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Ground improvement using rigid inclusions in Durban soft clay: A South African case study

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ABSTRACT: Construction on soft clays located in the Durban area (also known as 'hippo muds') has always posed a significant challenge for geotechnical and structural engineers. In addition to the characteristics of soft clay, i.e. low strength, stiffness and permeability, the 'hippo muds' are further complicated by its extreme variability, both spatially and in its engineering properties (Jones & Davies 1985). The Clairwood Logistics Park, located on the old Clairwood Race Course in Durban, South Africa, consisted of numerous large footprint warehouse structures and required a cost effective foundation solution which would meet the stringent differential settlement criteria. A case study is presented on the use of rigid inclusions as a ground improvement technique for the warehouse structures of the Clairwood Logistics Park. As a novel technique in South African, the design and construct proposal included a detailed preconstruction test program and field monitoring of the settlement performance during construction and operation. This paper presents the design philosophy and construction methodology of ground improvement using rigid inclusions as well as the results of the preconstruction testing and platform settlement from the Clairwood Logistic Park. In addition, back-analysis of the field test and monitoring results provided additional insight into the behaviour and engineering properties of the problematic 'hippo muds'.

1 INTRODUCTION

Construction on soft clays has always posed a great challenge for the geotechnical engineers. Soft clay is characterised by low strength, stiffness and permeability which leads to bearing capacity and long term settlement related problems if foundations are inadequately designed.

The Durban area has developed on the mouth of three main rivers, the Mgeni, Mbilo and Mlazi. The underlying estuarine deposits, locally known as the Harbour Beds (King & Maud 1964), is characterised by lenticular sand deposits intercalated with silts and clays overlain by thick layers of dark grey, soft silty clay (locally known as the Hippo Mud) which may extend to depths of up to 30 m. Jones and Davies (1985), in their state-of-the-art-paper on soft clays published in 1985, attributed the main challenge as the ability to characterise the deposit which is extremely variable, both spatially and in its engineering properties. Due to this uncertainty, structures are generally founded on deep pile foundations which are often conservatively designed and expensive.

A foundation solution was required for the 350,000 square meter Clairwood Logistic Park development, located on the old Clairwood Race Course approximately 3km north east of the old Durban International Airport. The site is underlain by soft clays extending to depths of 35 m and traditional piled foundations are financially not feasible. The proposed solution was ground improvement with the use of Hybrid Columns (CMM®), a combination of rigid inclusion and gravel column.

2 GROUND IMPROVEMENT USING RIGID INCLUSIONS

Possibly the first application of rigid inclusions techniques for ground improvement was recorded in 1904 where engineers proposed to support the Mexican parliament building on driven metal inclusions not connected to the structure. Thereafter various case studies have been published including Broms (1969) using piles inserted into a perforated hollow raft; Girault (1969) using overlapping piles in Mexico; Coles (1986) using driven inclined wooden piles with perforated planks for road foundations; Smoltczyk (1976) for road embankment supported by rigid inclusions topped by perforated caps in West Germany; Gigan (1975) using vibro driven micropiles to support a bridge abutment in France, to name a few. By the late 90s it was evident that rigid inclusion techniques have been and could be applied in various foundation solutions but require standardised approaches on design and implementation techniques as well as inclusion material. In 1999 a proposal was made by the French Geotechnical Society for a national project on the topic. This ultimately led to a four year national research project (ASIRI) in 2005 and the publication of Recommendations for the design, construction and control of rigid inclusion ground improvement in 2012 as a guideline for design and implementation of rigid inclusions. The technique is now a well-established ground improvement solution used around the world.

The principles of ground improvement with rigid inclusions requires concrete columns to be installed in a grid format and founded on rock or a competent soil layer. These concrete columns do not necessary improve the mechanical properties of the clay, but reinforces the soil to create a composite soil/concrete mass with significantly improved mechanical properties. The system also requires a load transfer platform (LTP) constructed above the column head to transfer load from the structure to the rigid inclusions, similar in function to a pile cap which transfers load from the column to the piles. The difference in operating principle, in comparison to other common deep foundation systems, is illustrated in Figure 1.

