Soil improvement by stone columns for the ore storage yard at the Rio de Janeiro steel plant on soft, alluvial deposits

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ABSTRACT
ThyssenKrupp Steel AG is presently setting up a new steel plant on an area of 9 km² consisting predominately of alluvial terrain in the State of Rio de Janeiro in Brazil. The planned annual production is 5.0 mio ton of crude steel. Cohesive sediments of soft to very soft consistency up to considerable depths and a groundwater level close to the surface provide extreme difficult foundation conditions for heavy industry structures of the envisaged nature. A major challenge is the geotechnical foundation solution by stone column soil improvement for the heavily loaded iron ore storage yard and the adjacent corridors for loading and transport facilities. The project had to be completed by 2009 in only 3 years. This article describes the way of gathering and processing basic site data for an industrial project of the planned magnitude. Subsoil data available are reviewed and are then used in the soil improvement analysis. The results of the full-scale load test are reported. Furthermore the enormous project requirements with regard to site and material logistics as well as to production progress are shown.

Keywords : Vibro Replacement, stone columns, raw material stockyard, reclaimer foundation

RÉSUMÉ
Thyssen Krupp Steel AG construit actuellement une nouvelle usine sidérurgique dans l'Etat de Rio de Janeiro au Brésil, sur une zone de 9 km^2 présentant principalement un terrain alluvionnaire. Des sédiments cohésifs de consistance molle à très molle sur des profondeurs importantes et un niveau de nappe phréatique proche de la surface rendent les conditions de sol de fondations extrêmement difficiles pour la construction des lourdes structures industrielles projetées. La réalisation d'un renforcement de sol par colonnes ballastées sous l'aire de stockage du minerai de fer à forte charge, ainsi que sous les accès adjacents des infrastructures de chargement et de transport, représente un véritable défi. Cet article décrit la manière de rassembler et de traiter les données de base du site pour un projet industriel d'une telle amplitude. Les données de sol disponibles sont passées en revue et ensuite utilisées pour l'analyse du renforcement de sol. Les résultats de l'essai de chargement à taille réelle sont présentés.

Mots-clés : Colonnes ballastées, renforcement de sol, stockage de matériau brut

1 INTRODUCTION

The integrated steel plant presently built in the state of Rio de Janeiro, Brazil, is the prime project for the capacity expansion plans of the ThyssenKrupp Steel AG. It comprises an investment volume of 3.7 billion € and shall have an annual production capacity of 5.0 mio crude steel. The project site is located at the bay of Sepetiba approx. 50 km west of the megacity of Rio de Janeiro on an area of about 2,000 m to 4,500 m (Fig. 1).

The steel plant complex comprises the following main components: a coking and a sintering plant, two furnaces, the steel plant, a power plant, the raw material storage and handling area as well as large infrastructure facilities, such as a deep-sea port and a railway line with a loading station for iron ore trains (Fig. 2).

The site is located between two rivers and the site surface is originally just 0 to 2.0 m above the sea water level mainly covered with swamps and grass vegetation. The extreme soft cohesive soil conditions of fluvial origin, which reach up to considerable depths, and the groundwater table close to site surface provide exceptionally difficult conditions for the foundation of the heavily loaded iron ore storage yard. The challenging geotechnical aspects of the soil improvement solution by stone columns are presented in the following.

Fig. 1: Bird´s eye view of the new steel plant project of ThyssenKrupp AG in the state of Rio de Janeiro, Brazil

