Foundation of a coal/coke stockyard on soft soil with geotextile encased columns and horizontal reinforcement

Stabilisation d'une aire de stockage charbon/coke sur un sol compressible à l'aide de colonnes encapsulés par géotextile et de renforcements horizontaux

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ABSTRACT

ThyssenKrupp Steel (TKCSA) is building a steel plant in the lowlands at the Brazilian seashore near Sepetiba inclusive of a stock yard for coal/coke. The total stockyard area is ca. 800 m x 600 m, the coal/coke part ca. 800 m x 350 m. The entire area consists of soft soils of very low bearing capacity; the ground water level is just below the surface. The thickness of soft soil clay layers varies between ca. 15 and 20 meters, being underlayed by sands and rock. Beside the stockpiles of ca. 13 m height, the coal/coke stockyards also include runways for the so called stacker/reclaimers similar to the heavy equipment in open mining. A deep foundation and/or soft soil improvement for the stockyard had to meet different and to some extent controversial requirements in the terms of settlement, bearing behavior, general deformability/ductility, costs for construction and later maintenance and in terms of construction time. Stiff piles were risky because of their brittle behavior and at the same time huge lateral stresses in the soft soil below the stock. The optimum solution found was a foundation of the runways on geotextile encased columns (GEC) in combination with horizontal high-strength geosynthetic reinforcement over the whole area. The main idea of GEC is to create a vertical pile-similar element consisting (usually) of compacted sand and a confining high-strength high-modular geotextile encasement providing bearing capacity and reducing compressibility. The high-strength horizontal geosynthetic reinforcement increases the overall stability of the system and reduces lateral pressures and horizontal displacements of the sensitive runways. Project-specific conditions in terms of geotechnical situation, loads, geometries and specific requirements to be met are described. The most important design concepts and results are shortly explained and the final optimized solution presented.

RÉSUMÉ

ThyssenKrupp Acier (TKCSA) construit un site industriel sidérurgique, incluant la zone de stockage pour le charbon/coke, dans les terres en contre bas au bord de mer brésilien prés de la ville de Sepetiba. Le stockage représente, à lui seul, une surface de 380 000 m². Le site entier se compose de sols compressibles, le niveau d'eaux souterraines est juste au-dessous du terrain naturel. A proximité, de la zone de stockage de charbon/coke, se situent les pistes pour les « bacs récupérateurs » semblables aux excavatrices lourdes des exploitations ouvertes. Une fondation profonde et/ou une amélioration de sol pour la zone de stockage doit répondre à différentes et dans une certaine mesure controversées, exigences en termes, de tassement, de capacité portante, de déformabilité générale/ductilité, de coûts pour la construction et d'entretien, et de temps de construction. La solution optimale trouvée était une fondation sur les colonnes encapsulées par un géotextile (GEC) en combination avec un renfort geosynthetique horizontal. L'idée principale de GEC est de créer une inclusion verticale consistant (habituellement) en une colonne de sable compact et un géotextile haute ténacité de haute résistance l'encapsulant et le confinant. Le renforcement geosynthetique horizontal de haute résistance augmente la stabilité globale du système et réduit les pressions latérales et les déplacements horizontaux des pistes. Les conditions spécifiques du projet en termes de situation géotechnique, charges, géométries sont décrites. Les plus importants concepts de dimensionnement ainsi que les résultats sont expliqués. La solution finale optimisée est présentée.

Keywords : soft soil, stock yard, high strengthgeosynthetic reinforcement, geotextile encased columns

1 INTRODUCTION

ThyssenKrupp Steel (TKCSA: ThyssenKrupp CSA Siderúrgica do Atlântico) is building a steel plant in the lowlands at the Brazilian seashore near Sepetiba inclusive of a stock yard for coal/coke. The total stock yard area is ca. 800 m x 600 m, the coal/coke part ca. 800 m x 350 m. The entire area consists of soft soils of very low bearing capacity; the ground water level is just below the surface. There are two rivers on both sides, and a mangrove zone at the sea side. The thickness of soft soil varies between ca. 15 and 20 meters, being underlayed by sands and rock. Beside the stockpiles of ca. 13 m height (surcharge of up to 140 kN/m^2 plus bearing platform), the coal/coke stock yards also include runways (RW) for the so called stacker/reclaimers (S/R) similar to the heavy equipment in open mining (Fig. 1). The focal point of this publication is the foundation solutions for the stock piles and RW under these extremely problematic conditions.

