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Geosynthetic reinforcement for the protection of buried pipes against surface surcharge

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ABSTRACT

Damages on pressurized buried pipes can cause major accidents with significant material losses and not rarely the loss of lives. Reinforcement using geosynthetics can be used to protect buried pipes against damages caused by surcharges applied on the soil surface. This paper presents and discusses a model study on the influence of the presence of geosynthetic reinforcement to reduce the stress distribution around buried pipes and strains along the external surface of the pipe caused by surface surcharge (plane-strain condition). Experimental model tests were carried out using a rigid steel box 1500 mm long by 500 mm high by 500 mm high, with a transparent frontal face to allow visual inspection of displacements and failure mechanisms. Different types of reinforcements and reinforcement arrangements were tested. Three types of reinforcements were used with varying values of tensile stiffness. A reinforcement layer installed horizontally above the pipe, inverted U around the pipe and the reinforcement completely enveloping the pipe were the reinforcement arrangements used on the laboratory tests. The results showed the beneficial effects due to the reinforcement presence, such as significant reductions in vertical stresses transmitted to the pipe. Furthermore, it was observed that the presence of the reinforcement reduced compressive strains at the top and bottom of the pipe in comparison with the situation without the presence of the reinforcement.

RESUMO

Danos em canos enterrados pressurizados podem causar acidentes graves com perdas materiais significativas e não raramente a perda de vidas. O reforço geossintético pode ser usado para proteger tubulações enterradas contra danos causados por sobrecargas aplicadas na superfície do solo. Este artigo apresenta e discute um estudo de modelo 1:4 sobre a influência da presença de reforço geossintético para reduzir a distribuição de tensões em torno do duto enterradas e as deformações ao longo da superfície externa do tubo causada por sobrecarga superficial (condição de deformação plana). Os ensaios experimentais foram realizados em uma caixa de aço rígida de 1500 mm de comprimento por 500 mm de altura por 500 mm de altura, com face frontal transparente para permitir a inspeção visual dos deslocamentos e dos mecanismos de falha. Diferentes tipos de reforços e arranjos de reforço foram testados. Três tipos de reforços foram usados com valores variáveis de rigidez à tração. Os resultados mostraram os efeitos benéficos devido à presença de reforço, como reduções significativas nas tensões verticais transmitidas ao tubo. Além disso, observou-se que a presença do reforço reduziu as tensões compressivas no topo e no fundo do tubo em comparação com a situação sem a presença do reforço.

1. INTRODUCTION

Buried pipes represent one of the most safe and inexpensive mode of fluid transport. These structures interact strongly with the surrounding soil and, due to differences in material rigidity, cause intense stress redistribution. Thus, it is necessary to adapt the structure to the environment, in order to maximize uniformity of the surrounding tensions and, if possible, reduce them. However, by interconnecting large distances, pipelines may be susceptible to increased risks of leaks and explosions, especially in urban, industrial and agricultural regions, where there is greater possibility of interference and increased loads.

Many accidents involving buried pipes are associated with the operating conditions, conservation and maintenance of the ducts, which can cause damage and lead to rupture of pipes and / or connections due to mechanical failure, operational failure, nature action and human action. In addition, it can be note that accidents are caused by the lack of knowledge of the existence of a buried pipe or of its accurate location

NTSB (2016) reports the case of the explosion and fire cause for collapsed due to a natural gas-fueled explosion in the community of Silver Spring, Montgomery County, Maryland (Figure 1a). As a result of this accident, 7 residents died, 65 residents were transported to the hospital, and 3 firefighters were treated and released from the hospital. Other similar accident was reported in 2018, where a series of fires and explosions occurred in upstate Massachusetts. In this case, the incident was caused by the overloading of the natural gas distribution system, where the company responsible released high pressure gas into a low pressure gas distribution system. Several structures were damaged and others were completely destroyed by the explosion, as shown in Figure 1b.