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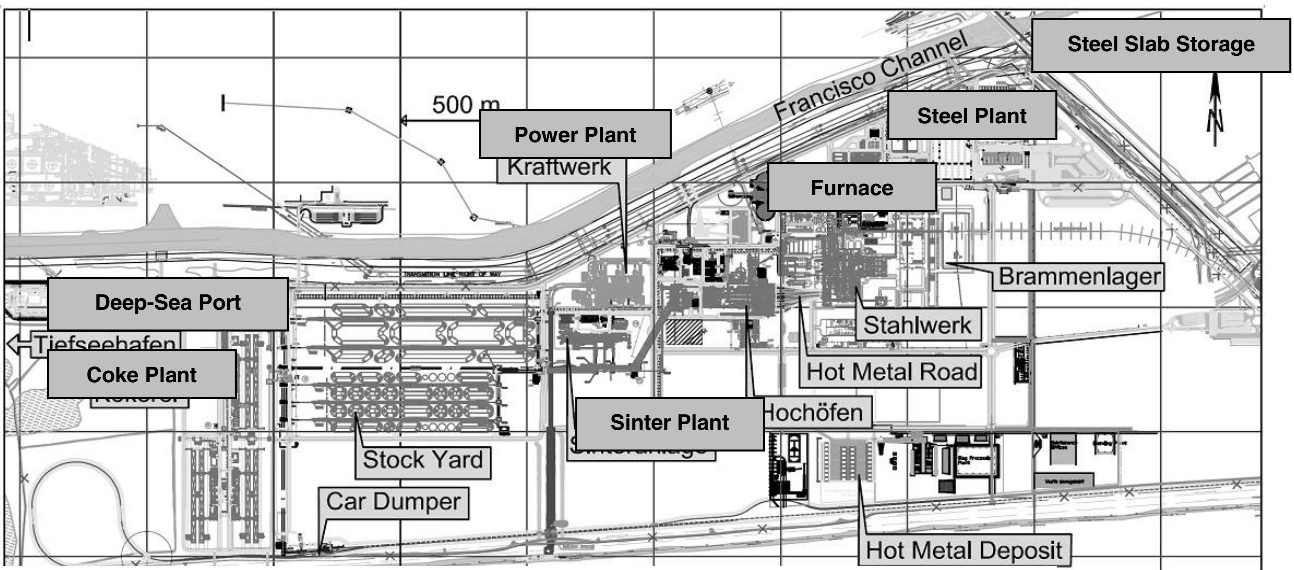

Fig. 2: Layout section of the new steel plant of TK CSA Companhia Siderúrgica, Rio de Janeiro, Brazil

2 SUBSOIL SITUATION

Subsoil conditions in the Bay of Sepetiba are dominated by fluvial and fluvio-marine sediments of quaternary origin, which are encountered at site as alternating stratification of sands, silts and clays, as well as fluvial gravel and younger mangrove deposits. They are underlain at a depth of 30 m to 50 m by Precambrian rock formations, mainly granite, gneiss and volcanic intrusions (trachytes and basalts), which are in the upper 1.0 m to 5.0 m in weathered condition depending on the rock origin (1).

In the area of the proposed raw material handling yard (Fig. 3) the quaternary sediments consist in general up to a depth of 12 m to 15 m (in one section up to 17 m) of soft to very soft soils, the Upper Clay, which contains in most cases higher portions of organic material. At a depth of 6 m to 9 m a thin silty sand layer is embedded in this Upper Clay. This stratum is followed by a 4 m to 10 m thick layer of medium to dense sand, normally underlain by the Lower Clay, a material of normally stiff consistency, in general 2 m to 8 m thick. Below the Lower Clay stratum up to the horizon of the base rock formation sand layers, partly with gravel or embedded silt lenses, are found with densities, which increase with depth.

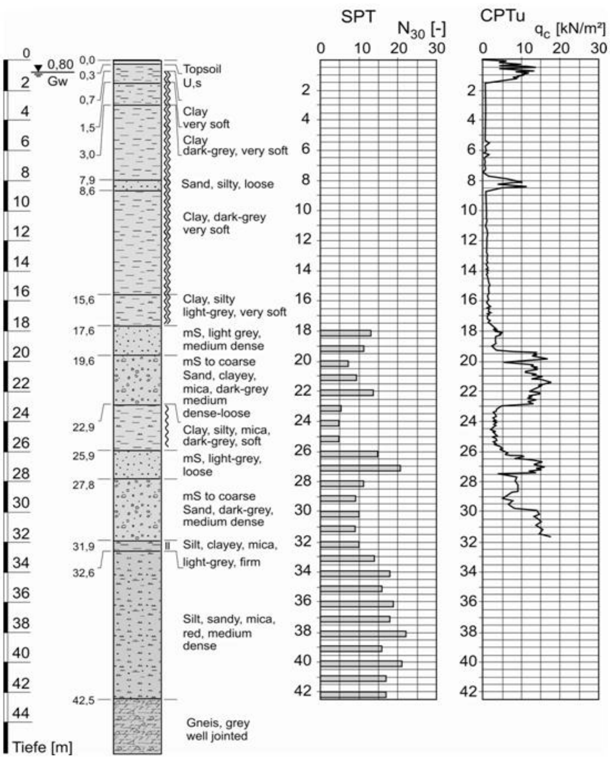

Fig. 3 (left): Typical subsoil profile fort the raw material yard.

