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Wide range of application of ground reinforcement by means of rigid inclusions in foundation works

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ABSTRACT: Rigid Inclusions (RIs) are stiff elements introduced into the ground mass to improve the geotechnical performance of weak ground. While the technique was initially developed in Europe for road and railway embankment applications, the rapid advancement of the technique and the technical and commercial success have broadened its application in industrial and residential buildings, warehouses, storage tanks and foundations of wind turbines and solar panels. In contrast, standards and specifications have not been developed systematically in many countries. The publication titled "Recommendation for the design, construction and control of rigid inclusion ground improvement" commonly known as ASIRI guidelines was published in France in 2013. This paper discusses the differences between the ASIRI guidelines and the standards and specifications adopted locally, namely AS2159, RMS R225 and BS8006. Applications of ASIRI guidelines are demonstrated using two case studies of RIs for storage tanks and an industrial building.

1 INTRODUCTION

The development of rigid inclusions (RIs) dates back in the 1990's. The technique was initially used in Europe for supporting road and railway embankments over soft grounds. The rapid development, technical and commercial success of this ground improvement method have widened its applications to other structures, including low to medium height commercial and residential buildings, large footprint warehouses, storage tanks and foundations for wind turbines and solar panels.

Ensuring the appropriate application of this new technique requires that the design, construction and testing guidelines are developed in the forms of national standards. The piling code AS2159-2009 (Standards Australia 2009) is generally not applicable to ground improvement works. BS8006-1:2010 (The British Standards Institution 2010) is only applicable to basal reinforcement over piled road embankments. Research carried out in France between 2005 and 2011, has resulted in the publication titled "Recommendation for the design, construction and control of rigid inclusion ground improvement" commonly known as ASIRI (Simon 2013). The ASIRI presents RI design in three scenarios: one where RIs are used to reduce settlement, second where RIs are required to increase bearing capacity and the third is a special case for embankments on RIs. These recommendations are presented, discussed and compared with the Australian Standard and relevant specifications.

Two cases studies are presented to demonstrate the design approaches for ground reinforcement by means of rigid inclusions. The designs were performed based on ASIRI and validated by two different analytical methods using computer programs: Finite Element (FEM) based Plaxis and Load Transfer Method (LTM) based Keller Improvement Designer (KID). The case studies also show the methodology of ground improvement selection, design calculations, verification and testing of the design assumptions on site.

2 OVERVIEW OF RI TECHNIQUE

Rigid Inclusions generally refer to stiff columnar elements installed in soft ground to increase the bearing capacity, reduce the settlement and/or the differential settlement. The term "rigid" is used to indicate the relatively high stiffness of column material as compared to the in-situ soft soil. Whilst concrete columns are the mostly used, timber or steel can also be adopted. Rigid inclusions can be installed using various techniques such as driven precast, drilled displacement and continuous flight angering. Each technique can have different installation effects. In local practice, most rigid inclusions are installed using rotary displacement method or vibrated steel tube. These methods provide very high productivity output in range of 400-600lm/shift, and they generate minimal spoil, which is advantageous for soft soils with high acidic sulphate potential that is costly to dispose.

Similar to other ground improvement methods, RI technique is typically effective and economical for large area soft ground improvement to support distributed loads. They can also be used to support point loads, which in most cases are less than those can be supported by conventional piled foundation.

2.1 *Basic mechanics*

The load transfer mechanism between rigid inclusions and soil is similar to that of piles but the design principle is quite different. Figure 1 below illustrates the differences between a suspended slab on piles, a piled raft and a foundation on rigid inclusions. A suspended slab on piles design assumes that all the loads are transferred to piles and the ground does not provide any support on the underside of the slab. In comparison, a piled raft relies on support by both the soil and the piles. The load sharing between piles and soil is dependent on the relative stiffness response of piles and soil as well as the rigidity of the slab. When constructed in soft soils the system may turn into suspended slab on piles as soil settles away from the soffit of raft.

