SOIL IMPROVEMENT OF A RAILWAY EMBANKMENT GROUND IN CROATIA WITH INJECTIONS OF URETEK GEOPLUS® RESIN

AMÈLIORATION DE SOL D'UN REMBLAI DE CHEMIN DE FER EN CROATIE AVEC DES INJECTIONS DE RÈSINE URETEK GEOPLUS®

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ABSTRACT - Due to the placement of a gas pipeline through a railway embankment in Croatia, a tunnel drilling of the underground has been made using the HDD technology. The pipe inserting procedure caused an increase of the stress state in the construction, which resulted in excessive deformations and continues settlements (approximately 5 cm/week). The embankment was built with uniform stone materials, size 5÷20 cm, without small and fine particles characterized by a large share of voids. To increase the stiffness of the constitutive soil of the embankment, injections of high pressure expanding resin Uretek Geoplus® have been made, based on the results of a 3D FEM analysis. During the whole intervention a real time monitoring enabled an accurate control of the operations and major settlements have been prevented.

RÉSUMÉ - Lors de la mise en place d'un gazoduc à travers un remblai de chemin de fer en Croatie, un tunnel a été percé à l'aide de la technologie HDD. La procédure d'insertion de la canalisation a provoqué une augmentation de l'état de contrainte dans l'ouvrage, ce qui a entraîné des déformations excessives et des tassements continus (environ 5 cm / semaine). Le remblai a été réalisé à l'aide de pierres uniformes, de taille 5÷20 cm, sans petites particules, ni fines, ce qui implique une part importante des vides. Pour augmenter la rigidité du sol constituant le remblai, des injections de résine Uretek Geoplus® à haute pression de gonflement, ont été réalisées sur la base des résultats d'une analyse 3D FEM. Au cours de l'ensemble de l'intervention, un suivi en temps réel a permis un contrôle précis des opérations et des tassements importants ont été évités.

1. Introduction

In the month of May 2010 the Uretek company has been contact to perform a ground improving intervention, with polyurethane resin injections, of a railway embankment in Rijeka (Croatia). The project aimed to the execution of an horizontal directional drilling (HDD) through the soil body and the compensation grouting (Pasquetto et al., 2008) with polyurethane resin had to prevent excessive deformations. Several meetings took place to define the guidelines for Uretek intervention and also an executive project has been asked to obtain the authorization for working by the Croatian Railway Company.

1.1. Context framing

The railway embankment was made about 150 years ago on a North-South oriented slope and it's made of a stone replenishment, which fills a previously excavated pit to a depth of about 13,0 m underneath the todays railway. The embankment's base is about 30,0 m long and it's used not only for the railway but also for 2 roads (one on the north side of the railway and another on the south side).

In order to place a gas pipeline below the embankment, a 650 mm diameter tunnel drilling of the underground has been previously made, using the HDD technology. On April 1st, after the tunnel drilling and during the pipe inserting procedure, a landslide under the railway has been noticed, which caused the stuck of the equipment and of the pipe itself.

The stress state in the railway embankment lead to major deformations of it's one part and to a continuous 5 cm/week settlement, which had to be frequently compensated with new stone replenishments, figure 1. The dotted rectangle show the fault zone.

Figure 1. [a] View of the railway embankment from South. [b] Railway embankment with the damage induced by the pipeline HDD installation process before compensation grouting design.

2. Compensation grouting with polyurethane resin injections

Polyurethane resin injections, at high pressure expansion, are frequently used in stabilizing shallow foundations such as road and railway embankments and riverbanks.

The process that determines the improvement of the mechanical properties of the soil is quite often difficult to frame in a theoretical way, because of the intrinsic heterogeneity of the soil and the partially random spreading of the resin.

A correct theoretical interpretation of the resin expansion phenomena is however the base for a correct designing of a compensation grouting intervention and therefore the behavior of the resin injection has been modelled both in an analytical (Yu and Houlsby, 1991) such as in a numerical way (3D FEM analysis).

2.1. The Uretek Deep Injections® method

The injection at a given depth of Uretek Geoplus® resin at high pressure expansion generally determines a notable improvement of the geotechnical properties on the surrounding soil inducing a radial compression and a reduction of the voids ratio due to permeation.