(a) Montgomery County, Maryland (NTSB, 2016) (b) Massachusetts (NTSB (2018).

Figura 1. Some accidents with gas pipelines.

According to Palmeira (1987), the reinforcement soil through inclusions consists in installing them in regions of the mass where it will cause favorable redistributions of stress and deformation. Inclusion causes an increase in the strength of the composite material and a decrease in its compressibility. Studies on the use of geosynthetics as a soil reinforcement can be found in the literature, like that a study of geosynthetic behavior as a soil reinforcement element. In recent years, geosynthetic have been used as reinforcement elements in geotechnical engineering.

Several researchers have studied the beneficial effect of geosynthetic reinforcement to protect buried pipes or to reduce the consequences of explosions (Mohri et al. 2003; Plácido 2006; Tafreshi et al. 2008; Palmeira and Andrade 2010; Khatri et al. 2014; Palmeira and Bernal 2015; Hegde and Sitharan 2015). Viana and Bueno(1988) analyzed the use of geotextile inserted in the soil mass surrounding the buried pipe to evaluate the reduction of efforts from the simulation of the construction of an overlying backfill. Through the results, obtained in tests, it was possible a reduction of stress on the structure in all tested configurations, which allows us to conclude that the geotextile is an efficient material. This study contributed to the creation of a new important method to reduction the vertical stress denominated Geovala.

Palmeira and Andrade (2010) carried out model test simulating influence of the geosynthetic reinforcement to reduction the effects on buried pipe caused by a penetration of a rigid plate They observed that the penetration of the load plate into the ground required greater forces in the geosynthetic reinforced mass and that the inclusion of the reinforcement favorably altered the stress state and around the buried pipe, achieving total stress reductions of up to 81% at the top of the duct in the geogrid test compared to the reference test without reinforcement

Kou et al. (2018) presented an analysis of the influence of geotextile reinforcement width on pressure distribution around the flexible pipe. Experimental tests have shown that the effect of the reinforcement benefit occurs as the width of the reinforcement is increased, ranging from one to four times the diameter of the tube (= 160 mm). Elsheshenyet al. (2019) evaluated the behavior of flexible pipes buried in unreinforced backfill and reinforced with geogrid subjected to cyclic loading. The study addressed the influence of the installation depth of the pipe and the arrangement of reinforcement in the mass.

In this context, this paper presents and discusses the results of model tests performed in the laboratory to assess the influence of the presence of geosynthetic layers in protecting buried pipes against the effects of surface surcharges.

2. METHODOLOGY USED IN TEST

2.1 Equipament

Model test were performed the use of geosynthetic reinforcement for the protection of buried pipes submitted to loads located on the surface of the soil by means of model tests (1:4 scale). The model tests were carried out in a rigid steel box with dimensions 1500 mm (length) x 500 mm (height) x 500 mm (width), and with a transparent (acrylic) frontal face 12 mm thick. The load reaction frame was attached a hydraulic jack with capacity of 100kN was connected to it as shown in Figure 2.

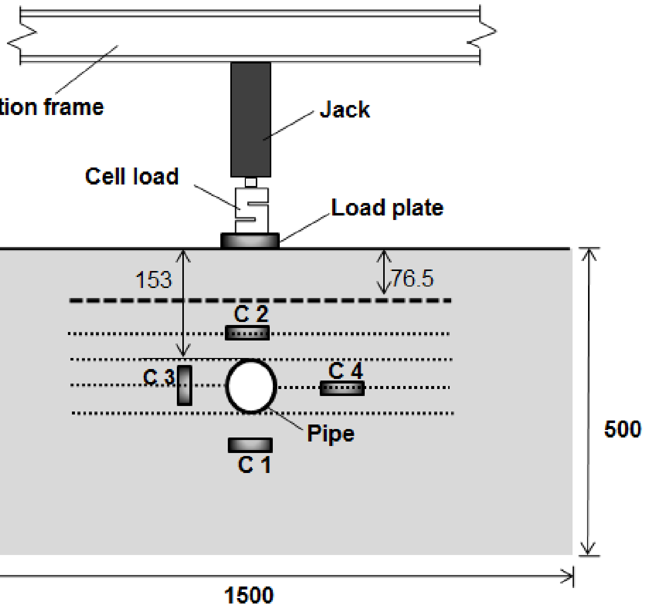


Figure 2. Model test (Dimension in mm).