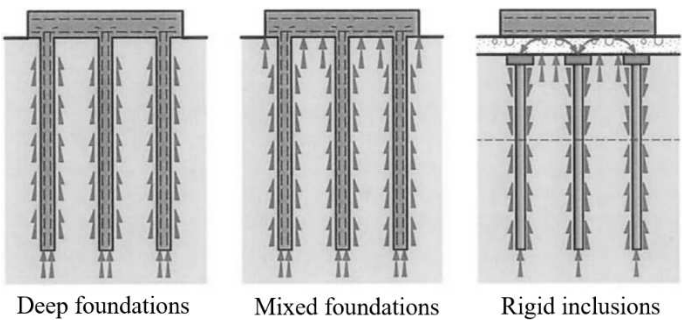

Figure 1. Operating mechanisms of deep foundation types (IREX, 2012)

Ground improvement with rigid inclusions has numerous advantages compared to conventional piled foundations, particularly in challenging ground conditions. As with all ground improvement techniques, structures are founded on inexpensive light/shallow foundations once the ground improvement is complete. This generally leads to significant reduction on the cost of the overall foundation system when compared with piled solutions which requires pile caps, ground beams and significantly thick rafts or slabs. Installation of rigid inclusions are significantly faster than conventional piling, particularly in challenging soil conditions, and often leads to program and cost benefits for the project. Furthermore, the inherent redundancy in ground improvement solutions provides reduced risk in challenging ground conditions (in ground characterisation, design and implementation) when compared to piled foundations which provides the full bearing resistance for the structure. It is an alternative to piling for structures over large footprint with distributed loads such as warehouses, storage reservoirs, treatment plants, basins and retention facilities, road embankments etc. which often have stringent differential settlement criteria. It is however not suitable for structures with high concentrated loads or structures with stringent total settlement requirements.

3 CLAIRWOOD LOGISTICS PARK PROJECT

Franki Africa was awarded the ground improvement works for the Clairwood Logistics Park development in late 2016, which included installation of over 45, 000 rigid inclusions to depths of over 35 m. The work scope included site characterisation, design, implementation, control and monitoring of the ground improvement system. SMC Structural Engineers, assisted by SRK Consulting Engineers, provided independent review and control of the geotechnical works as well as interface between the geotechnical and structural design.

Installation of rigid inclusions were carried out by Liebherr LRB 255 crawler rigs specially equipped with model 32 VMR ring vibrators (Fig. 2) to drive temporary steel tubes to the required depths. The use of the vibratory driving method allowed the rigid inclusion lengths to be installed based on the actual ground condition/profiles rather than to some designed depth which may be inadequate or over-conservative in the highly variable ground conditions.

Figure 2. Liebherr LRB 255 crawler rigs equipped with ring vibrators for driving steel tubes

The rigid inclusions were finished with a gravel head (installed using Keller Vibrocat rigs) and topped with 2-3 m engineered fill which acts as the load transfer platform (LTP). The proposed solution is schematically illustrated in Figure 3. The combination of rigid inclusions and gravel head, also known as a Hybrid

Column (CMM®), reduces the risk of column head damage by construction vehicles or the environment and reduces the punching stresses and moments on the floor slabs.

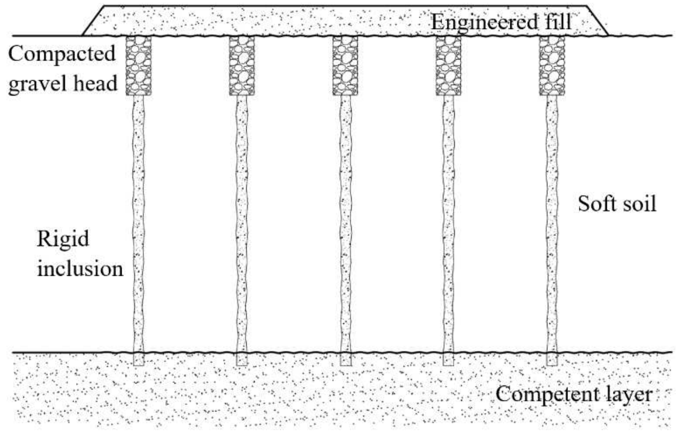

Figure 3. Typical ground improvement system using Hybrid Columns (CMM®)

Hybrid Columns were installed to control the settlement of the warehouse structures. Due to the large structure footprint, soil behaviour will be predominantly one-dimensional, and analyses were carried out by simplifying the system to a unit cell shown in Figure 4. The simplified model is then analysed using 2D axisymmetric FEM analysis as well as Load Transfer Method (LTM) developed by Bohn (2015). Analyses of simplified models require little computational time and are used as quick checks for various ground conditions and fill scenarios.