The resin is obtained from a chemical reaction of two components, which cause a quick expansion of the mixture (within a 6''-10'' seconds) that develops a swelling pressure up to 10 MPa.

To establish its main mechanical characteristics, the resin was subjected to vertical unconfined compression tests and swelling tests at the geotechnical laboratory of the

University of Padua. The results reported in figure 2.a show how the compression resistance, σ_c, rapidly increases with the volume weight, γ_r, of the resin.

The tests made it possible also to identify the modulus of elasticity of the resin, E_r, with values between 15 MPa and 80 MPa, comparable to the typical moduli $E_{50\%}$ and $E_{25\%}$ of alluvial soils. This signifies that, in a volume of soil exposed to treatment with resin, the average stiffness of the soil mass does not undergo significant variations.

The values of swelling pressure measured during the tests are indicative of the pressure that the resin can generate whenever it gets injected into the soil (figure 2.b). The state of stress in the ground determines the pressure of expansion to which the resin completes the reaction of polymerization. The final volume weight of the resin and the degree of volumetric expansion, measured at the end of the process, are both functions of such value of stress.

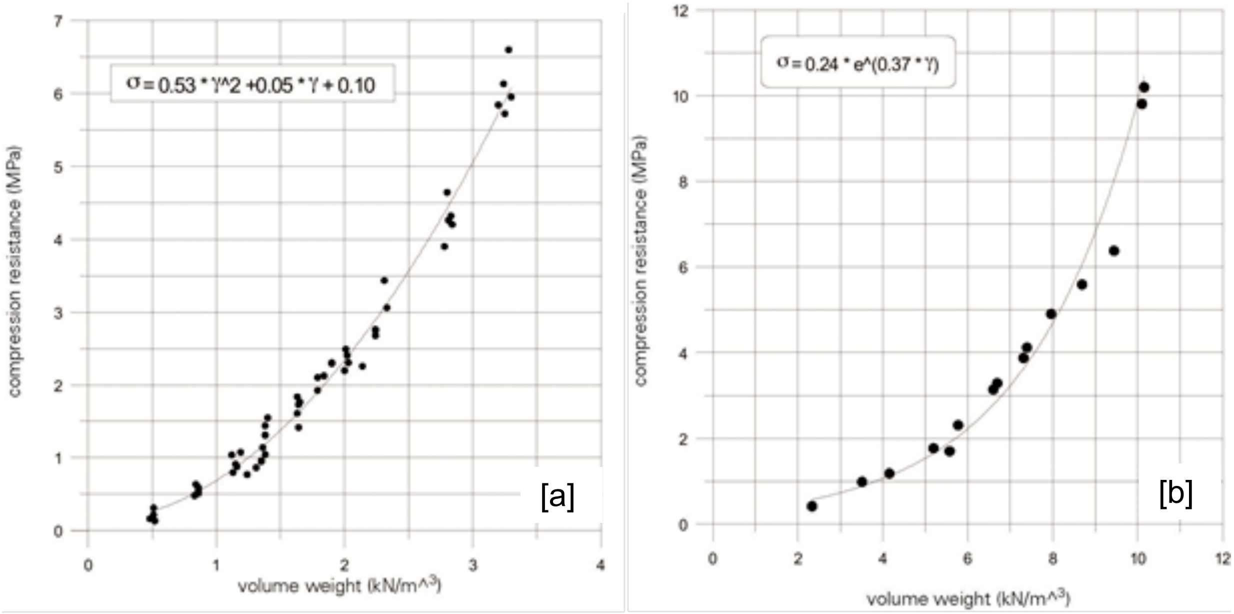

Figure 2. [a] Unconfined compression tests: tendency of the compression resistance, σ_c, with the volume weight, γ_r, of the resin. [b] Swelling tests: tendency of the maximum swelling pressure, σ_{sw}, with the volume weight, γ_r, of the resin.

