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Field performance of instrumented geosynthetics reinforced soil walls under large scale blast loading

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ABSTRACT: Severe damage to property and injury to human lives can be induced by accidental detonations or terrorist bomb attacks. The geosynthetics Reinforced Soil (RS) structures are capable of protecting structures and human lives from blast effects. Thus, explosive charges of 5 to 27 ton equivalent TNT were detonated to enable the investigation of the performance and safety margins of RS walls against different levels of blast loading. The RS walls were designed with varying dimensions and located at different scaled distances. A wide variety of instruments such as air pressure transducers, accelerometers, total pressure cells and specially designed strain gauges on geotextiles were used to record the blast loading and response of RS walls during these blast events. The field tests were conducted successfully and the instrumentation systems worked with high fidelity. Test results show that RS walls performed very well during the large blast events. Except RS0, all other RS walls survived and were structurally stable only with limited deflections and some minor damages to the surfaces. One of RS walls, which was specially designed with narrow section and located at small scaled distance, experienced more than 400 mm horizontal deflection, and hence this wall was considered as just reached its ultimate serviceability limit state. For all RS walls, whether survived or collapsed, no sharp secondary debris was produced. Thus, RS walls have great potentials in protective applications against blast effects.

1 INTRODUCTION

As a natural material, soil is widely used for civil and military structures to absorb ground shock and stop sharp debris from explosives. Unreinforced soil structures, which do not have enough shear strength and occupy large areas, make them not suitable for applications as aboveground protective structures. With inclusion of modern soil reinforcing materials such as geotextile, soil structures can be effectively used in the protection of property and personnel from accidental explosions of stored explosives or terrorist bomb attacks due to their rapid construction, cost-effectiveness, minimal occupied ground area, ability to withstand large deformation before failure and high tolerance for differential settlements.

It was shown in previous research (e.g., Southwest Research Institute, 1980; Lu et al., 2001; Ng et al., 2000) that soil and soil structures have excellent blast energy-absorbing capabilities. However, only limited information is available on the field performance of RS structures subject to blast loads. Thus, research is needed to investigate the field performance and the safety margins of Reinforced Soil (RS) walls against large blasts.

In 2002 blast trial, seven full-scaled reinforced soil (RS) walls were constructed and tested under two separate detonations in Woomera, Australia. The typical configuration of a RS wall is shown in Figure 1. The vertical spacing between adjacent geotextile layers is 0.5 m. During the 27 ton blast, RS0, the wall situated at 1 m from the denotation, collapsed, while all other walls survived the blasts with only minimum deflections.

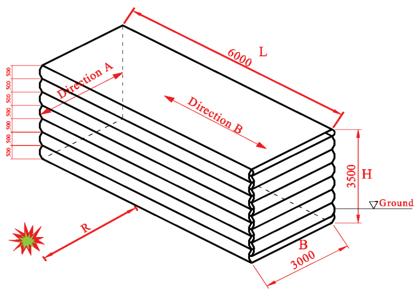

Figure 1. Typical configuration for RS wall.

To further investigate the safety margins of RS walls subjected to blast loading, four more RS walls

Table 1. Layout of RS walls for blast tests.

Charge Weight	Target	R (m)	$Z = R/W^{1/3}$	Height# H(m)	Width B(m)	Length L(m)	Geotextile
27 ton TNT (2002)	RS0	<10	<0.33	4.1	7.8	15.6	Type 1
	RS1	60	2.00	3.0	6.0	7.8	Type 1
	RS2	60	2.00	3.0	6.0	7.8	Type 2
	RS3	90	3.00	3.0	6.0	7.8	Type 1
5 ton TNT (2002)	RS4	34	1.99	3.0	6.0	7.8	Type 1
	RS5	34	1.99	3.0	6.0	7.8	Type 2
	RS6	51	2.98	3.0	6.0	7.8	Type 1
6 ton TNT (2004)	RS1	23	1.27	3.0	3.0	6.0	Type 1
	RS2	23	1.27	3.0	2.0	6.0	Type 1
	RS3	36	1.98	3.0	2.0	6.0	Type 1

Note: # with 0.5 m embedment into ground.

were tested to the detonation of 6 ton equivalent TNT in 2004. As shown in Table 1, three of them were also reinforced with type-1 geotextile while with narrower sections and being placed at smaller scaled distance Z. During the blast, RS2 achieved 400 mm horizontal deflection and was deemed to have just reached its ultimate serviceability limit state. Walls RS1 & RS3 survived with large deflections.

In this research, the effect of the air blast pressure is the main concern for RS walls. The peak air blast pressure is directly related to the scaled distance Z.

It is defined as the ratio of the distance over the cubic root of charge weight. Targets with smaller Z will be subject to higher blast pressure. RS2 in 2004 blast trial was located at Z = 1.27 and was subject to a peak air blast pressure of 1250 kPa.

In this paper, the extent of damage, typical results of wall deflections, air blast pressure, and dynamic soil pressure will be presented and discussed. Finally, the design chart for RS walls in protective applications was presented.