2.2 Materials

The backfill material used in all test was a uniform sand, with particle diameters varying between 0.075 mm and 1.2 mm (D_{10} equal to 0.16 and D85 equal to 0.39 mm). The proprieties of soil are present in Table 1. The construction of the soil layer was achieved using the sand rain technique in order to obtain a homogeneous and dense soil mass (relative density of 80%), yielding to a dry unit weight of 16.7kN/m³. Horizontal colored sand layers and markers were installed at different locations at the sand–acrylic wall interface to assess failure mechanisms and displacements of the soil mass during the tests.

Table 1. Soil properties.

Properties	
Mean particle diameter, D_{50} (mm)	0.27
Coefficient of uniformy, C_u	1.8
Soil particle density	2.64
Relative density (%)	80
Friction angle (°)	35-43
Soil Classification (USCS)	SP

2.3 Geogrid

Three different types of geogrids with varying values of tensile stiffness were used as reinforcements. Table 1 presents the main physical and mechanical properties of the reinforcements. The aperture sizes of the geogrids varied between 0.2 mm x 0.2 mm to 2 mm x 2 mm. Their mechanical properties were obtained by tensile tests. The model grids tested cover a wide range of tensile stiffness values under prototype conditions (for geometrical scales factor of 4 the prototype grids would be 16 times stiffer than the model grids).

Table 2. Geogrid properties.

Reinforcement	Aperture size (mm)	$J_{5\%}$ (kN/m)	ε_{max}(%)	Tmax (kN/m)
R1	0.2 x 0.2	8.75	41	1.45
R2	2.0 x 2.0	140	9	12.0
R3	1.0 x 1.0	103	28	20.5

Notes: $J_{5\%}$ = tensile stiffness at 5% strain, ε_{max} = maximum tensile strain and T_{max} = tensile strength. Tensile properties using ASTM D6637 method of test.

2.4 Steel pipe

A 76.5 mm external diameter steel pipe was used in the research program. The pipe had a thickness of 1.4 mm thickness with 490 mm long. The pipe was instrumented with strain gauges to assess the strains developed along the pipe perimeter as a result of surcharges applied by a100 mm wide rigid platen (plane strain conditions). The strain gauges were installed at the central cross-section of the pipe spaced 45°. The Figure 3 shows the preparation of the bonding of strain gauges.

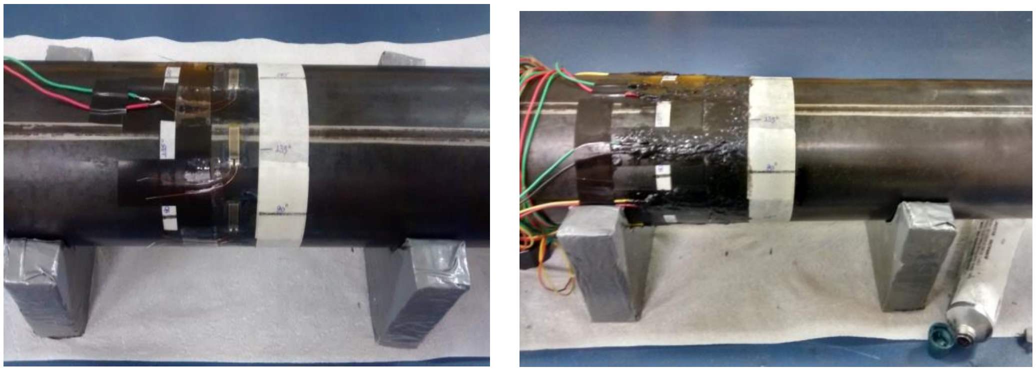


Figure 3. Preparation of the instrumentation of the pipe.