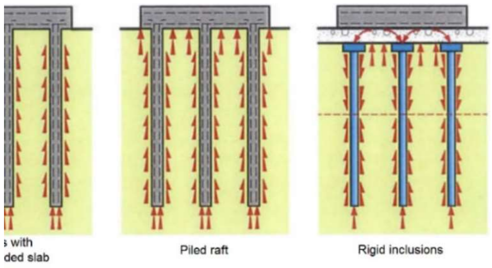

Figure 1. Different load transfer mechanism of foundations (Simon 2013)

The key difference between a foundation on rigid inclusions and a piled raft is that the supported structure is separated from the inclusions with a layer termed 'Load Transfer Platform" (LTP). The purpose of the layer is to transfer loads from the structure to the inclusions through arching effect in the granular material. This results in more uniform stress distribution at the soffit of slab and hence allows the slab thickness and reinforcement design to be optimised. The load being transferred to soil would cause it to settle, which in turn results in load transfer from the soil onto the rigid inclusion through negative skin friction. This soil to inclusion load transfer diminishes along the depth as the soil carries lesser load and settles less relative to the inclusions.

2.2 *Applications*

One of the major applications of rigid inclusions is supporting road and railway embankment over soft ground. It can also be used to provide foundation support to building and other civil structures that does not impose very large load and are not sensitive to settlement. In general, the applications can be divided into three categories (Simon 2013):

- Industrial and commercial building slabs, where the loads are typically not very high and bearing capacity is generally not a problem due to the large dimension of slab. Essentially the design is mainly governed by settlement;
- Liquid storage tanks and basins, where the loads are relatively high but the structures are flexible enough to tolerate larger settlement. In such cases, the design is often driven by settlement control and possibly bearing capacity too;
- Embankments, where settlement control and stability of the slope are is required.

3 COMMONLY ADOPTED GUIDELINES

Local practices for the design and construction of rigid inclusions often make references to documents such as AS2159-2009, BS8006:1-2010 and RMS QA Specification R225. Although these documents provide some good guidance for certain aspects of rigid inclusion works, they cannot be applied to projects indiscriminately and sometime can lead to design that cannot be constructed on site.

The piling standard AS2159-2009 provides useful recommendations on the overall quality control of different installation techniques. The advice on various testing procedures is also valuable in ensuring performance of reliable tests. The principle of incorporating geotechnical uncertainties and load testing into the design safety factor is also prudent. However, the design methodologies specified in the standard are mostly suitable for piling works and not ground improvement works, which often have different design principles. Also, little information on the analytical methods is included in the code. This is perhaps done intentionally to allow sufficient flexibility as stated in the foreword of the code.

The British Standard BS8006:1-2010 is generally only used for the design of basal reinforcement of embankment. The document provides detailed analytical methods for designing various components of a reinforced soil retaining wall or a reinforced embankment. In particular, Section 8.3.3 of the code is devised only for the design of 'piled embankment'. As stated in the code, the design approach assumes all loads are carried by the piles and the ground does not provide any support to the embankment. In order to satisfy this assumption, stiff geo-reinforcement (such as geotextile and geogrid) is often required to transfer the loads to piles. In addition, the code adopts simplified calculation methods and focuses on the design of embankment structure above the foundation/ground level. It does not consider pile-soil interaction, which can be critical in many cases. Consequently, it often leads to conservative design which is uneconomical.

Locally in New South Wales, Australia, The RMS QA Specification R225 or D&C Specification R225 are often adopted for the construction of rigid inclusions. These specifications are developed for Concrete Injection Column (CIC), which is to be installed using displacement auger only. As discussed in the following sections, certain requirements in these specifications can also be impractical to satisfy such as coring of small diameter columns, dynamic load testing and hit and miss construction sequence.

4 ASIRI

ASIRI is the abbreviation of French term “Amélioration des Sols par les Inclusions Rigides”, which translates to “soil improvement by rigid inclusions”. It was a French national research project conducted between 2005 and 2011 to study the behaviour of rigid inclusions for ground reinforcement. The main goal of the study was to establish industry-wide guidelines by engaging key stakeholders including academics, consultants and contractors. As a product of the project, The Recommendations for the Design, Construction and Control of Rigid Inclusion Ground Improvements or commonly known as ASIRI guidelines was published. It presents the theoretical basis of RIs as well as detailed design approaches, construction considerations and testing and verification requirements.