2.1. Theoretical approach

The process of expansion of the resin, injected into the soil, is theoretically treated with the theory of expansion of a spherical cavity (or cylindrical, if it entails more injections close to each other placed along a vertical axis) in almost static conditions. The soil is characterized by an elastic-perfectly plastic behavior and is exposed to an initial anisotropic K_0 tensional state, with mean pressure:

$$p_0 = (1 + 2K_0) \cdot \sigma_{v0} / 3 + dp \tag{1}$$

where dp represents the increase in mean pressure due to an existing load, calculated at the depth of injection z according to Boussinesque's theory. The geometrical properties of the cavity and the elastic and plastic areas are, with reference to (figure 3):

ra radius of the cavity, an initial value is assumed ra0=0.006 m;

rb radius of the plastic zone, it represents the boundary between the plastic and elastic zone;

r_c radius of the elastic zone, the distance beyond which the stress difference ($\sigma_c - p_0$) is $\leq 0.01 p_0$ (the radius of influence of the injection).

In the first part of the expansion process, as the pressure inside the cavity increase, the soil is in the elastic field. On reaching a certain value of internal pressure the plastic deformations begin; during the expansion process the elastic zone and the plastic one expand until the pressure limit (σ_{lim}) is reached.

The process of expansion is treated theoretically, according to the analytical approach presented by Yu and Houlsby (1991), opting for a large-strain analysis in the plastic zone and a small-strain analysis in the elastic zone.

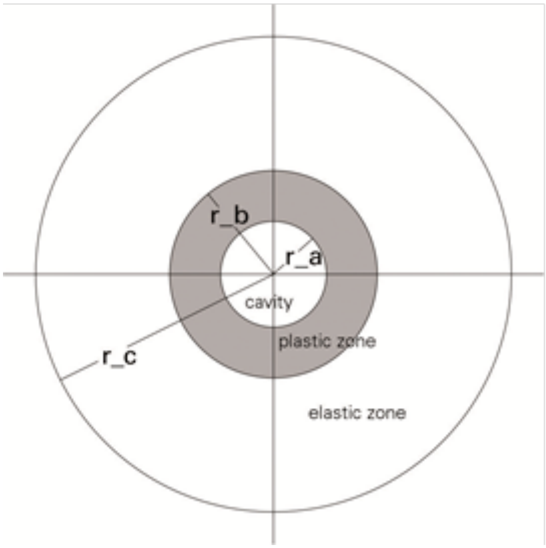

Figure 3. Schematic representation of the plastic and the elastic zones that surround the cavity.

2.2. Numerical approach

In order to analyze the soil volume mostly influenced by the drilling of the pipeline, with the benefit of the Uretek Deep Injections® method, a consolidation of the embankment was studied. The first phase was made by simple computation in order to find out the ring area along the center line of the designed pipeline where the influence of excavation doesn't produce appreciable deformation of the drilling hole.

After the first phase, a second study with a 2D approach and a preliminary 3D FEM analysis has been performed using, respectively, the Phase2 software code (Rocscience Inc., Canada) and the fully 3D software code Midas GTS Geotechnical and Tunnel analysis System (Midas IT Ltd, Japan), which is based on state of the art finite element and graphical technology and enables to generate complex geotechnical models.

2.2.1. Geotechnical Soil Parameter

The railroad embankment was built with uniform stone materials, most likely with stone of irregular shape, size 5÷20 cm, without small and fine particles. This structure is characterized by a large share of voids. According to data collected by drilling and experience in similar building structures on the line Zagreb - Rijeka, a void index around 35% has to be estimated in the upper part of the embankment and 30% in the lower part of it. For the analysis following parameters have been used:

c = 0 kN/m2

φ = 35°
γ = 20 kN/m3
Ms = 15˙000 kN/m2

Natural soil is made of two basic types of materials: a blanket (talus and deluvius) and basic rocks (flysch in lower and limestone carbonate rocks on upper side). These materials have much better physical and mechanical properties than the material the railway embankment is made of. Uniaxial strength of limestone rocks in the weathered zone are not higher than 50 MN/m^2, in less weathered zones up to 100 MN/m^2. The flysch has an uniaxial strength up to 470 kN/m^2 in the superficial layer and up to 1˙100 kN/m^2 down deeper. In hydrogeological terms, carbonate rocks have a good water permeability, while the flysch is almost impermeable. Covering on the flysch (red soil and debris with a thin layer of quaternary deluvious sediment) below the embankment of the road can be considered partially water permeable. For the cover layer over the flysch (at the interface with flysch) in the analysis have been taken following parameters:

c = 0 kN/m2
φ = 19°
γ = 20 kN/m3
Ms = 5˙000 kN/m2

The soil treated with Uretek Geoplus® resin increase, according with the formulae shown on figure 1a, the resistance in terms of effective cohesion equal to 25 kPa and no modification of the frictional angle of the natural soils due to the large dimension of the void. For safety reason, into the calculation, no modification of elastic modulus of the natural soil was assumed.