2.5 Test details

The research methodology consists of conducting model scale tests to evaluate the influence of the presence of reinforcement in massifs where buried pipes are requested by surface loads (overload). The proposed test condition the overload will be applied concentric to the pipe by means of a 250 mm wide rigid plate simulating flat deformation conditions. The pipe was installed at a depth of 153 mm (= 2 pipe diameters).

Three different types of geosynthetics, specifically geogrids, will reinforce the sand mass containing the buried pipe. The reinforced tests will be performed with three distinct geometric configurations: horizontal layer above the pipe and inverted U shaped reinforcement and enveloped reinforcement. Figure 4 illustrates the arrangements to be used.

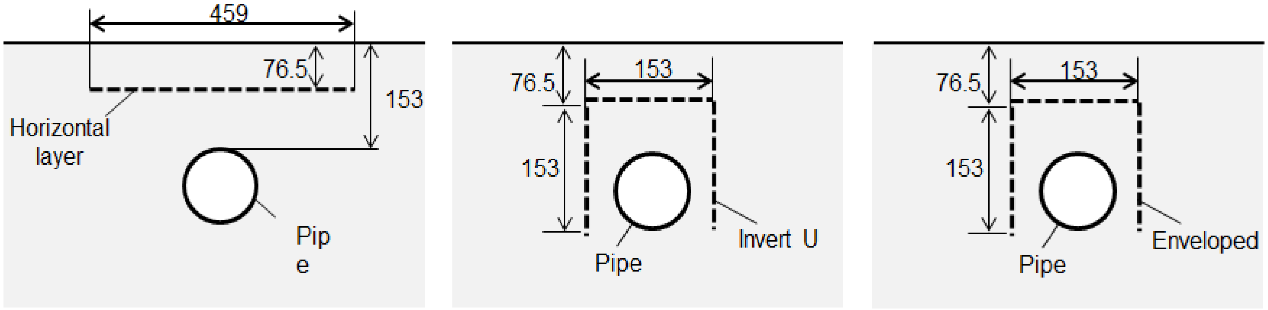


Figura 4. Reinforced arrangements.

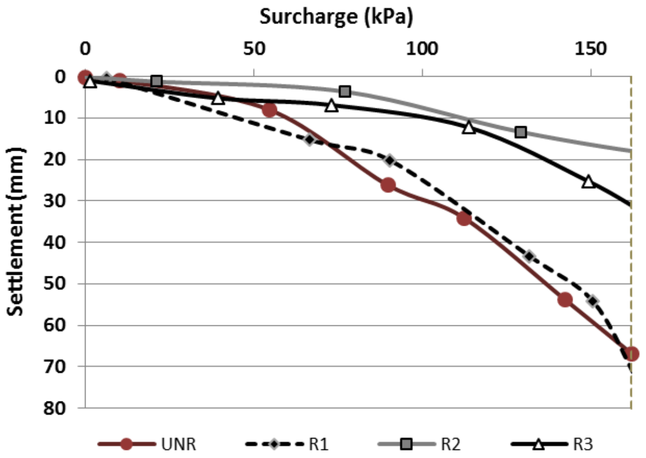
All tests were monitored by instruments such as a load cell, electric total stress cells and strain gauges glued to the external pipe surface. The vertical displacements and the monotonic load applied to the plate were measured by displacement transducers and a load cell, respectively. Four pressure cells were installed at different locations around the pipe to assess the influence of the reinforcement presence on the pressure distribution. In addition, for a better visualization of the displacement field and failure mechanisms, markers and horizontal colored sand lines were installed in contact with the transparent face of the test box. A photographic technique was employed to register markers' displacements and failure mechanisms.