2 DEVELOPMENT OF RS WALLS FOR FIELD BLAST TRIALS

The design of RS walls was based on the previous experience and a preliminary numerical modeling of RS walls subject to blast loading. The dimension and configurations are shown in Table 1. The technical data for geotextile and soil for construction was listed in Table 2 and Table 3 respectively.

In the design for 27 ton blast, RS0 was expected to collapse during the blast and shield blast pressure and fragments for other targets. RS1, RS2 and RS3 were designed to remain stable. The performance of RS1 and RS2 were used to compare the effect of different geotextile materials as they were located at the same scaled distance. In order to compare the effects of different levels of detonation on RS walls, RS4, RS5 and RS6 in the 5 ton blast had identical configuration and were located at the same scaled distances as RS1, RS2 and RS3 in 27 ton blast.

The specific objective of the 6 ton blast of RS walls in the trial 2004 is to investigate the safety

Table 2. Technical data of the geotextile.

	Unit	Type 1 geotextile Polypropylene needle punched non-woven base with high strength PET yarns	Type 2 geotextile 100% polypropylene needle punched non-woven
Orientation of reinforcement	–	Mono-directional	Bi-directional
Tensile strength (T_{ult}) (MD/CD)	kN/m	200/10	28/28
Elongation at break (MD/CD)	%	13/–	80/40 (maximum)
Thickness	mm	2.9 (@2kPa)	3.2 (@2kPa) 1.5 (@200kPa)
Mass	g/m^2	540	385

Note: MD – Machine Direction; CD – Cross Direction

Table 3. Properties of *in-situ* soil for construction.

Properties	Unit	Value
Specific Gravity of soil	–	2.65
Natural water content	%	7.7
Optimum Water Content	%	23.5
Water content at construction	%	20
Bulk Density	kN/m^3	18
Friction angle	Degree	35
Cohesion	kN/m^2	20

margins of RS walls under large blast loading. Thus, they were designed with narrower sections and were located at smaller scaled distances. RS2 was expected to just collapse during the blast while RS1 and RS3 were expected to survive and produce large deflections.

The internal stability of the RS walls under self weight and vertical surcharge were checked. For RS1, RS3, RS4 and RS6 (2002) which were reinforced by Type-1 geotextile, the minimum factor of safety against rupture failure is 11.2 and the minimum factor of safety against pullout failure is 10.8. For RS2 and RS5 (2002) which were reinforced by Type-2 geotextile, the minimum factor of safety against rupture failure is 1.6 and the minimum factor of safety against pullout failure is 10.8. For RS1, RS2 and RS3 (2004) which were also reinforced by Type-1 geotextile, the minimum factor of safety against rupture failure is 11.2 and the minimum factor of safety against pullout failure is 8.1. Thus, all these RS walls were safe under self weight and vertical surcharge. They also had some safety margins to resist against blast loading.

As all RS walls in the tests had 0.5 m embedment into ground, the bottoms of the walls are considered as fixed. The RS wall would behave as a cantilever under blast pressure.

3 FIELD PERFORMANCE OF RS WALLS IN BLAST TRIAL 2002

During the 27 ton detonation, the wall RS0 collapsed with 20% of its reinforced soil mass still sprawling at the location. Due to extremely high temperature developed during the blast, soil was baked and turned into grey colour while some burned geotextile pieces were observed to have mixed with soil boulders.

RS1, RS2 & RS3 survived the 27 ton blast with less than 100 mm peak horizontal deflections. It was observed that small pieces of geotextile placed at the corners of the RS walls, aimed to bridge the longitudinal and transverse geotextile, were partially pulled out by the blast pressure and the soil fell out from the corners. The deflection of RS2 was only slightly higher than that of RS1 though the modulus of type-2 geotextile is much higher than that of type 2. It shows that the difference of geotextiles did not significantly affect the performance of RS walls in such cases.

RS4, RS5 & RS6 survived the 5 ton blast with small deflections while arresting fragments from the detonation. The performance of these walls was similar to that of RS1 to RS3 in 27 ton blast.

Further details of RS walls in this trial can be found in the literature (He et al. 2004).
During the blasts, the deflection of RS walls is small; hence the safety margin of RS walls should be further investigated in the following field trial.

4 FIELD PERFORMANCE OF RS WALLS IN BLAST TRIAL 2004

As shown in Table 1, RS walls were designed with smaller width B and placed at a smaller scaled distance Z in this trial. The RS walls were reinforced by geotextile Type 1 with configurations shown in Figure 1. For the convenience of comparison, RS1 and RS2 were designed at same scaled distance but had different B/H ratios. RS2 and RS3 had same B/H but were located at different scaled distances. Also, as RS2 had the smallest B/H and had the smallest Z, it was expected to produce the largest deflection.

After the trial, it was surveyed that RS2 had more than 400 mm horizontal deflection and was deemed to have just reached its ultimate serviceability limit state, as planned. RS 2 before and after the blast is shown in Figure 2. The Deformed shaped of RS2 is shown in Figure 3. The typical air blast pressure and soil pressure are shown in Figure 4 and 5 respectively.

Figure 2. RS2 before and after 6 ton blast (Blast Trial 2004).