In general the groundwater horizon is at the original site level and is influenced by tidal movements. After heavy rain larger parts of the original site surface are flooded.

The site investigation programme for the whole complex comprises a large number of SPT- and CPTu-soundings as well as in-situ vane tests, furthermore a laboratory test programme with oedometer- and triaxial tests.

Because of the soft to very soft nature of the Upper Clay and the high groundwater level the site is not accessible for vehicle and could only partly be crossed by walking. Therefore a 1.5 m to 2.0 m thick layer of sand is placed at site surface, which is available from dredging works carried out in connection with the construction of the deep-sea port. After drainage of the excess water the sand layer is in general of medium dense condition and provided a safe and stable working platform.

Since the strong plastic nature of the Upper Clay is of great importance for the assessment of the soil improvement works as well as for other geotechnical engineering measure, the soil mechanical parameters of this layer shall be discussed closely in the following. Table 1 summarizes the anticipated average parameters for the raw material handling area (Stock Yard).

The values are separated in two sections, one above the embedded sand layer at -6 m to -9 m (av. -8 m) and one below this layer.

Based on the results of the CPTu-soundings and the oedometer-tests the Upper Clay can in most parts be assumed as normal-consolidated. The constraint modulus of the first loading cycle can be described in accordance with the applied stresses as follows: $E_{sE} = (1+e_0) \cdot 2.3/C_c \cdot \sigma'_v$ and is estimated for the soil parameters at site as E_{sE} (MN/m²) = $0.1 + 0.06 \cdot t$ with t(m) as depth. The undrained shear strength (c_u) in the critical, upper section of the Upper Clay has very low values of 5 kN/m² und 15 kN/m².

Table 1: Average Soil Parameters of Upper Clay in Stock Yard Area.

Upper clay:	Approx. depth	-8 m	-15 m
Classification as per USCS		CE,CH,MH,OH	
natural water content [%]	w	95	
liquid limit [%]	w_L	112	
organic content [%]	V_{gl}	5-15	
void ratio [-]	e_0	1.5-3.5	1.2-3.0
bulk density [t/m³]	ρ	1.4	1.5
coefficient of compressibility [-]	C	0.4-1.8	0.3-1.5
constrained Modulus [MN/m²]	$E_{s,E}$	0.2-0.5	1.0-2.5
coefficient of creep[-]	C_α	0.03-0.07	0.02-0.06
viscosity index [-]	$I_v = C_\alpha/C_C$	0.04-0.06	
vert. consolidation coefficient, [m²/s]		$2 \cdot 10^{-8} \div 4 \cdot 10^{-8}$	
undrained shear strenght [kN/m²]		5-15	20-60
angle of ternal friction[°]		25	25
effective cohesion [kN/m²]		0-5	5-10

3 SOIL IMPROVEMENT BY STONE COLUMNS

These very critical soil conditions required a challenging foundation solution for the 380,000 m^2 area of the raw material handling yard with its 13 m high cone shaped stockpiles of coal, ore and additives, which undergo very fast loading and unloading operations. The stockpile areas have lengths of up to 800 m and width of 100 m. The planned area loads are in the range of 100 kN/m^2 for the coal and coke and 340 kN/m^2 for the iron ore, which would have created ground settlement of approx. 4 m, if not special soil improvement measures are provided.

Furthermore the transport corridors between the stockpiles will be used by large, rail mounted stackers and reclaimers with 50 m long cantilever arms and this giant machinery requires precise positioning of the rails and constant availability of the runways. After having evaluated technical and economic considerations as well as having assessed the capability of the local construction market in general and in view of the requirements at other parts of this project it is decided to foresee soil improvement treatment at this area in combination with a gravel cushion which will allow level adjustments of the sleeper supported stacker/reclaimer rail system when necessary (Fig. 4).

Because of the lateral stresses to be expected from the envisaged settlement under the stockpiles a pile foundation is not taken into consideration for the runways.

Because of the large technical requirements for the heavily loaded ore stock pile with regard to settlement reduction and ground stability under the stock pile slopes the installation of so-called stone columns using the Vibro-Replacement system is chosen. In total 400,000 lin. m of stone columns are installed at the ore stock pile area in one year.

Because of the limited quarry capacity for this magnitude of material demand it is decided to use alternative soil improvement measure for the lower loaded stock pile areas, such as vertical drains and surcharge as well as columns, for which large geotextile encased sand amounts of sand material are available from the dredging operations at the deep-sea port.