3. RESULTS

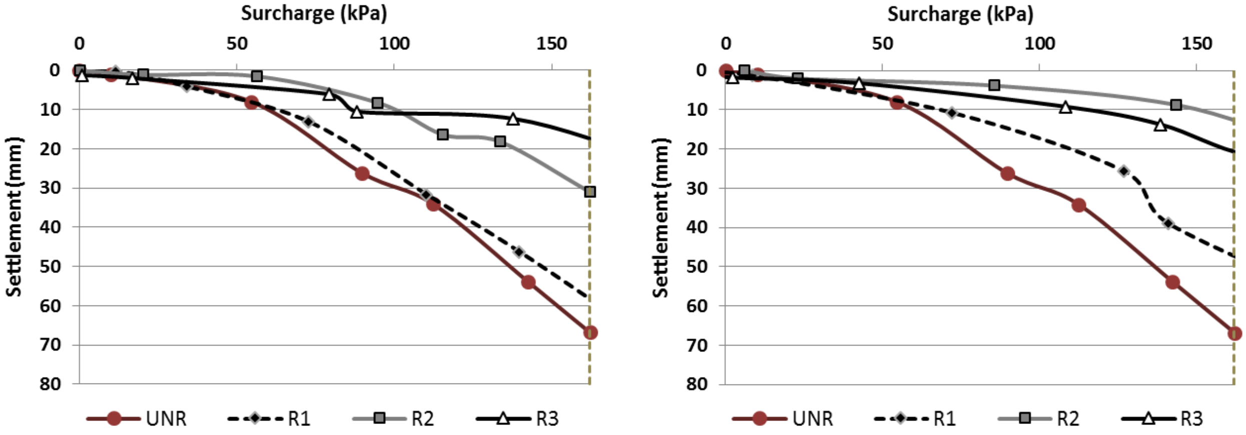
Based on the results provided by the instrumentation used in the model tests, it was possible to analyze the soil-pipe interaction regarding the stress distribution in the soil and deformations suffered by the pipe due to the vertical overload applied to the surface.

3.1 Loading Plate Settlement

Figure 5a-c presents the results obtained from the tests performed using the reinforcements. In the first case, horizontal layer, it can be seen that the settlement in unreinforced test was 67 mm, for a maximum applied pressure on the landfill surface of 162 kPa. For this same pressure level in the reinforced tests, indicating that the displacements obtained in the tests performed with the reinforcement R2 and R3 were smaller than the reference test, results shows a reduction between 55 to 75%, respectively.



(a) Horizontal layer



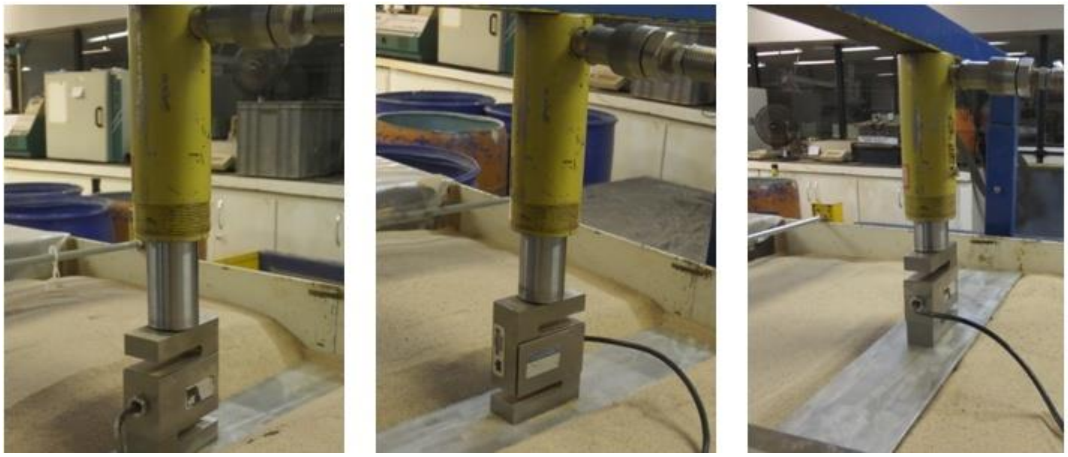
(b) Invert U

(c) Enveloped arrangement

Figura 6. Plate Settlement versus surcharge.