4.1 *Design*

Rigid inclusions are typically installed in regular grid pattern to treat an area of soft ground to support distributed loads. As such, in most cased the design can be simplified to a unit cell, which can be analysed using an axisymmetric model as shown in Figure 2. Through the analysis, the settlement of the improved ground (serviceability limit state) can be estimated. The load transfer between the soil and the inclusions (geotechnical ultimate limit state) can be assessed and compared to available data as well as to the actual static load test results obtained in-situ. The stress in the rigid inclusion can also be obtained to determining the compressive strength (structural ultimate limit state) required for the inclusions.

In the case where rigid inclusions are installed under foundation slabs, the presence of the rigid inclusions creates hard points which would induce additional bending moments. A hogging bending moment is generated in the slab over the location of the RIs and sagging bending moment is generated between the columns. The bending moments in the slab can be minimised by either reducing the spacing of RIs or increasing the thickness of the load transfer platform layer. These additional bending moments if present in the slab should be considered in the slab design.

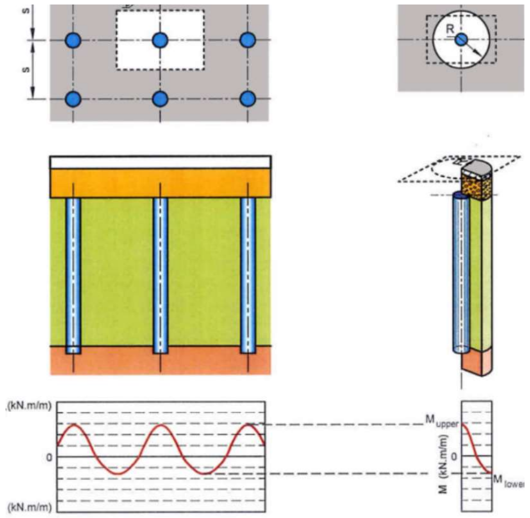

Figure 2. Model approximation of rigid inclusions (Simon 2013)

4.2 *Construction*

The ASIRI guidelines provide recommendations on a range of construction specifications. Table 1 below compares the requirements to the RMS QA specification R225.

Table 1. Comparisons of construction specifications

Criteria	ASIRI	RMS R225
Installation method	Any	Displacement auger
Minimum diameter	250mm	-
Minimum spacing	3-4 times dia.	-
Maximum spacing	3m*	-
Plan position tolerance	200mm^	75mm
Elevation tolerance	50mm	-
Inclination	1:50	1:100
Allowable heave	-	25mm
Installation sequence		‘hit-one-miss-one’#

* For inclusions up to 0.5m diameter. Special requirement for pavements, which maximum clear distance should be less than twice the embankment thickness above column head.
^ 100mm for footings
# Minimum waiting time 24 hours

It is permitted in RMS specifications to install columns in a ‘hit-one-miss-one’ sequence with minimum waiting time of 24 hours. Although this sequence minimises the risk of necking caused by the concrete squeezing in adjacent installed column, it increases the risk of inducing cracks or even breakage of the adjacent column. This is because the squeezing of concrete a sign of soil displacement during installation. The displacement may break and push the hardened concrete in adjacent column. Once the material separation occurs, the concrete in the column is unlikely to re-connect as it is already hardened. As a result, column would be discontinuous. The more suitable approach to avoiding concrete squeezing should be adopted. If smaller spacing is necessary due to design loading or other requirements, the delay in installation of adjacent column should be closely linked to the concrete initial setting time or consideration given to use reinforcement in first pass of columns or non-displacement installation method adopted.

It is also critical to ensure a positive concrete oversupply to ensure the column diameter. Both AS2159-2009 and RMS QA Specification R225 require at least 105% of concrete to be used as compared to the theoretical volume. However, there should also be an upper limit to avoid causing too much soil displacement and damaging installed columns, as RIs are typically installed in a grid pattern over large area.

4.3 *Testing and verification*

ASIRI guidelines also require a comprehensive testing regime for quality control. The requirements are summarised and compared to RMS R225 in Table 2.

