrier. The internal/external stability issues that arise from this shape are mitigated by the mobilization of the soil and reinforcements in both longitudinal and transversal directions of the bund. In Section 2, the preparation of the tests in reduced scale are described by explaining the theoretical basis and relevant assumptions, followed by the empirical dimensioning of the bunds, the construction materials and the installed instrumentation. In Section 3, the first results are presented by also aiming to interpret them with regard to the in situ observations. Section 4 contains briefly the conclusions of this experimental campaign.

2 REDUCED SCALE TESTS

2.1 The variation of parameters between real and reduced scales

The rules of similarity in soils have been used by many researchers up to now (Garnier, 2002; Jenck, 2005; Scott, 1989). It is important to judge which parameters need to be scaled based on the phenomenon to be observed.

The scale factor “n” for each parameter A is defined as the ratio:

$$n = \frac{A}{A^m} \quad (1)$$

where: A = the real scale parameter; A^m = the model scale parameter.

In order to have proper similarity between the two scales in dynamic conditions, certain rules of dynamic similarity of granular materials apply (Weber, 1971):

- all physical dimensions including soil grain sizes are divided by the scale factor,
- the material specific mass, Poisson ratio and friction angle are kept unchanged,
- the modulus of deformation is divided by the scale factor.

In our case, a scale factor of three is chosen and we attempted to keep as many variables as possible unchanged in the reduced scale. The dimensions of the bund are reduced by the scale factor but the soil grain sizes are retained for not altering the friction mechanism between soil

and geogrids and to maintain the same dynamic behaviour of the soil in the two cases. In general, by keeping the same soil, all the mechanical characteristics are kept unchanged, including the modulus of deformation.

The kinetic energy of the impacting block is defined by its mass and speed. Assuming that the dynamic response of the bund is dependent on the loading speed, we choose to preserve this variable constant between the different test scales. In this way, we exclude the possible speed dependent response of the reinforced soil bund. Since for the impact we used a pendulum system, this implies that we need to drop the reduced size block from the same height (Fig. 2).

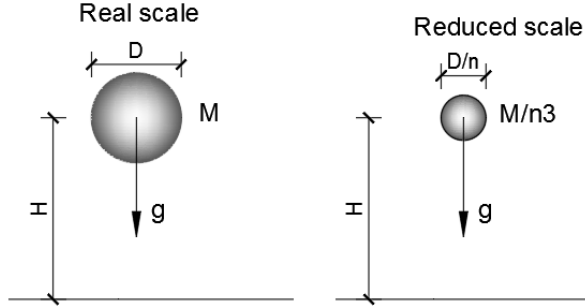


Figure 2. Downsizing impacting block.

Consequently, the kinetic energy of the block, E_k , just before the impact is calculated:

$$E_k^m = \frac{M}{n^3} \cdot \frac{v^2}{2} = \frac{E_k}{n^3} \quad (2)$$

where: M = the mass of the block in the real scale.

The prediction of the front penetration of the impacting block to the reinforced soil bund is sometimes used as a dimensioning parameter even if the relations used are adopted from vertical impact experiments on soil (Brunet et al., 2009). Peila et al. (2007) suggests to evaluate the impact force and penetration using the empirical formula proposed by Labiouse et al., (1996), which is valid for rock sheds calculations or the Mayne and Jones (1983) formula obtained from dynamic compaction of soils. Using the approach from Mayne and Jones (1983) and the work principle of the impact force (Lambert and Kister, 2017; Peila et al., 2007), we can derive a relation for the penetration of the boulder between the two scales. By Mayne and Jones (1983) the impact force is calculated :

$$F_{\max} = \sqrt{\frac{32 \cdot WH \cdot G \cdot r_0}{\pi^2 (1-\nu)}} \quad (3)$$

where: r_0 = the radius of the impacting block; G = the dynamic shear modulus of soil, calculated from soil density and shear wave velocity ($G = \rho V^2 / 10$); ν = the Poisson ratio; W = the weight of the block; H = the height of the fall. Then the penetration may be calculated using the averaged formula based on the work principle of the impact force:

$$p_{\max} = \frac{m \cdot v^2}{F_{\max}} \quad (4)$$

By using the index “m” to refer to the reduced scale parameters and no index to refer to real scale parameters, we determine the ratio of the impacting forces and penetrations:

$$\frac{F}{F^m} = \sqrt{\frac{32 \cdot M \cdot g \cdot H \cdot G \cdot R_0}{\pi^2 (1-\nu)}} \cdot \sqrt{\frac{\pi^2 (1-\nu)}{32 \cdot \frac{M}{n^3} \cdot g \cdot H \cdot G \cdot \frac{R_0}{n}}} = n^2 \Rightarrow F^m = F \frac{1}{n^2} \quad (5)$$

$$\frac{p}{p^m} = \frac{M \cdot v^2}{F} \cdot \frac{F^m}{\frac{M}{n^3} \cdot v^2} = n^3 \cdot \frac{F^m}{F} = n \Rightarrow p^m = \frac{p}{n} \quad (6)$$

This approach may serve as a way to extrapolate the test results to the real scale.