2.2.2 Simplified estimation of the consolidation ring

In order to identify the consolidation ring dimension a preliminary handmade calculation was done with this simple hypothesis: the soil material is isotropic with Mohr Coulomb material model, initial stress isotropic, soil improvement confined around a concentric circle passing through the centerline of the pipeline according with Yu and Houlsby (1991).

In order to limit the vertical settlement induced by the hole, the ring of treated material has to be large enough to maintain the soil far from the collapse condition and this can be reached if around the treated material the existing natural soil can be close to failure zone but in elastic behavior.

The geometry and the soil characteristic of the site allowed to identify the final limit pressure equal to 82 kPa. By simple calculation the radial pressure that the soil has to have outside the ring of treated material, to remain in elastic behaviour, was equal to 90 kPa with a consolidated ring area of about 2 m all around the hole dimension. Inside the treated ring the soil material can develop plastic condition.

2.2.3. Bi-dimensional approach (2D Analysis)

In order to check the preliminary dimension of the treated ring, a 2D analysis was done to verify the ring dimension; a simplified model was developed and a load surcharge equal to 40 kPa was used to simulate the railway external load.

The main results of the calculation are reported in figure 4. On caption [4.a] are shown the principal shear stresses around the treated soil and close to the hole. As we can observe all the stresses are concentered on the top and on the bottom of the hole and outside the treated ring (represented by the polyline in the figure), no appreciable change can be observed in respect to the internal treated soil material. The assumption of 2 m of treated area around the hole was verified. On caption [4.b] the principal radial stresses around the treated soil and close to the hole is also presented. In this case we can observe that all around the hole there's a concentration of stresses that induce a plastic region all around the hole. On the top, the plastic deformation seems to extend to the limits of the treated soil but the external area seems to be in elastic condition or close to it. On the bottom part, the extension of radial influence doesn't touch the limits of the treated area.

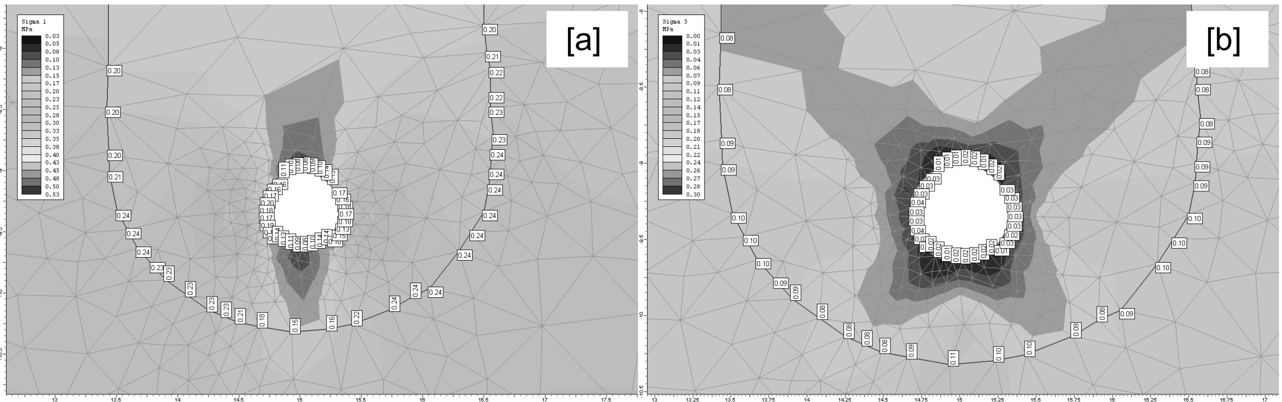

Figure 4. [a] Principal shear stresses around the treated soil and close to the hole. [b] Principal radial stresses around the treated soil and close to the hole.