In this arrangement it can be noted that reinforcement R1 was similar in behavior for the reference test as in the inverted U-reinforced tests, as shown in Figure 5b. Besides that, for the inverted U-reinforced the results showed a similar behavior to that observed in the layered arrangement. In this case, the reinforcements R2 and R3 regarding the increase of the resistance to the penetration of the plate in the soil, reducing up to 75%.

The enveloped arrangement can be considered the most beneficial among the geometric configurations under study. In these tests can be noted a decrease in plate vertical displacement values between 29 and 84% (Figura 5c). In this particularly arrangement, it can conclude that geometrical configuration and reinforcement stiffness were the factor in this analysis because there were more resistance for settlement. Figure 6 presents the settlement in the reinforced test. However, it is noteworthy that the effect of the benefit is not observed for the lower pressures (less than 25 kPa).



(a) R1 (b) R2 (c) R3

Figure 6. Plate Settlement in the enveloped reinforced test.

3.2 Stresses on the pipe

In the model tests the maximum vertical stress (σ_{unr}) applied on the soil surface in the unreinforced test was equal to 162 kPa, which would correspond to a vertical stress value close to typical tire pressures under prototype conditions. For comparison purposes, the results obtained in reinforced tests for that vertical surcharge will be the ones presented.

The vertical stress at the bottom of the pipe was registered in the cell 01 with the maximum value was equal 218 kPa. It can be observed in the reinforced mass tests that the stress values recorded in the region below the pipe were lower compared to the reference test. Particularly, it can be noted that for the inverted and enveloped U configurations they presented larger stress reductions than the layered arrangement.

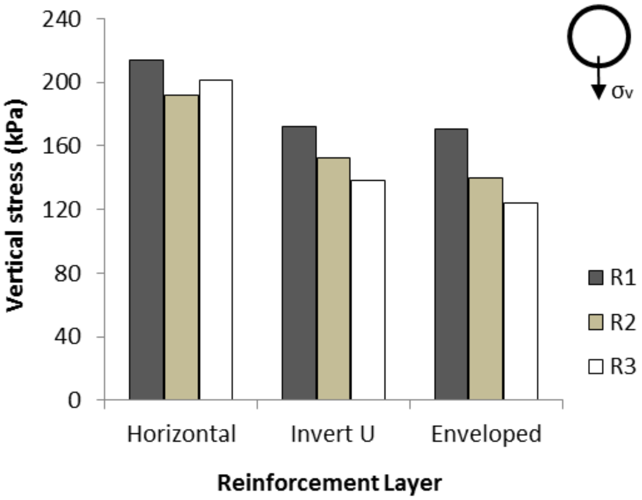


Figure 7. Vertical stress measured in the bottom of pipe for cell 1.

The highest pressures in the tests were recorded by strain cell 02, above the top of the tube in the unreinforced test (= 415 kPa). In this region the highest stresses are concentrated due to the proximity to the surface. The results obtained by this cell are presented in Figure 8. It can be seen that the presence of reinforcement for all configurations led to a reduction in the stress levels in the mass compared to the unreinforced test. However, in the inverted U and enveloped arrangement, there are significantly reductions in soil stress values, particularly for reinforcements R2 and R3. Therefore, it is observed that the tensile behavior in the reinforced mass depends as much on the geometric installation configuration as on the tensile strength of the reinforcements. The vertical stress reductions between 13% to 75% in the region above the top of the tube, depending on the reinforcement and arrangement considered.