Table 2. Comparisons of testing regime

Test	ASIRI	RMS R225
Trial Column	For every zone	Project specific
Static load test	1 in 75 to 1 in 500	Cracked columns
Integrity test	3-5*	10%
Column exposure	Trial columns	min. 2^
Compressive strength	7 and 28 days	28 days
	6 samples / 100m^3	4 pairs per day
Column coring	-	1% of columns
Slump test	2 tests / truck	-

* 1in 150 with minimum of 3 for settlement reduction; 1 in 75 with minimum of 5 for bearing capacity;
^ On columns failed integrity test

The RMS specifications require both cast and core samples to be obtained for concrete strength testing. This can be difficult to execute as rigid inclusions are often of small diameters (<350mm) and the core barrel will run away at shallow column depths. Also, a static load test is required when a cracked column is discovered. In contrast, ASIRI guidelines requires cast sample testing only and at the same time mandates static load testing.

The types of static load test and the corresponding test loads specified in ASIRI guidelines are similar to those in AS2159-2009. However, the loading schedule in the former is shorter, which in turn is less costly and more convenient to conduct. Table 3 below summarises the loading schedule as per ASIRI guidelines.

Table 3. Static Load Test – Schedule as per ASIRI Guidelines

Test	Load	Duration
Initial stage	10%	15min
	0%	-
Loading	Increments of 20%	min. 15min*
Unloading	Decrements of 20%	5min^

* The load can be increased to next step if the movement is less than 0.02mm/min in two consecutive readings. Readings are taken for each loading stage at 1, 2, 4, 8, 15, 30 & 60 min;
^ Readings are taken for each unloading stage at 1, 2, 3, 4 & 5 min.

5 DESIGN METHODOLOGY

Design of rigid inclusions typically involves numerical modelling of the interaction between soil and rigid inclusion elements. In practice, Finite Element Method (FEM) based computer program such as Plaxis is often used. This method allows using advance soil models that captures realistic soil behaviour and hence more accurate results can be obtained. It can also simulate the time-dependent behaviour of consolidating soil, which is often of great interest in soft-ground improvement. However, the analysis is often more time consuming as compare to other simplified methods. Also, extensive and good quality soil testing is often required to obtain the input parameters. The cost of carrying out such tests may not be justifiable for a small project.

Keller's in-house software – Keller Improvement Designer (KID) can perform RI design calculations using Load Transfer Method (LTM), which is known as t-z method. The design follows the simplified approach presented in ASIRI guidelines. Detailed description of LTM can be found in many publications on pile design such as Poulos and Davies (1980). In general, shaft friction and end bearing of RI are represented in the model by a series of springs as illustrated in Figure 3. The load-deformation behaviour of the springs can be specified using mobilisation functions, which can be found in literatures such as those summarised in Bohn et al (2016) or calibrated using load test results. The problem is solved by iterations until equilibrium is achieved while all boundary conditions are met.

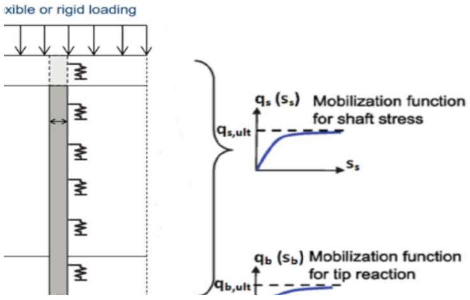

Figure 3. Principles of Load Transfer Method (LTM)

6 CASE STUDIES

6.1 *Foundation for tanks*

Two stormwater tanks have been constructed in the Newcastle area. The tanks were 25m and 32m in diameter and both are 11m high. The tanks were constructed with steel shell founded on reinforced concrete slab. The subsoil of the site is relatively uniform, and the profile is presented in Table 4 below. The cost of initial foundation scheme was substantial. After reviewing the project information, RIs were proposed as a more economical alternative while meeting all performance criteria. As a result, significant savings were made on the total cost and project duration. The adopted solution comprised 400mm diameter columns installed under the footprints of the tanks. The columns were installed with 2m socket into the medium dense sand layer underlying the soft to firm clay. A cross-section of the ground improvement scheme is shown in Figure 4.