As a final remarks of the calculation the handmade procedure and the computation analysis give the same results that confirm the reliability of the computation, all around the hole was observed the developing of a plastic zone. The plastic critical zone was found close to the hole internal surface and no plastic condition seems to be reached outside the treated material.

The embankment seems to remain in elastic condition outside the treated zone and the maximum settlement at the top of it was accepted by Railways Authority.

But due to the complex geometry of the problem and due to the low coverage of the pipeline into the embankment a fully 3D analysis was required and presented on next point.

2.2.4. Three-dimensional approach (3D Analysis)

As mentioned above also a fully 3D analysis was done with some simplification of the problem in order to reduce the computational time analysis made with a bi-Xeon workstation. To accelerate the computational time the pipeline was assumed linear and not curved shaped, safety assumption that minimize the coverage of the pipeline close to the top of embankment and close to the above existing road. Also the treated soil material was simulate in a rectangular shape and not in a curved shape. No fault or interface was simulated between the independent soil elements and the model was an extrusion of the geotechnical section where the centerline of the pipeline passed.

In figure 5 is shown the geometrical 3D model with the identification of the different soil type material, according with the geotechnical parameter described above and the treated volume of the embankment. The simulation was done with a progressive removal of the soil around the pipeline in order to simulate the squeezing effect in front of the excavation and the convergence of the entire hole with a step of 2 m for every phase. Also in figure 5 we can see that the 2D condition can be assumed representative of the problem only on the center line of the existing embankment with the maximum coverage, but due to the geometry of the pipeline and the slope of the embankment a progressive reduction of the coverage reduce the elastic part of the soils.

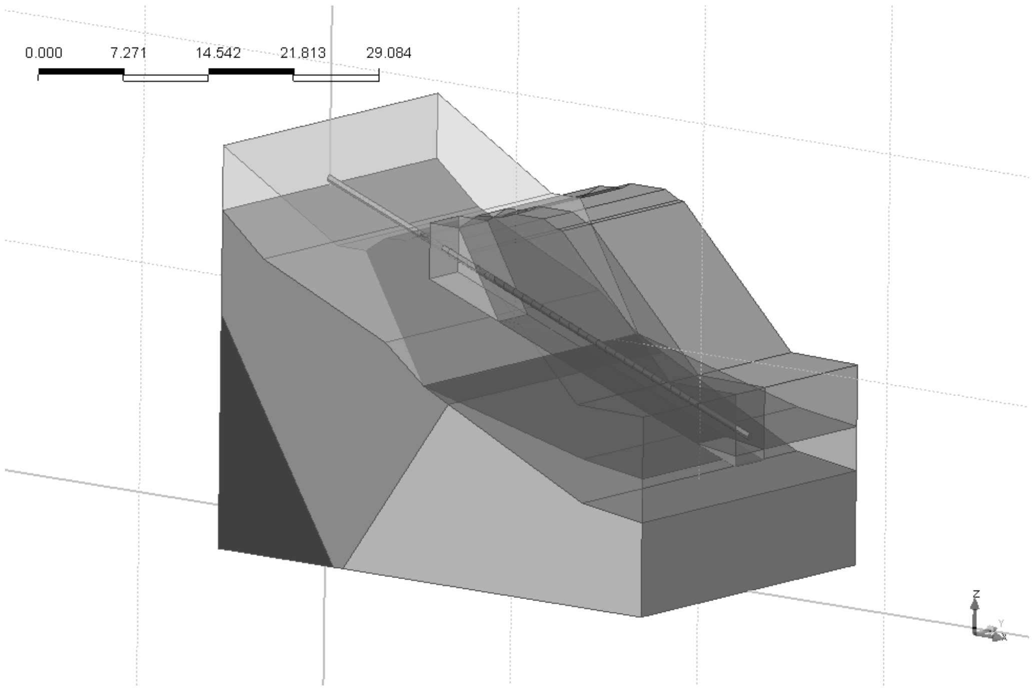

Figure 5. Geometry of the 3D model used on computation.