Figure 1. TKCSA steel plant near Sepetiba: overview, in front the stock yard with stock piles and runways with stacker/reclaimers

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2 GEOTECHNICAL CONDITIONS

The typical geotechnical conditions are shown in Figure 2.

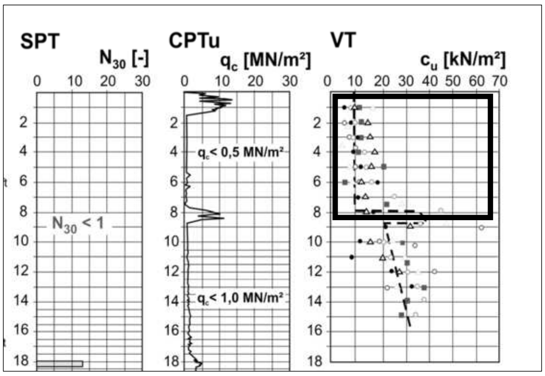

Figure 2. Typical geotechnical conditions (down to ca. 20 m below surface); the most critical so called "upper clay" is marked by a frame

The general profile is as follows: very soft saturated clays down to ca. 10 m ("upper clay"), a layer of better sandy layers, then again soft clays down to ca. 20 m, sands and rock bed at 30 to 50 m below surface. More detailed information on the whole project can be found in (Glockner et al, 2008).

The most critical "upper clay" of high plasticity and low consistency is normally consolidated with the following main parameters: oedometric modulus approximately $E_{s,E}$ [MN/m²] = 0,1 + 0,06 • t with t = depth [m], say only ≈ 0,2 - 0,5 MN/m², c_v = 2-4 · 10^{-8} m/s, and an undrained shear strength of only c_u = 5-15 kN/m². The ground water level is practically at the surface, after heavy rains the terrain is under water.

Because under such conditions any construction activities were practically not possible, at the beginning a sand platform with a thickness of ca. 1.5 to 2 m was dredged on the entire area.

3 STOCK YARD

Additional significant difficulties for the foundation of the 380.000 m² stock yard resulted beside the soft soil e.g. from the changing shape, geometry and positions of the stock piles with heights of up to 13 m, a fast loading-unloading process under operation, say surcharge changing quickly from 0 to >100 kN/ m² (coal/coke) and to >340 kN/ m² (ore), the limited allowed deformations of any type of the runways (RW) for the 750 tons stacker/reclaimers (S/R) etc. (Figures 2&3).

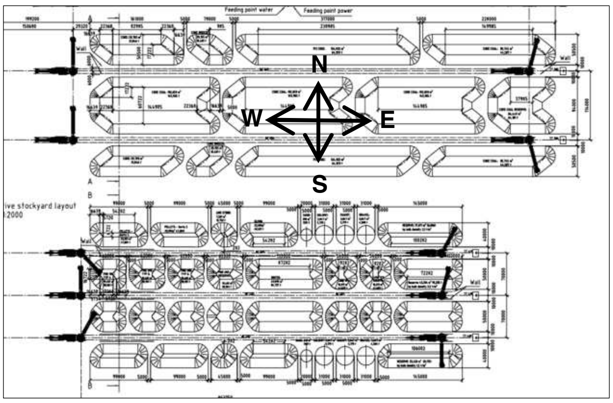

Figure 3. Stock Yard; up (North) coal/coke, down (South) ore/additives, runways for the stacker/reclaimers running West-East

Beside the insufficient stability, the calculated settlements amounted up to 4 m. Consequently, appropriate technical solutions had to be found to solve both problems. For brevity all further comments are focusing only on the coal/coke area with the RWs. The solution optimization had to consider not only technical points of view but also other factors like costs, the very limited time for execution of ca. two years, the different requirements for different zones, logistic aspects and the availability of different techniques in Brasil as well.