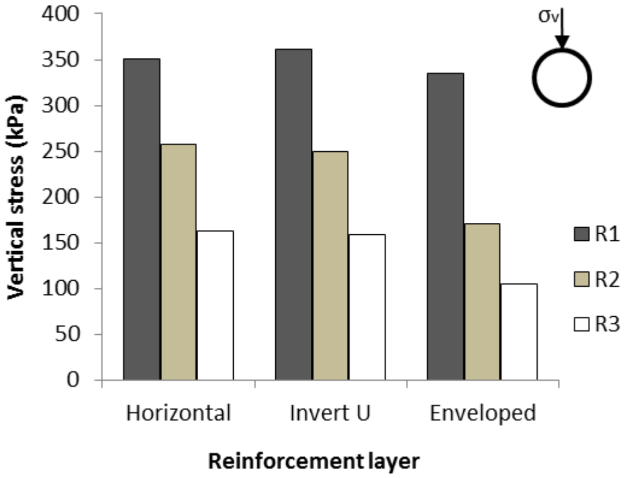


Figure 8. Vertical stress measured in the top of the pipe for cell 2.

Horizontal stresses in the reinforced tests were similar to those described in the cell 02 readings, where it was found that the presence of the reinforcement contributed to reduce the horizontal stress values in the soil between 8 and 55%. In all cases the enveloped arrangement was the most effective in reducing stresses in the tube region. Regarding the tensions recorded in the lateral region of the tube, it is possible to notice the lower values of horizontal and vertical tension recorded in comparison with the regions above and below the tube. Such behavior occurs because the stress concentration occurs primarily above the pipe due to the approximation with the loading area, justifying the stress values obtained by cell 02.

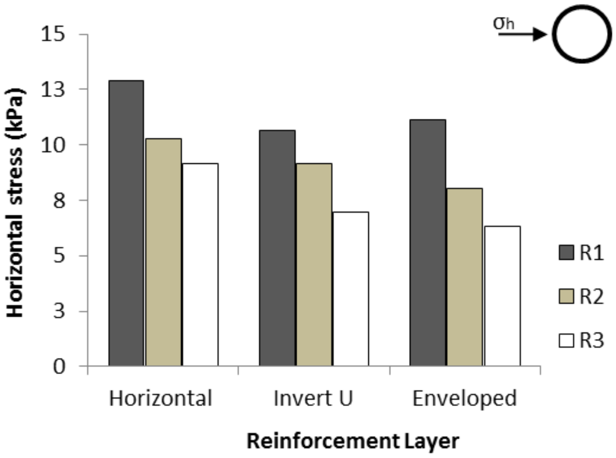


Figure 9. Horizontal stress registered for pressure cell 3.

3.3 Strains in the pipe

Figure 5a-c shows the distribution of deformations along the pipe perimeter in the non-reinforced and reinforced tests for a maximum stress level of 162 kPa (σ_{SR}) applied to the ground surface. According to the results of the unreinforced tests (SR), the highest values of -577 and -489 με were found in the instrumented points for measuring the deformation of the pipe crest (SG 0°) and bottom (SG 180 °) points, respectively. At all the other locations, tensile strains varying between 308 and 462 με were obtained at the end of the test.