Two models were developed. The topology of the element was linear shape function with 14 nodes for each element, automatic mesh feature was used to increase the number of element around the pipeline and sparse element was used outside the interesting area of the model.

The first model simulates the behavior of the embankment without any type of consolidation or treated area in order to make a back analysis that produce the failure of the embankment and to rebuilt the settlement measured on site.

On figure 6 is presented the main results of the computation, in terms of global displacement of a cutting section passing through the axis of the pipeline and the strain of the soil in the same phase.

As we can observe on caption [6.a] in the middle of the excavation, that was done from the bottom to the top, a global settlement on the top of the embankment was measured close to 50 mm (on site the estimation was of about 70 mm) and after that phase the model collapse and doesn't reach the final excavation of the pipeline. On caption [6.b] we can observe that in that phase a potential slip surface can occur on the embankment close to the existing slope and also on all the platform of the railways tracks. A deeper potential deep surface can be shown on the contact between the soil with poor geotechnical characteristic and the underlying bedrock.

After the back analysis model a second model was developed with the imposition of the consolidation treatment with the modified soil parameter described above. Due to the lacking condition of the embankment after the first HDD trial, only the effective cohesion parameter was changed with respect to the previous computation, with a safety value of 25 kPa.

In this scenario all the pipeline was progressively excavated with the same sequence of the previous computation. In figure 7 are shown the main results of the computation. On caption [7.a] the global settlement is represented, but in this case with the entire pipeline excavated. A maximum settlement of 30 mm was calculated, with a reduction of about 25% respect the previous one but with the entire excavation. The results was affected by the assumption of conservative design parameter. Close to the pipeline a reduction of the settlement and convergence phenomena close to 10 mm was calculated.

More important assume the strain condition shown on caption [7.b], where the effect of the treatment is more relevant. As we can observe, with the total excavation of the pipeline, remains the same potential global slip surface between the deeper soil strata but a substantial reduction of the potential slip surface on the embankment slope on toe and top and a global reduction close to the top surface of the railway trucks platform, with the entire pipeline excavated.

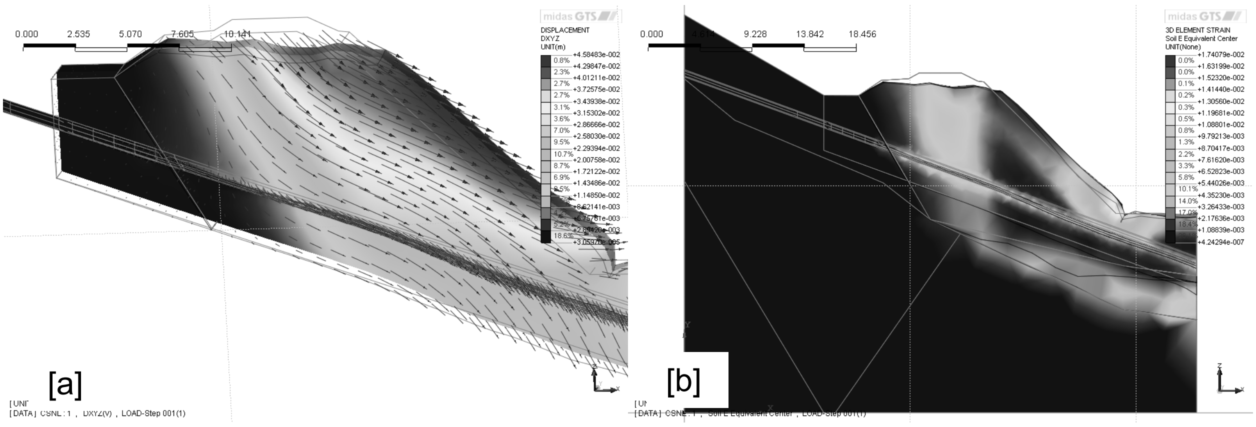

Figure 6. [a] Global settlement of the embankment, [b] Total strain of the element of soils, on a cutting plane passing through the centerline of pipeline.