3.1 Foundation of the coal/coke stockpiles

Local and global stability had to be adequate, settlements and settlement differences to be reduced and especially the horizontal displacements („spreading") from the stockpiles outwards to the RWs to be minimized to acceptable values. The „spreading" was of critical importance. Although for the RWs an adjustable ballast bed scheme was chosen, they remained very sensitive to all types of deformations. A horizontal trust from the adjacent stockpile bed endangers not only the stability but also the proper operation of the S/Rs being of key importance for the entire steel plant. All ultimate (ULS) and serviceability limit state (SLS) calculations had to be performed for different shapes and positions of the coal/coke stockpiles and the S/Rs on the R/Ws during stockyard operation and for the two main axes: N-S and W-E (Figure 3). Both analytical and numerical analyses (FEM) were performed and the results compared. Some analytical procedures were well known (e.g. Bishop or Janbu), for many specific cases they were simply not available and had to be consequently developed (see below and Section 3.2). In all cases and in all directions the ULS and SLS analyses resulted in the necessity of horizontal geosynthetic reinforcements in the sand platform (Section 2) in two directions: N-S & W-E. In some cases the ULS controlled the design, in others: the SLS. The required short- and long-term tensile stiffness of the reinforcements and their design strength varied in a wide range, but they are in all cases substantial (see below). Beside the calculation results other factors had to be considered for the final optimized solution as well: customized production of the reinforcements to save costs, an optimum between differentiation and unification, long rolls to avoid overlaps in the main bearing direction, high bond coefficients to the sand platform etc. For brevity this paper will not deal with all the details of the final optimized solution.

Generally the solution is as follows: a woven geofabric unrolled transverse to the W-E (longitudinal) axes of the stockpile beds and in some places continuing under the RWs, followed by a 15 cm thick compacted intermediate sand layer, on which a geogrid was laid the parallel to the longitudinal axes. Due to the importance of the above-mentioned critical reduction of lateral spread deformation, it was decided to calculate it based on a suitable analysis procedure in addition to the FEM analysis. A simplified method was used that had been developed by the first author some time ago. The method allows spreading stresses under an embankment to be calculated for practically any conditions. For brevity this procedure will be reported in a separate publication. The tensile forces in the reinforcement can be determined from the calculated spreading stress (an example of a tensile force diagram is given in Figure 4). Using isochrones of the reinforcement and by integrating the strains, the runway-endangering outward displacement of the stockpile was calculated. For the case shown in Figure 4 with a high-modulus PVA reinforcement (see below), it was approximately 0.30 m. Although the spreading displacements towards the runway are the most critical, the analogous displacements in other directions are not without significance, especially due to the changing shape and position of the stockpiles. Because of the limits placed on these displacements, the tensile stiffness even of a high-strength polyester reinforcement is not sufficient; therefore woven geotextiles and geogrids made from much stiffer polyvinylalcohol (PVA) were selected (Alexiew et al, 2000).

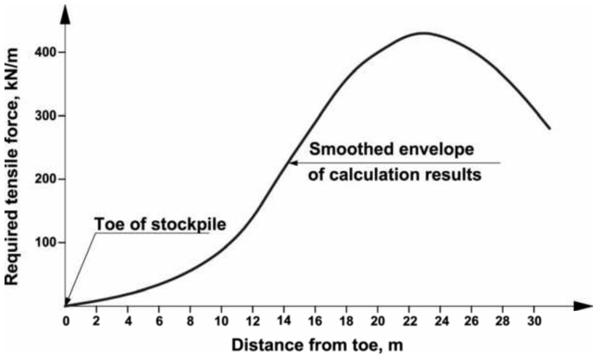

Figure 4. Example of an analytically calculated tensile force diagram in geosynthetic reinforcement due to spreading

It was pleasing to find that the deformation results from the above-mentioned simplified analysis procedure agreed very well with those from the FEM analyses, which made it easier to reliably determine the final horizontal reinforcement from the point of view of “antispreading” reinforcement.

Products from the PVA geowoven family "Robutec^{R}" and the PVA geogrid family "Fortrac^{R} M" with short-term strengths ranging from 500 kN/m to 1600 kN/m were used. The need for these strengths arises partly from the ULS-analyses and partly from the SLS-analyses in particular with regard to the problem of lateral spreading. An additional effect was a reduction of the lateral pressure on the geotextile-encased columns (GEC) under the RWs (see below).

Precise installation drawings were made for all the reinforced areas to ensure the high quality of construction and to save the cost of excess materials for the client TKCSA by producing project-specific roll lengths. In spite of careful planning, some changes to the construction sequences were required on site e.g. some areas (e.g. the erection areas for the S/Rs on the runways, see below) had to be completed earlier than originally planned. This required new calculations and analyses. The problem, which proved to be anything other than simple, was in the end successfully solved also with an optimum solution.