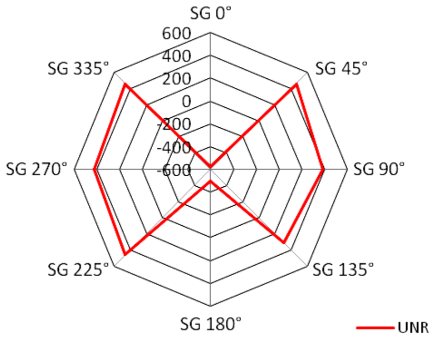
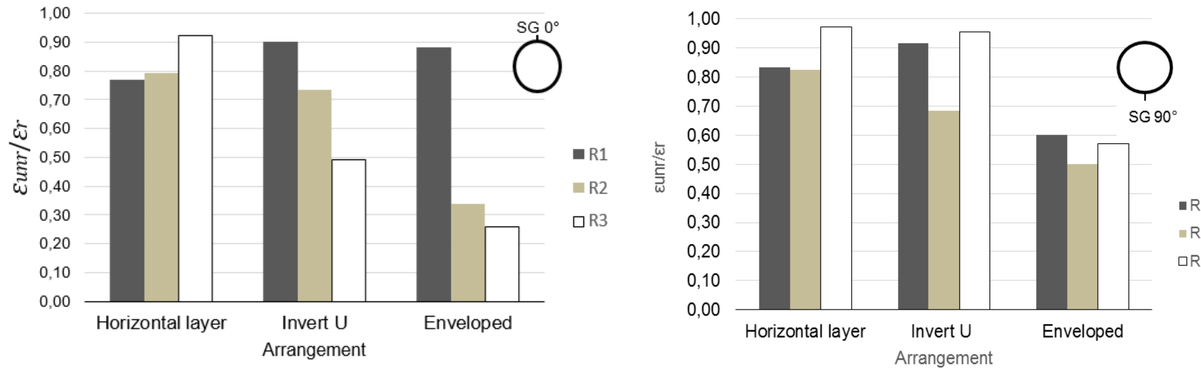


Figure 10. Strain distribution along the pipe perimeter in the unreinforced test.

It was verified that the main compression deformations occurred in the crest and the bottom pipe, being these compression deformations. The ratios between strains in reinforced (ε_r) and unreinforced (ε_{unr}) tests at the crest of the pipe for a surface surcharge of 162 kPa is shown in Figure 11a. Significant reductions in compressive strains at that location can be noted, particularly for the enveloped arrangement. In the inverted U tests, it was shown that the use of R2 reinforcement resulted mainly in lower deformation values at all points evaluated compared to the other tests. For this geometric configuration, deformation reductions of 40% were recorded at crest pipe, while at the bottom the reductions reached approximately 70%. In the enveloped tests there were reductions of about 75% and 65% in the top and bottom deformations, respectively, compared to the unreinforced test.

On the sides, there was an increase of deformation in the reinforced tests up to 34% in the reinforced tests. This may be justified by fact that lower values of horizontal stresses were recorded in the reinforced tests. However, other aspects may have contributed to this behavior, such as the influence of the presence of the pipe, the soil density on the sides of the pipe from the landfill construction method. The variation of strain at the spring line oh the pipe (SG 90°) with the surcharge pressure in unreinforced and reinforced tests are presents in Figure 11b.



(a) Crest pipe

(b) Bottom of pipe

Figure 11. Strains at the pipe for a surface surcharge of 162 kPa

4. CONCLUSION

This paper presented results of model tests on buried pipes with and without the presence of geosynthetic reinforcement. The tests allow the evaluation of the reinforcement potential and reinforcement arrangements, contribute to the reduction or minimization of the magnitude of the efforts in relation to the values introduced when dealing with a surface overload. In general, a reinforcing sheet in is beneficial, contributing favorably to the change in stress state in the mass. A geometrical installation configuration and tension stiffness were important in evaluating the behavior of the backfill landing and, consequently, in the response developed by the soil-pipe interaction.

Furthermore, it was observed that in the tests performed with the most rigid tensile reinforcements there were significant reductions in the stresses transmitted to the ground around the pipe and in the deformations suffered by the pipe. The inclusion of these reinforcements provided relief from vertical and horizontal stresses in the soil surrounding the pipe, regardless of the assumed configuration.

Another important result concerns the deformations suffered by the pipe, where it was verified that the major deformations (compression) occurred at the crest and at the bottom of the pipe. The presence of the reinforcement also reduced significantly the stains in the pipe in comparison with the situation without reinforcement.

5. ACKNOWLEDGEMENTS

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