For building edges, corners and other situations where one-dimensional behaviour does not apply, 3D FEM analysis was used.

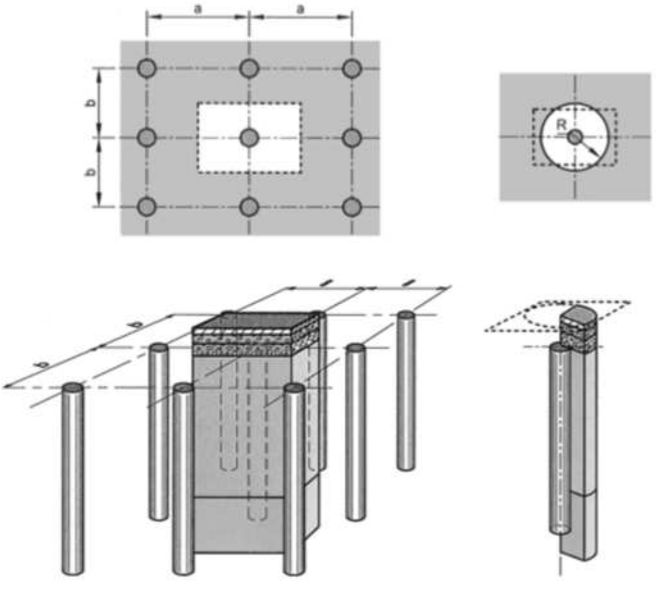

Figure 4. Model representing a single unit cell of distributed load supported by soil reinforced by rigid inclusions (IREX, 2012).

Without improvement, ground settlement is estimated at between 200 and 400 mm with consolidation periods of between 2 and 5 years. The use of Hybrid Columns significantly increases the vertical stiffness of the soil mass and reduces the stresses applied to the soft clays. The result is significantly reduced settlement of between 75 and 150 mm and more importantly significantly reduced consolidation time.

4 FULL SCALE FIELD TEST

As the proposed ground improvement solution is untested in South African ground conditions, a full-scale field test program was conducted before commencement of works to validate the viability of the system. The test program included a grid of 25 rigid inclusions installed in a 5 × 5 grid and spaced at 1.75 m, topped by 1.4 m thick compacted granular fill. The test pad was instrumented with vibrating wire extensometers positioned at various depth to monitor vertical ground strains, hydraulic settlement cells and embedded survey points to monitor surface settlement as well as pressure cells to monitor vertical pressure below the compacted fill. Load was applied as uniform pressure of 50 kPa over an area of 11 × 11 m and maintained over a period of 2 months. In addition to the full-scale test pad, fully instrumented single column tests were also carried out as part of the preconstruction testing program. These tests are used to establish the load transfer characteristics of an inclusion in the ground which is then used in the settlement analysis.

Surface settlement of the test pad under a maintained load of 50 kPa is plotted in Figure 5. Extrapolation of the test results using a hyperbolic function indicated a final settlement of approximately 30 mm, with a time to 90 % consolidation of 99 days. The use of CMMs significantly reduced the total settlement and the consolidation time, estimated at approximately 100 mm and 1 year respectively for the untreated soil.

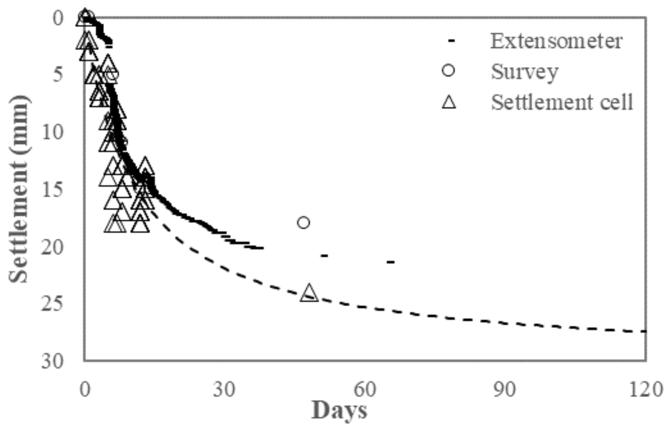

Figure 5. Surface settlement of test pad.