2.2 Dimensioning of bunds

The scope of this project is to propose a slender shape with a ratio height/width equal to 2 and to experiment different options for the reinforcement position until the most efficient design is found. In the following part, the dimensioning of the bunds is done using real scale size and then the reduction factor of three is applied. The available space for the installation of the bunds allows for the construction of a 12m long wall, so we decided to split this length in three parts and construct three reinforced soil bunds that have the same size but different reinforcement design. Hence, only the width of the bunds needs to be defined since the height is double the width and the length is fixed to 4m. The dimensions of the bunds are determined using existing approaches in the literature. Two of the different methods that are used for the dimensioning are presented below.

- Brunet et al. (2009) method:

In this design approach, the penetration of the block in the bund is calculated using charts that were built from vertical drop tests on soil after Calvetti and di Prisco (2007). This method is based on the following assumptions: a) the impact occurs normal to the surface; b) the impacting block is spherical with radius R and unit weight of 25 kN/m³; c) the soil used is mostly granular material, well graded and well compacted; d) the soil thickness is at least 2m and lies on a rigid base. The authors obtain the design width of the bund by multiplying the calculated penetration with the minimal factor of two. For the case of trapezoidal bunds they use the width at the maximal height of impact as design value. Since we want to use constant width, we propose to limit the penetration to 33% of the width by using a factor of three. As our block radius on the real scale is 1.42m and is larger than the largest block tested in this study (0.98m), we use linear extrapolation with the maximal radius of 0.98m:

$$\frac{0.98}{p_{0.98}} = \frac{1.42}{p_{1.42}} \Rightarrow p_{1.42} = \frac{0.56 \cdot 1.42}{0.98} = 0.81m \quad (7)$$

Where p_i = the penetrations of the two blocks considered. So the bund width in the real scale must be higher than:

$$w_{Brunet} = 3 \cdot 0.81 = 2.43m \approx 2.4m \quad (8)$$

- Peila et al. (2007) empirical method

The real scale experiments performed by Peila et al. (2007), consisted of soil bunds with trapezoidal shape subjected to concrete blocks impact with the weights of 5000kg and 8700kg at the impact speed of 31 m/s, representing a kinetic energy of 2.4 and 4.18 MJ, respectively. All the reinforced soil bunds tested resisted well the impacts despite the large deformations. Although the shape of our bund is rectangular, we can consider an average section width of their bund (3m) and extrapolate it to our kinetic energy level of 4590 kJ.

$$w_{Peila} = 3m \cdot \frac{4.59MJ}{4.18MJ} = 3.29 \approx 3.3m \quad (9)$$

From the two mentioned dimensioning approaches, the Peila et. al. (2007) one yields the highest value. Therefore, we use this value as a reference to dimension our bunds. Considering the construction steps it is advisable to maintain a proportionality to 0.6m for both real and reduced scale heights. Also the dimensions of the real scale need to be proportional to the scale factor of three. Concluding the dimensions that satisfy these conditions in the real scale are 3.6x7.2m and in the reduced scale 1.2x2.4m.

2.3 Materials and instrumentation

The horizontal impact tests are performed using a large pendulum system installed at the top of an almost vertical cliff. The system is able to produce an impact energy limited to 400kJ by using standard concrete blocks (ETAG-027, 2013) as impactors. The impacting block used for the tests has an outer dimension of 0.95m, mass of 1639kg and reaches the speed of 14.4 m/sec before the impact. In terms of kinetic energy, this corresponds to 170 kJ, which are equivalent to 4590 kJ in the real scale.

The bunds are constructed using granular soil and reinforcements conform Terre Armée company technology. The soil granulometry is 0-40mm with maximum 10% of fines. The uniaxial geogrids consist of HDPE reinforced with polyester yarns inside. They are specially designed for the reduced scale tests using strips of 2.5cm width placed every 7.5cm in the working direction and every 22.5cm in the transversal direction (Fig. 3). The joints between the ribs are formed by hot air welding. The aperture between the strips was chosen to have a good interlocking effect with the selected soil. The tensile capacity of the geogrids is estimated 77kN/m (5.5kN/rib) in the working direction and 27.5kN/m in the transversal direction. These uniaxial geogrids were installed in Bund 1 and 2 but not in Bund 3. Instead there was applied an outer wrapping of the bund using a flexible steel mesh (Fig. 3).



Figure 3. Geogrid reinforcement (left), granular soil (middle), flexible steel mesh (right).