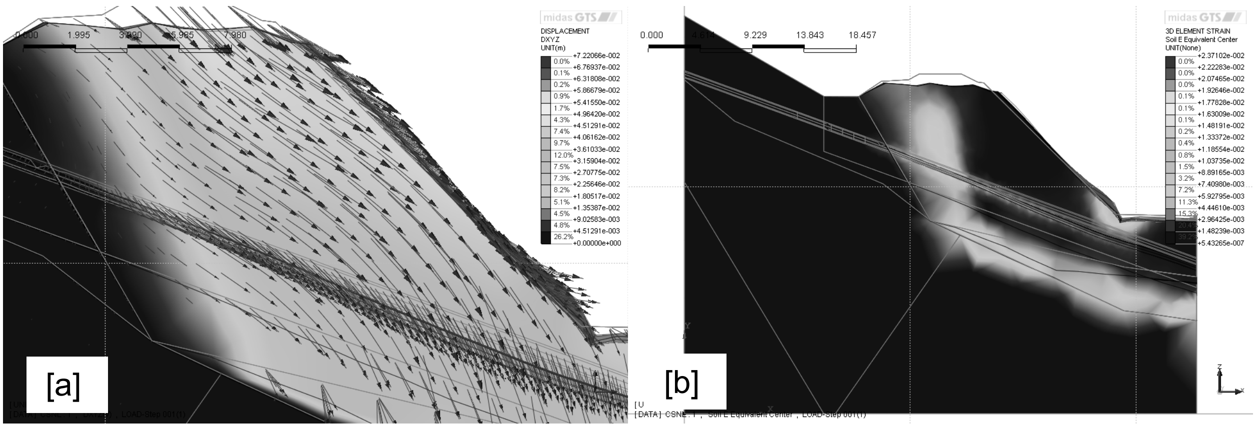

Figure 7. [a] Global settlement of the embankment, [b] Total strain of the element of soils, on a cutting plane passing through the centerline of pipeline with the consolidation treatment.

3. Intervention design and execution

The purpose of the intervention was to increase the stiffness of the constitutive soil of the embankment, with injections of expanding resin meant as a voids rate reduction measure.

The technology, protected by European patent No. 0851064 property of Tur S.r.l. company, allows the ground parameter improvement with injections of high expansion pressure polyurethane resin.

On figure 8 is represented the intervention design: on the top the theoretical dimension in a given section of the consolidation ring, on the middle the schematic design position of the injection point and the relative injection position and on the bottom the geological cross section close to the pipeline centerline position.