Vertical strain in the soil layers below the test pad was measured using the vibrating wire strain gauges and used to estimate layer settlements at depth. The values were compared to settlements calculated using 2D axisymmetric and 3D FEM analyses and results are summarised in Figure 6. The measured settlements compared well with results of the 3D FEM analysis, but was somewhat lower than the settlements obtained from the 2D axisymmetric FEM analysis. The nature of the axisymmetric analysis assumed one-dimensional (oedometric) conditions and therefore results in higher settlement.
The full-scale test pad confirmed the validity of the ground improvement solution and provides information for which engineering properties of the subsoil could be back calculated for design purposes.

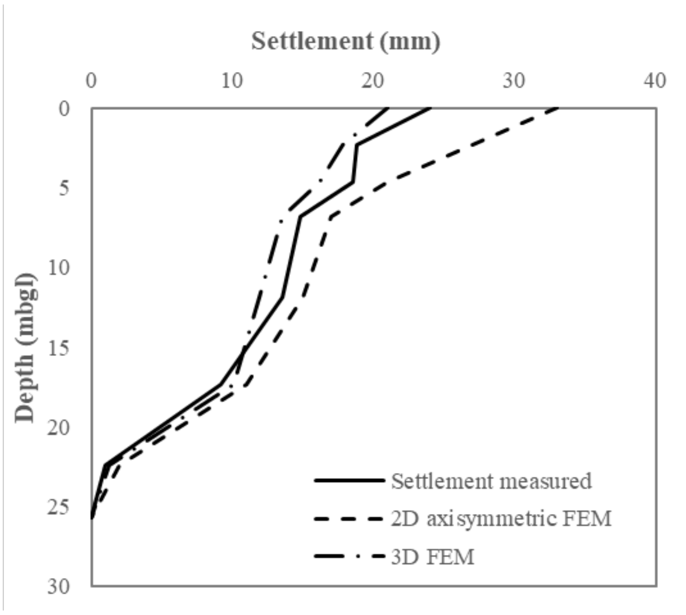

Figure 6. Comparison of layer settlement.

Young's modulus E for the best-fit FEM results can be compared to the cone resistance of the hippo mud layer as given in Equation 1.

$$E = 3.6q_c \tag{1}$$

The observed correlation compares well with values published by Webb (1970) for estuarine soils on the KwaZulu Natal coast where α (E / q_c) ranges between 4.5 - 5.5 and recommended values for soft clay of low plasticity where $\alpha = 2 – 5$ (CEN 2004).

Time-related settlement behaviour of the test pad was less predictable, with 90 % consolidation estimated at between 8 and 12 months whilst the extrapolated period was 99 days. The permeability of the hippo mud layer in the 3D FEM analysis was adjusted to match the measured layer settlement. The best estimate, as illustrated in Figure 7, was achieved using a permeability of 10^{-9} m/s, slightly higher than the values of 10^{-10} to 10^{-11} m/s reported by Brink (1985).

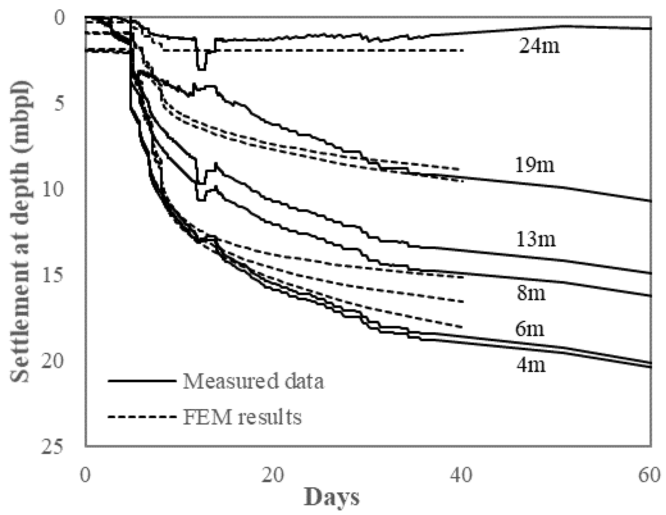

Figure 7. Comparison of time-dependent behaviour.

The reduced consolidation period greatly reduces the risk associated with time-related settlement, as majority of the settlement resulting from the weight of the fill would occur before construction of the floors and reduces the differential settlement on the floor.

In addition to the test pad, single column tests were conducted to better understand the load transfer characteristics of the column. Mobilised friction for various soil layers can be back-analysed from strain measurements taken at various depths along the column. The average mobilised friction is presented in Figure 8, together with results of four cone penetration tests conducted in the test area.