In addition, geostraps (Terre Armée company) of 5cm wide with 20kN/m strength and welded steel mesh are used to hold vertically the faces of the walls. In order to avoid mutual interaction, two polystyrene sheets separated the bunds with each other.

Several instrumentations are used in this experimental campaign. In order to measure the internal reinforcements' deformation, twenty-eight strain gauges per bund are fixed on the uniaxial geogrids. Two pressure sensors are installed at the bottom of each bund in the impact axis to measure the variation of pressure between the front and the back of the base. The soil behavior is monitored by five accelerometers placed at the impact height in each bund. Four of them are combined two by two to form biaxial accelerometers, while one of them is placed in front of the impact point at 0.4m distance from the bund face. Five wire sensors are attached in the back of the bunds for real time measurement of displacements. They are installed on a rigid frame that is fixed on a concrete block, which in turn was placed over a shock absorbing layer, so that the vibrations of the soil from the impact would not affect the readings. The impacting block is equipped with a 3D accelerometer for monitoring its deceleration. The global deformation is important in understanding the failure mechanisms of the bund, so a 3D laser device is used to digitize the exact shape before and after the impacts.

3 RESULTS

3.1 Global response of the bunds

All the bunds were subjected to two impacts with the same energy. They resisted the first impact but two of them collapsed after the second one (Bund 1 and Bund 2). Their behavior during the first impact and their final deformation are different in each of them, probably due to the differences in the reinforcements (Fig. 4). The local plastification in the front face was followed by

an overall extrusion in the back face, which means that there was a good distribution of the impact energy in the soil volume. In general, the bunds experienced some degree of overturning and local plastification the back part. This phenomenon could be less important if the bunds were longer but this is a limitation of our tests. However, important measurements and conclusions are derived from these tests.



Figure 4. Front face view of all the bunds after the first impact.

The bunds did not experience the same deformation after the first impact. Due to their global deformation, it is difficult to judge for the block penetration, but it is possible to compare the displacements of the impact position and the back extrusion (Fig. 5). The difference between them was 8, 3 and 5cm for the design 1, 2 and 3 bunds, respectively. The Bund 2 performance is the best by showing the least deformation and the maximal geogrid mobilization. The slender shape of the bunds leads to local plastification at the bottom back part. This could be caused by the higher vertical pressure resulting from the partial overturning.

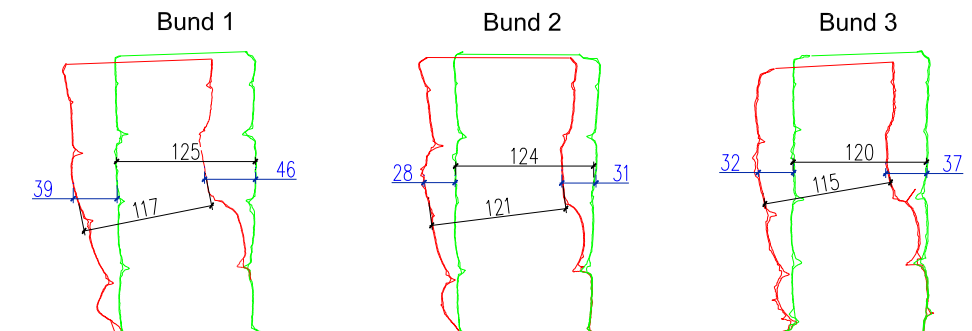


Figure 5. Middle cross section of all the bunds before (green) and after (red) the first impact.

3.2 Instrumentation measurements

Most of the instrumentation recordings provided valid and consistent data. However, in Bunds 1 and 2, the presence of the reinforcements disturbed significantly a part of the data, recorded by the accelerometers that were installed in the bunds. The 3D accelerometer in the impacting block showed similar response from the first impact on the Bunds 2 and 3 but lower for Bund 1 (Fig. 6). An explanation to this measurement may be the lighter compaction of the soil during the construction of Bund 1 due to unfavorable position of the reinforcements. The differences in the reinforcement could also have an important role to the bund stiffness.

Only a few devices were damaged from the impacts and could not provide any data. In brief, three strain gauges and one wire displacement sensor failed after the first impact.

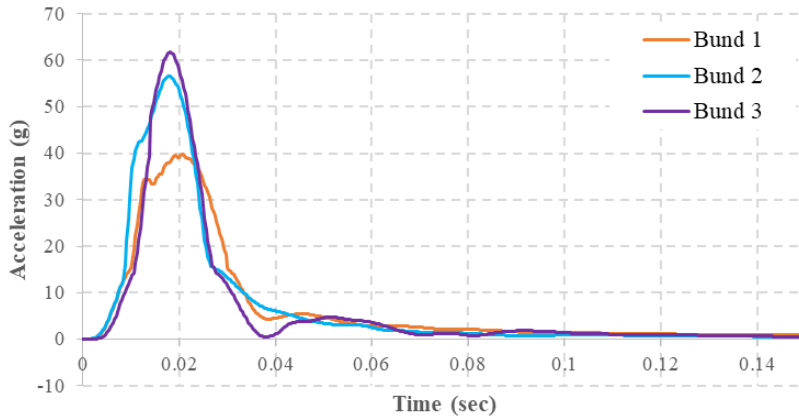


Figure 6. The impacting block accelerometer recordings during the first impact.