Last but not least - a few words about the deep stabilization of the soft subsoil. Although the design was accomplished within an extremely compact timescale relative to the difficulty of the project, it involved consideration of several concepts and scenarios. In arriving at the final design many factors came into play: economy, safety, risks and consequences, execution and possible consolidation times and (crucial) considerations of availability and capacity for each option in Brazil. In the end it was decided to use strip drains below the stock pile beds. As the consolidation times considered are longer than the scheduled start of operation, an expert assessment by analysis and instrumentation of the start-up of operations is foreseen. The filling of the stockpiles in plan area and height would be controlled so that subsoil conditions (pore water pressure, shear strength etc.) correspond with the assumptions and calculations, including the horizontal reinforcement, i.e. the so called observational method will be used.

Now some words about the execution on site. It is well known that even the best geosynthetic reinforcement is less efficient if it is not handled or laid properly. Added to that are site-specific factors such as the acute shortage of time, the very large areas to be reinforced, the considerable weight of the geosynthetic rolls, the long lengths of material to be installed in precisely parallel lanes, the Brazilian sun and rain and the lack of experience of the site personnel. All good reasons for very carefully thinking through construction in great detail: unloading the rolls from the containers and transporting them over very poor ground, accurate formation of the sand platform, parallel laying under tension while maintaining overlap lengths, protection of partially placed rolls of reinforcement against UV radiation with foil etc. The rolls were given labels in the factory showing project- and location-specific descriptions. Thanks to this planning and precautions, the installation of the materials on site has been and continues to be neatly and properly carried out.

3.2 Foundations for the runways (RWs) for the stackers/reclaimers (S/Rs)

As mentioned earlier, the runways are heavily loaded linear structures (8 m wide railway tracks) between the stockpile beds. The weight of an S/R is approximately 750 tonnes. The runways also include erection (assembly) areas for the S/Rs. The allowable deformations (settlements, differential settlements, torsion and lateral displacements) are strictly limited.

In the erection areas typical issues among others are the very high loads under the assembly vehicle support plates (up to 2000 kN). Conventional stability calculations with parallel FEM analyses were carried out in both directions for the RWs under operating conditions and for the assembly areas in a similar manner to those for the stockpile beds (Section 3.1) inclusive of the required reinforcement. The point was to achieve even lower deformability than under the stockpiles in a shorter construction time. Consequently, the issue of the soft soils was addressed again (cf. Sections 2 & 3.1). Again technical, economic and time factors together with some typically Brazilian factors (the availability of technology and capacities) had to be considered. One option was e.g. to form a foundation with geogrid reinforcement over driven precast concrete piles or similar solutions (previous experience available in Brazil). Due to the magnitude of the anticipated lateral pressures from the stockpile beds (in spite of the anti-lateral-spreading measures for the stockpiles, Section 3.1) stiff systems appeared too risky (bending/buckling of the piles). The optimum solution for the foundations for the RWs and erection areas was sand-filled geotextile-encased columns (GEC) (Alexiew et al 2005). Sand of a suitable grading for filling the columns was available in unlimited quantities from the port construction works. All calculations were carried out based on the Raithel’s method (Raithel 1999 & 2005) and the draft EBGEO recommendations (EBGEO Draft 2007), with a 0.78 m column diameter being adopted because it was the installation steel tube size readily available in Brazil. The length of the GECs was approximately 10 to 12 m; the axial grid spacing mainly 2.0 x 2.0 m. The columns pass through the very soft Upper Clay (Figure 2) and found in the better sandy intermediate layer.

As geotextile encasements the products Ringtrac^{R} 100/250 and 100/275 are used (Alexiew et al 2005). Due to the very soft soil the so called displacement method is used for installation, and the Ringtrac^{R} diameter corresponds exactly with the installation tube inner diameter to ensure early mobilization of the system at very low settlements. After optimization the usual pace of installation is 3 to 4 columns per hour. The density of at least every tenth column (at the start, then fewer) was checked using a penetrometer. Records were made of the installation process. A discussion point was the long-term behavior of the GECs under concentrated heavy loads moving over them (the S/Rs), with a great difference between dead and live load, which would be a slowly applied rather stochastic, large amplitude pulsating load. These thoughts were dismissed among other reasons because of the study of Di Prisco et al (2006), which found that GECs stiffened after loading-unloading cycles.

Figure 5 shows a partial cross section of the actual solution for both the coal/coke stockpile beds and runways.