Table 4. Subsoil profile under the stormwater tanks

Depth (mAHD)	Thickness (m)	Material	Consistency
2.75 – 0.0	2.75	Fill	Medium dense
0.0 – -3.0	3.0	Silty Clay	Soft to firm
-3.0 – -8.5	5.5	Sand	Medium dense
-8.5 – -13.0	4.5	Sand	Dense to very dense
-13.0 – -16.5	3.5	Clay	Very stiff
-16.5 – -23.5	7.0	Clay	Stiff

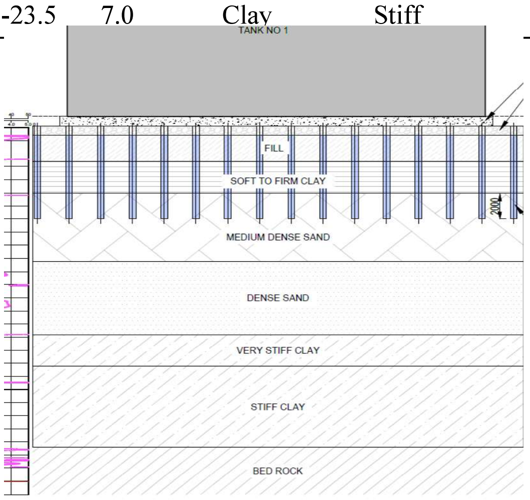

Figure 4. Rigid inclusion scheme under tanks

Axisymmetric unit-cell model has been analysed using computer program Plaxis to assess the geotechnical performance of the individual RIs. The results were also cross-checked by Load Transfer Method (LTM) using Keller's in-house design software Keller Improvement Designer (KID). The comparisons of the results are shown in Figure 5. Overall the results from both methods are similar, except that LTM indicates more load is carried by the RIs. This is likely due to the fact that Mohr-Coulomb model is used in Plaxis which often results in 'softer' toe response.

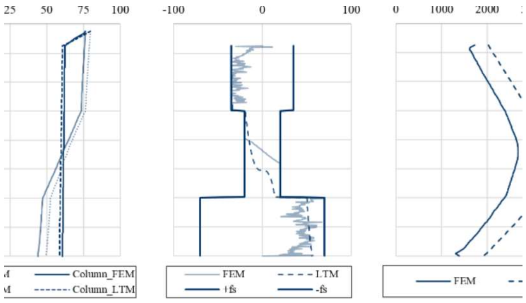

Figure 5. Comparisons between FEM and LTM for the rigid inclusions under the tanks

The project also implemented a rigorous testing and verification regime, which involved pre-production trial works, material testing, quality control documentations and a number of static load testing on both trial and production columns. In addition, plate load tests were also carried out to verify the compaction and stiffness of the completed load transfer platform.

During the static load tests, a test load of 370kN was applied on the top of test columns at platform level. Loading schedule as per ASIRI guidelines was adopted. The test load was estimated based on the predicted maximum columns load (250kN) plus two times of the negative shaft friction on the column (120kN). This ensured the part of column providing positive shaft friction is mobilised, and in turn verified the load vs. settlement behaviour. The test showed the test columns performed close to or slightly better than anticipated. Figure 6 below shows one of the typical static load test results, which generally showed better than expected performance.

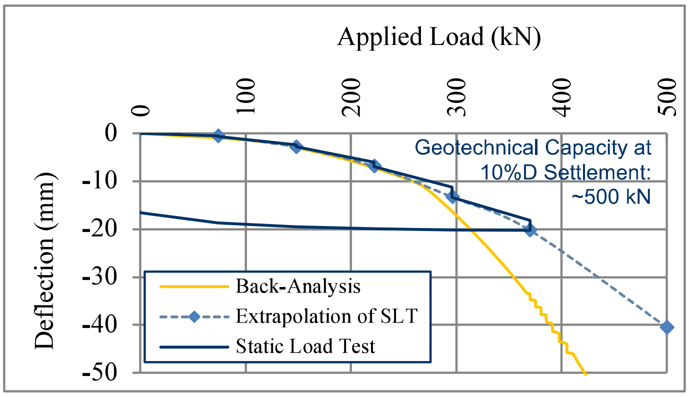

Figure 6. Static load test results for the RI under the tanks

6.2 *Foundation for industrial building*

An industrial building with floor area of over 6000m^2 has been proposed in the Port Adelaide area. The building is a steel frame warehouse with metallic roof and cladding. It will be used for the storage of bulk material, which will impose a floor loading of up to 90kPa. The site is underlain by a layer of existing fill followed by about 7m of firm clay. A typical soil profile under the warehouse is presented in Table 5.