Some data from the strain gauges placed on the geogrids of Bund 1 and Bund 2 and their respective position in each bund are shown in Figure 7. As expected, higher measurements are recorded close to the impact position. The gauges farther from the impact are loaded later and slower, indicating a propagation with attenuation of the deformation in the bund. The negative value at the start of some curves could mean either that the strain gauges were loaded in compression or that they lost the pretension that they had gained during the construction.

The strain gauges in Bund 2 are mobilized more than in Bund 1. Their position and orientation are the main reasons for this difference. In Bund 2 the geogrids are placed closer to the front face and oriented horizontally, while in Bund 1 they are farther from the front face and oriented vertically. Also it may be stated that the horizontal orientation of the geogrids facilitates the construction and maintains its position during compaction.

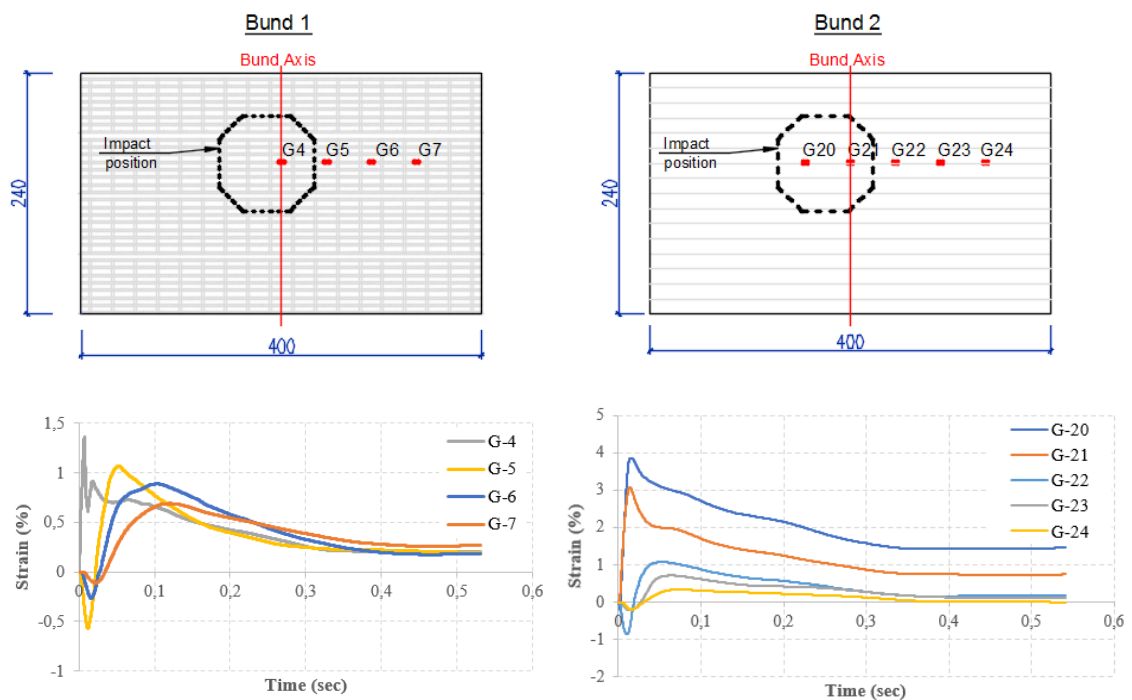


Figure 7. Data from strain gauges placed at the geogrids of Bund 1 (left) and Bund 2 (right).

Bund 3 which was not reinforced with geogrids but only with the flexible steel mesh wrapping, was equipped with three force meters in order to measure its mobilization. It turned out that this mesh had an important role in distributing the effect of the impact to a larger area and contributes to the global stability by mobilizing more soil mass.

4 CONCLUSIONS

The impacts on the three reinforced soil bunds showed that this type of barrier is able to stop effectively the blocks with energy 170kJ that corresponds to 4590kJ in the real scale. The bunds tested are more risked by overturning than shear failure that is caused by the block penetration. However, in our case the limited length of the bunds may cause this and real scale tests with a longer bund are required to verify this phenomenon.

This experimental campaign provided very useful information regarding the resistance and failure mechanism of the reinforced soil bund with vertical faces. This data will be used to design the forthcoming tests in real scale and higher energy level. In general, it may be stated that this solution looks promising and it may lead to the design of more elegant and cost effective reinforced soil barriers.

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