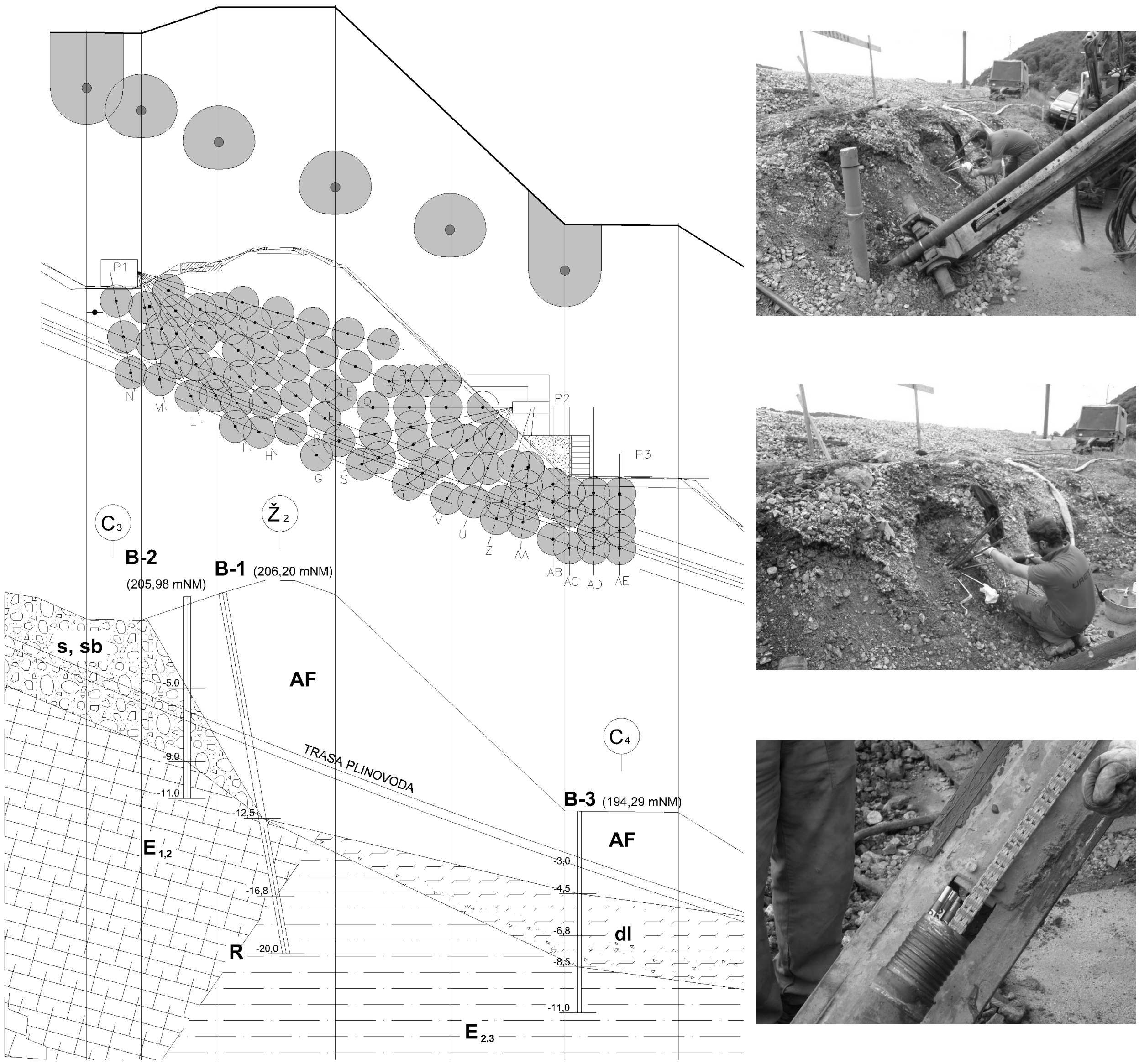

Figure 8. Schematic representation of the injection points, and execution picture.

3.1. Intervention execution

The drillings (90 mm diameter) have been made using a casing and several single use injection pipes with different lengths (12 mm diameter) have been inserted in every drilling afterwards. In this way it has been possible to reach the soil to be treated precisely in order to localize the effects of the injections.

The laying of the injection pipes have been performed right after each drilling and the injection phase took place, with alternate injections, using a special gun directly connected with the pipe.

The two components resin have been injected already mixed, in a special premix chamber, and started to develop its swelling pressure within few seconds.

The operator stopped injecting in case of a sudden increase of the injection pressure, when the volume of 40 l of injected resin has been reached or if the monitoring devices signaled any kind of movement. The injection sequence has been changed during the job site, according to the parameters obtained by the previous injections.

Injections usually followed an alternate order to allow the overpressure dissipation process due to the swelling of the resin into the soil.

3.1.1. Project numbers

During the job site a total of 12˙002,25 kg of resin were injected during 12 working days. It has been worked straight until the end of the injections phase (also during the week-end) without any interruption. Although two days have been lost at the beginning of the job site because of organization problem, the scheduled duration of works has been respected.

Treated volume	1˙434 m3
Injections number	414
Drillings number	126
Length of drillings	805,56 m
Injected resin (not expanded)	12˙002,25 kg

3.1.2. Monitoring

According to monitoring data, no relevant settlements have been measured after the injections.

4. Conclusions

In the month of May 2010 the Uretek company has been contact to perform a compensation grouting with polyurethane resin injections, to prevent excessive deformations in a railroad embankment in Rijeka (Croatia), during the execution of an horizontal directional drilling.

The behavior of the resin injection has been modelled both in an analytical (Yu and Houlsby, 1991) such as in a numerical way (3D FEM analysis).

The purpose of the intervention was to increase the stiffness of the constitutive soil of the embankment, with injections of expanding resin meant as a voids rate reduction measure.

During the job site a total of 12˙002,25 kg of resin were injected in 12 working days. and according to monitoring data, no relevant settlements have been measured during the drilling operations.

5. References

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