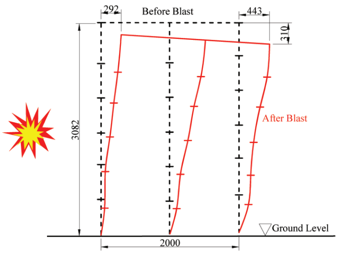

Figure 3. Deformed shape of RS2 (Blast Trial 2004).

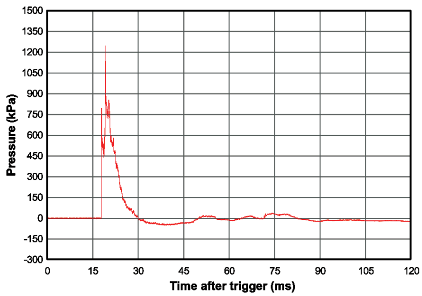

Figure 4. Typical blast air pressure (Blast Trial 2004).

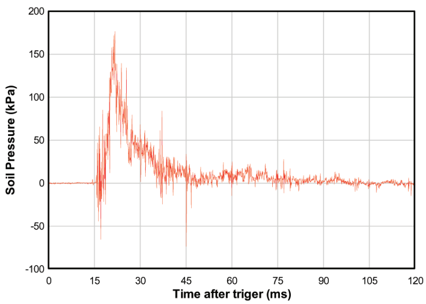

Figure 5. Typical soil pressure (Blast Trial 2004).

RS1 and RS3 remained stable with 100 to 200mm horizontal deflection. The further details of this trial can be found in literature (Chew et al. 2004).

5 THE DESIGN CHART OF RS WALLS IN PROTECTIVE APPLICATIONS

As the deformation is the most apparent response of RS walls during a blast event, it can be used to indicate the performance of a RS wall. Thus, the peak deflection at the upper corner at the rear facing (DX) of the RS wall is a good indication of the degrees of damage of RS walls; hence it is used as an index of the stability of RS walls under blast loading in this research. The deflection of all the RS walls in Woomera blast trials were surveyed and displayed in Figure 5.

As shown in this Figure, the above ground height of the wall is defined as H. The ratio of DX/H is used as a benchmark to judge the stability of RS walls under blast loading. Based on the results of previous blast tests, the ultimate serviceability limit is set as DX/H = 15% for permanent structures and 20% for temporary structures. As shown in this figure, the stability (indicated by DX/H) is a function of scaled distance Z, B/H ratio of the wall and the tensile strength of reinforcing materials.

If the scaled distance of the structure to the detonation is known, the allowable peak deflection ratio DX/H for the RS wall is selected according to its importance, then B/H and reinforcing materials can be decided from the chart. If the B/H ratio and reinforcing material are known, the expected deflection ratio DX/H can be predicted by using this chart.

At serviceability limit state (DX/H = 15%), the wall is considered as having a factor of safety (F.S.) of 1.0. Thus, the factor-of-safety with respect to the relative maximum wall deflection can be defined

$$F{\cdot}S_{DX} = \left(\frac{DX}{H}\right)_{\substack{\text{At-serviceability}\\ \text{lim-state}}} \Bigg/ \left(\frac{DX}{H}\right)_{\substack{\text{At-any-given}\\ \text{-loading}}} \quad (1)$$

For example, if the deflection ratio *DX*/*H* is found to be 5% from the chart, given $Z = 2.0$ & $B/H = 1.0$, then

$$F{\cdot}S_{DX} = \frac{15\%}{5\%} = 3 \quad (2)$$

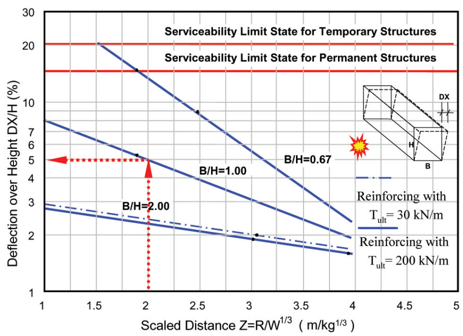

Figure 6. The design chart for RS walls.

6 CONCLUSIONS

During the large scale field blast tests, the type-1 geotextile had about 0.3~0.5% peak tensile strain. The type-2 had 0.5~1.0% peak strain. It was also observed that the maximum deflection of the RS wall was affected by the difference of geotextile (T_{ult} = 200 and T_{ult} = 30 kN/m). As the total amount of geotextile is almost the same, and the rupture of geotextile was not observed after the blast events, the difference must be due to the modulus of geotextile. The modulus of type-1 geotextile is more than 20 times of that of type-2 geotextile. However, the total amount of geotextile installed is quite small compared to the volume of soil in the RS wall. Hence, the difference of peak deflection of RS walls reinforced by these two types of geotextile is small.

The geotextile in the RS wall provides containment for soil. The reinforcing function mainly works at the facings and near facings.

As a summary, the stability of RS walls is a function of scaled distance, width over height ratio (B/H), and tensile strength of the reinforcing materials. Based on this, a design chart has been developed which can be very useful to aid the design of RS walls for protective applications.

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