The mobilised side friction envelop generally compares well with the ground profile represented by CPT results. Side friction in the upper layers are back calculated to be approximately 160 kPa for the silty sand layers located at depths of 0-2 m and 6-8 m and 50 kPa for the soft clayey silt layer located at depth of 2-6 m. The accuracy of these values are however limited due to the large spacing of the measurement points in relation to the layer thicknesses.

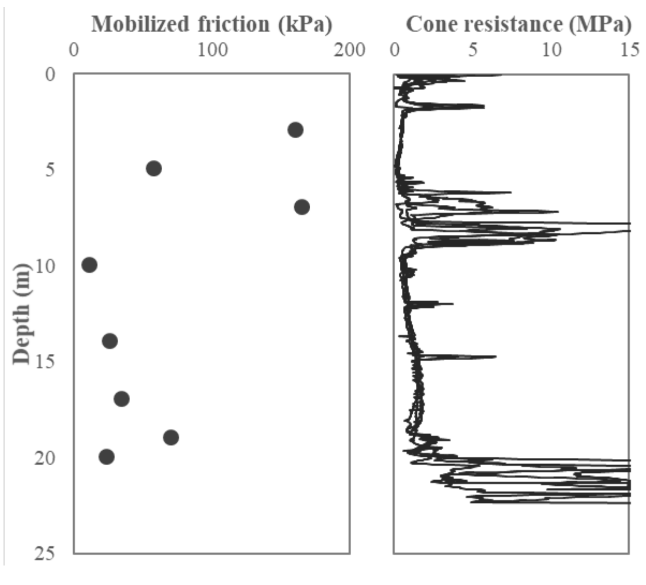

Figure 8. Mobilised friction from single column tests.

The side friction of the hippo mud layer, located at a depth of approximately 8 to 20 m, was measured with more accuracy, due to the thickness of the layer. The side friction increases from 11 to 35kPa over the thickness of the layer and corresponds to a correlation given in Equation 2.

$$q_s = 0.022q_c \quad (2)$$

The correlation compares well with values 0.025 q_c suggested by CEN (2004) for soft clay/silts with $q_c \leq$ 1 MPa, but are higher than the values suggested by Byrne & Berry (2008) of 0.015 q_c.

The full-scale field tests not only demonstrated the validity of the ground improvement system, but also provided insight into the behaviour of the hippo mud soil. The correlations developed in the test program were used in the analysis of the ground improvement systems for the warehouse structures.

5 FIELD PERFORMANCE

In addition to the preconstruction testing, numerous controls were put in place to verify the quality and performance of the completed ground improvement works.

Settlement performance was monitored on all completed platforms using survey monitoring, with the exception of the first platform, for which settlement was measured using vibrating wire liquid settlement sensors. Twelve sensors were positioned on a grid of 3 by 4 on a platform size of approximately 25,000 square meters. Typical settlement measured at one cross-section of the completed platform is shown in Figure 9, together with the CPT profiles taken on the three sensor positions.

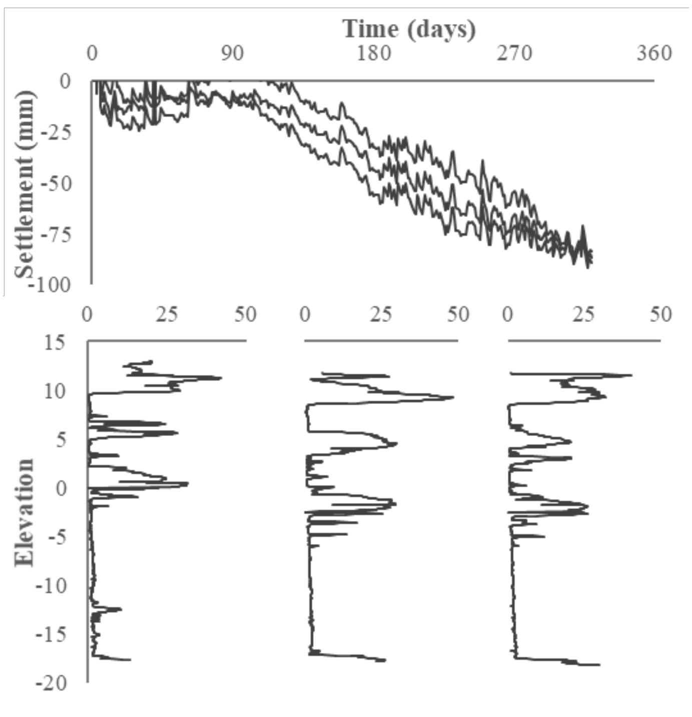

Figure 9. Settlement performance of first platform.