Table 5. Subsoil profile under the warehouse

Thickness (m)	Material	Consistency
1.0	Fill	Medium dense
2.0	Sandy Clay	Firm
5.0	St Kilda Formation	Firm
3.5	Glanville Formation	Medium dense
-	Hindmarsh Clay	Stiff to hard

Due to the presence of firm clay layer and the expected loading conditions, suspended slab on piles was considered initially. This solution would have provided a very good performance with a maximum settlement of 25mm or less. However, it was recognised that such performance was unnecessary considering the intended purpose of warehouse and the flexibility of the steel structure. Consequently, less stringent performance criteria were adopted for ground improvement option. The adopted RI solution enabled the slab to be designed as slab-on-ground, which provided additional savings on the slab. The scheme consists of 350mm diameter RIs installed at 2.2m square grid. The columns are founded 0.5m into the medium dense sand. The overall cost for the foundations (inclusive of slabs) is 30% less than the piling option. A schematic cross-section of the ground improvement is shown in Figure 7.

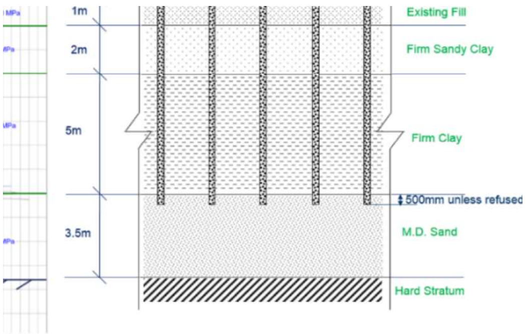

Figure 7. Rigid inclusions scheme under the warehouse

The design was carried out using Plaxis and the results were compared with the calculations performed based on LTM in Figure 8.

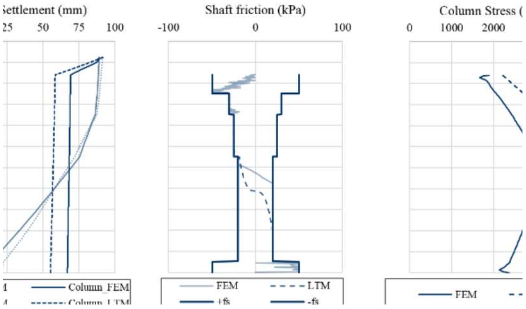

Figure 8. Comparisons between FEM and LTM for the rigid inclusions under the warehouse

Results from Plaixs and KID showed similar ground settlement. The mobilised shaft friction was also comparable. However, KID indicated greater load in columns as compared to Plaxis. For design purpose, higher stress value was adopted to ensure sufficient structural strength was provided in the columns.

In addition to the axisymmetric unit cell model, plane strain analysis has also been carried out using the "embedded beam row" in Plaxis to model the RIs. The main purpose the analysis is to assess the differential settlement of the warehouse slab. Figure 9 shows the settlement for one of the load cases.

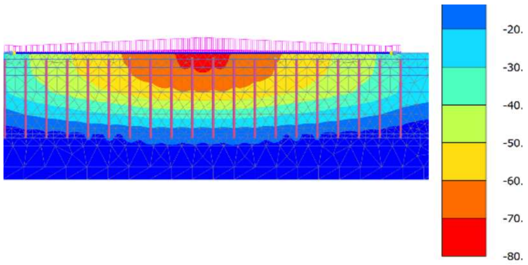

Figure 9. Overall settlement under the warehouse slab

7 CONCLUSIONS

Rapid development in rigid inclusions technique has outpaced the setting up of local code of practices. The specifications or codes currently used in many projects are either developed for other techniques or not able to encompass all rigid inclusion applications. The publication of "Recommendation for the design, construction and control of rigid inclusion ground improvement" commonly known as ASIRI has provided a much-needed and comprehensive guidance on the technique. It offers a streamlined approach from design, construction, testing to quality control.

Following the ASIRI guidelines, the RI design for two projects have been streamlined. The installation of columns has been carried out smoothly without constructability issues. Quality control and testing have validated relevant design assumptions and have verified the performance of RIs will meet the project criteria. In both projects significant savings in cost and time were also made as compared to the piling option.

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