The stone columns at the ore stock pile area have a nominal diameter of 1 m and are constructed using the so-called Alpha-S system, a crane-hung installation method, which can use – because of its flexibility – construction plant from the local market, such as conventional crawler cranes, and can therefore be mobilized to site in a rather short and economic manner (Fig. 5).

Fig. 5: Installation of stone columns using Alpha-S type vibrator (Keller Grundbau GmbH).

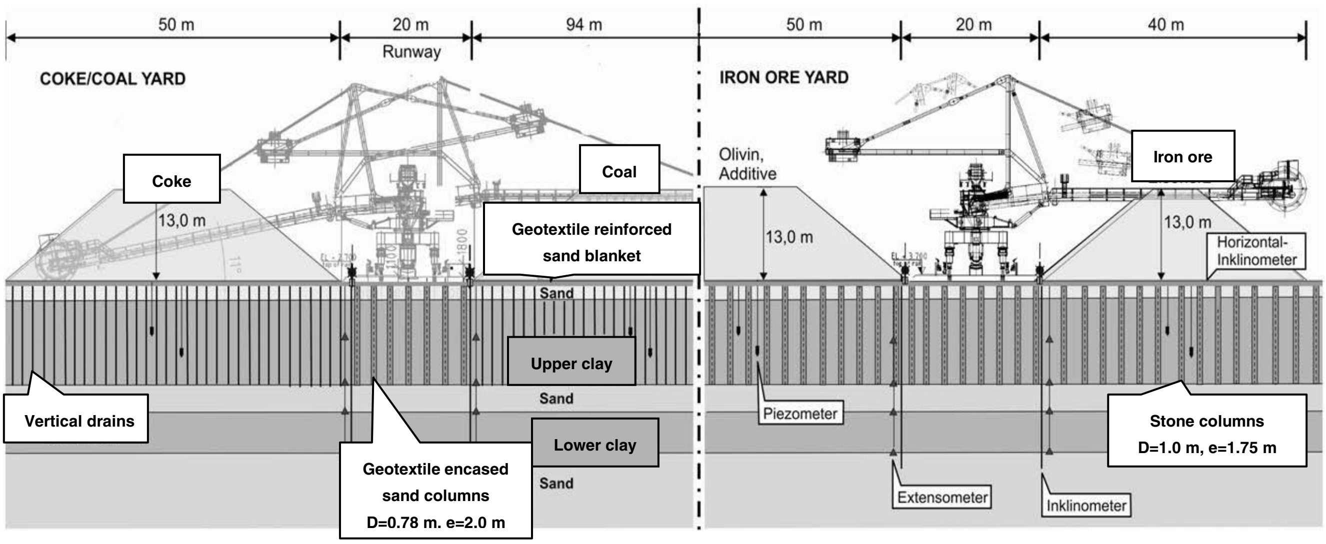

Fig. 4: Basic concept at the raw material yard; right side: stone columns under stock piles and runway corridor.

The stone columns have installation lengths of 10 m to 17 m, on an average 12 m and are installed in general in a square grid of 1.75 m x 1.75 m, in areas of lower stock pile loads in grids of 2.2 x 2.2 m.

After completion of the stone column works a geotextile reinforced blanket is placed at site surface. The reinforcement layer consisted of a bi-directional, double layered, high strength geogrid and geofabric with an uniaxial tension strength of up to 1,600 kN/m.

When developing and designing the soil improvement concept for the raw material handling area the required soil improvement by stone columns is assessed using the method of Priebe (2). Several conventional, analytic stability examinations are combined with finite element analyses, which allow the application of coupled elasto-plastic material models. In this manner a realistic view on the time dependent consolidation process and a prediction on the effects of the continuous, rather fast loading and unloading operations are possible with regard to the stock pile stability and to the expected deformations in the runway corridors (Fig. 6). By simulating a time depending increase in shear strength as the result of gradual ore material placement a further optimization of the stone column layout can be realized.

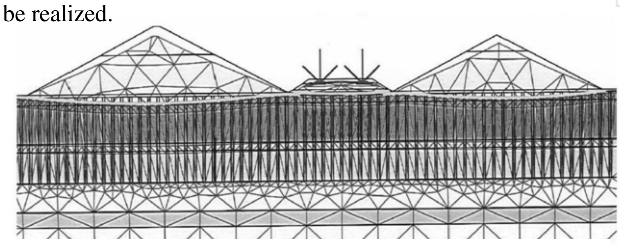

Fig. 6: Deformation prediction at runway corridor by FE-analysis.