Platform settlement was measured at around 80 to 90 mm for this section, with excellent differential settlement performance of 6 mm across a distance of approximately 120 m.

In addition, 20 load tests have been carried out on completed rigid inclusions as part of the quality control program. The aim of these load tests is to verify the capacity of the rigid inclusions, which may be affected by factors such as inadequate penetration into competent layer, necking, column imperfections, amung others. In order to overcome downdrag, a test load of 1500 kN (approximately double the maximum working column load) was required. The load deflection results of the column load tests are given in Figure 10, with the envelop of the results given in the dashed lines.

In addition, seven load tests were carried out with maximum load maintained over a period of between 7 and 37 days to investigate the creep behaviour of the rigid includions installed in soft hippo mud clays. Results of the creep tests are given in Figure 11.

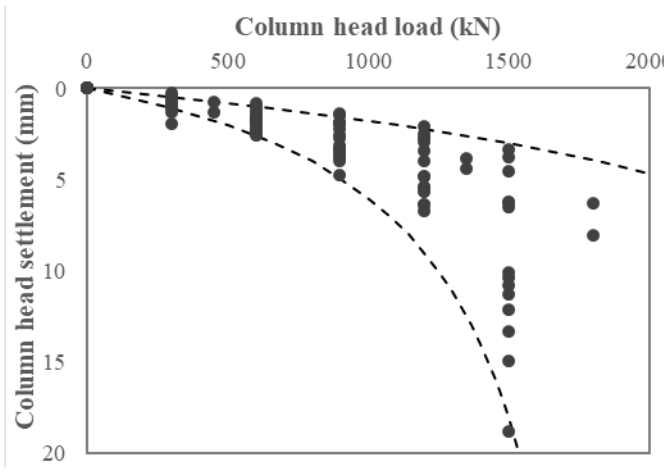

Figure 10. Load deflection curves for column load test

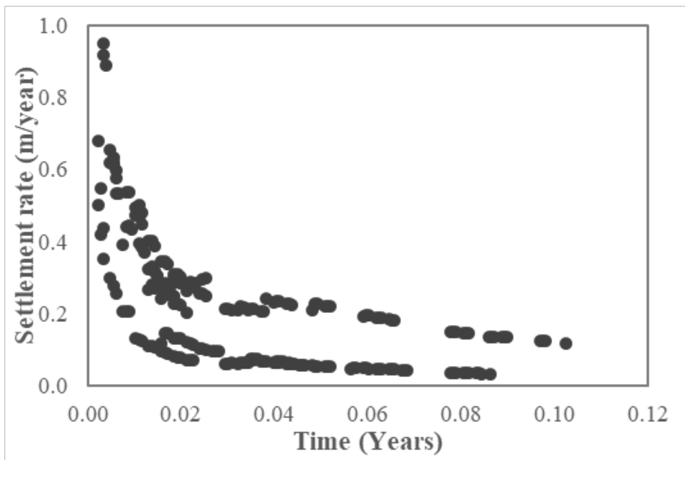

Figure 11. Settlement rate of rigid inclusions.

The load tests confirmed the suitability of the installed columns for the ground improvement works. Additional creep settlement can be extrapolated to approximately 5 - 20 mm over a period of 50 years.

The load tests also provided useful information on the use of rigid inclusions as conventional piles. For a 350 mm column driven to refusal, vertical load capacity of between 500 and 750 kN can be achieved with settlement less 5 mm.

6 CONCLUSIONS

Rigid inclusions is a ground improvement technique commonly used around the world, but has to date not been utilised in South Africa. The system requires concrete columns to be installed into soft soils to improve the mechanical properties of the soil mass.

Hybrid Columns (CMM®), a combination of rigid inclusions and gravel head, was used on the Clairwood Logistics Park project as ground improvement technique in the challenging hippo muds of KwaZulu Natal.

Extensive preconstruction testing program was carried out and verified the feasibility of the ground improvement system. Correlations between Young's modulus, E, and side friction, q_s, against cone resistance, q_c, was established to better model the behaviour of the hippo mud and more accurately predict the settlement performance of the ground improvement works.

Actual platform settlement was monitored and showed excellent differential settlement performance.

Numerous load tests carried out across the site showed that the rigid inclusions could be used as conventional pile foundations with load capacity of up to 750 kN.

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