Now back to the above-mentioned specific analyses in addition to FEM of the calculations for the reinforced load-bearing layers of the RWs and erection areas. In a number of cases there was no suitable analytical model available - one had to be developed first: e.g. in the cases "Punching mode of the reinforced RW transverse to the longitudinal axis", "Punching mode of the reinforced RW parallel to the longitudinal axis"

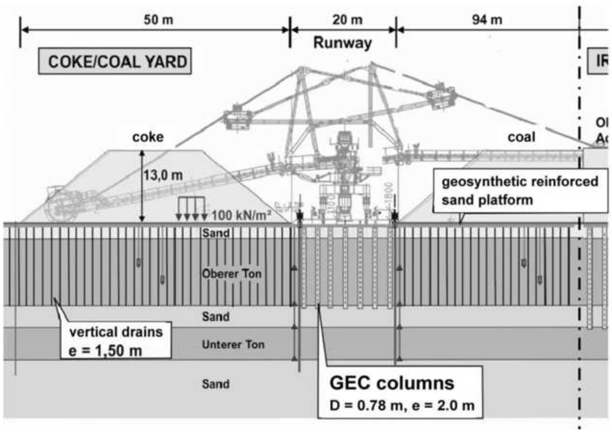

Figure 5. Typical solution in the coal/coke stockpile area

(tilting of the S/R forwards/backwards while moving), "Punching of the reinforced load bearing layer under the support plates in the erection areas" (with and without consideration of the supporting GECs below) etc. In some cases different models were developed and the results compared. Details have been omitted for brevity. Figure 6 shows the concept for one of several cases (illustrative only). All modes of failure required biaxially effective reinforcement, which was provided similar to the reinforcement under the stockpiles as two uniaxial layers (Robutec^{R} geofabric bottom transverse, intermediate sand layer, Fortrac^{R} M geogrid top longitudinal etc.). In some cases overall stability considerations were critical, while in other cases the results of the specific analyses of local failure modes controlled the design. Finally the reinforcement that runs transversely to the longitudinal axes of the stockpile beds and runways (reinforcement aligned north-south, Robutec^{R} geofabric) was unified as much as possible in order to place it in continuous lengths through several stockpile beds and runways without overlapping. Figures 7 and 8 show examples of placed reinforcements and a completed (but not yet covered) GEC.

As reinforcement in the ore/additives area (Section 3) on top of stone columns the same general reinforcing scheme and the same range and type of geotextiles and geogrids are used, but this is outside the scope of this publication.

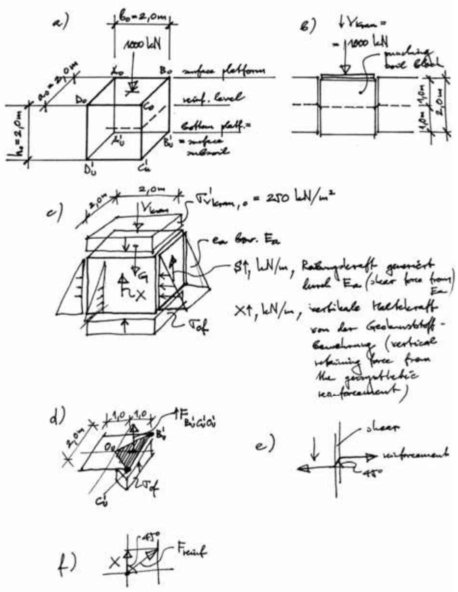

Figure 6. An example of an analytical model for a limited punching failure with reinforcement between GECs

4 FINAL REMARKS

The stock piles and runway areas are not fully completed yet. Nevertheless, some preliminary survey and measurements inclusive of temporary partial loading confirm the suitability and effectiveness of the concepts, design, optimized solutions and materials described. Further experience will be reported separately later.

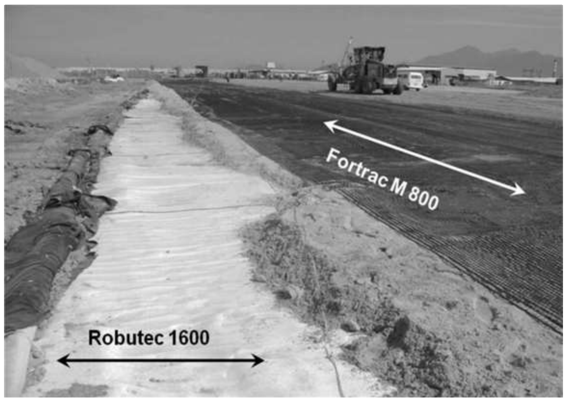

Figure 7. Placed reinforcement: longitudinal Fortrac® 800 M geogrid, transverse Robutec® 1600 woven with an intermediate sand layer

Figure 8. Recently installed sand-filled geotextile-encased column (GEC) using Ringtrac® 100/250

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