The design analyses of the soil improvement concept are validated by the execution of a large scale zone test combined with a comprehensive instrumentation programme (Fig. 7). A group of 16 stone columns out of an infinite grid is gradually loaded under a concrete slab using steel bars as kentledge and the direct deformations as well as stresses, horizontal and lateral displacement and pore-water pressure are monitored in-situ.

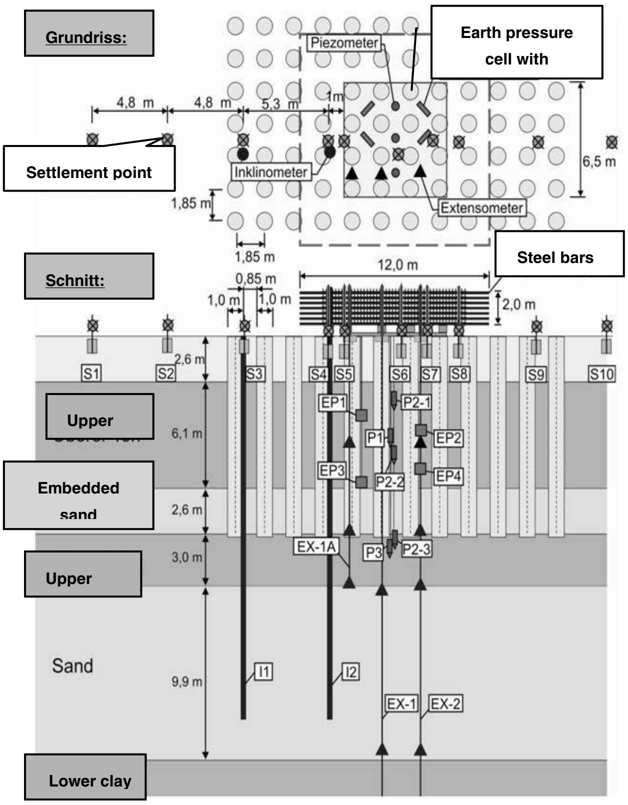

Fig. 7: Layout of large scale load test and instrumentation.

Due to a fast loading process and the chosen boundary conditions, in the test the ultimate state limit could be reached with a surface load of 180 kN/m². The test was successfully recalculated by using a 3-dimensinal model and the method of Beside the deformation behaviour especially the shear strength of the improved soil had to be verified in the test.finite elements. The results of the recalculations confirms the of the shear strength in dependence of the stage of consolidation

Together with the in-situ tested time/load – dependent increase and the stress state and the test results was the basis of a guideline for the stacking and reclaiming process, which is guided by limits of major stresses, e.g. excess pore pressure and major deformations. insitu tested shear resistance and deformation behaviour of the clay and therefore also the the design of the soil improvement.

During the first operation phase of the raw material handling yard the loading and unloading processes will be conducted and controlled by a geodetic and geotechnical instrumentation programme. The 250 m wide and 600 m long stockyard, including 3 runways for the stacker and reclaimer is monitored in sections every 50 m, where each section is equipped with piezometer and settlements cells with an automatic datalogging system and an online evaluation of the measurement results. Additionally the deformation behaviour of the underground along the runway is monitored by in-place inclinometer systems and extensometers, which are connected to the automatic reading and evaluating system. Furthermore manual reading systems, e. g. settlement profilers and inclinometer tubes, are installed to reduce the distance in between the automatic system. This equipment is currently in the installation process.

After the construction of the runway, the erection phase of the equipment and the finalized structure of the runway is monitored by geodetic survey. These measurements shows settlements rates of about 2 cm to 3 cm per month due to the self weight of the working platform, a dredged sand layer and the substructure of the runway (in total 50 kN/m^2) According to these monitorings the major settlements slow down after a observation period of around 4 month.

4 SUMMARY

The soil improvement programme by installation of stone columns is only one part of geotechnical construction measures required at this project. The stone column works could be performed in time and could contribute to the successful completion of this prime project despite the extremely difficult geotechnical conditions at site, the very short mobilisation and completion periods available and the limited capacities of the local construction market for such a megaproject. Finally it can be stated that in view of the extreme tight time frame available the uncomplicated, target and solution orientated cooperation between all parties involved and fascination of the participants in implementing a project of the described magnitude contributes to a large extent to the successful execution of this venture.

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