13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.)

Foundation analysis and ground improvement for industrial high-bay warehouse developments

M. Haertsch, G. Mostyn & A. Salim

ABSTRACT: This paper discusses key challenges encountered during foundation analysis and design of ground improvement to achieve stringent differential settlement limits for industrial high-bay warehouse facilities. These high-bay warehouse facilities are typically forty metres high and comprise fully automated storage retrieval systems (ASRS). Differential settlement limits of 1V:2000H are often imposed on the slab supporting the high-density storage units and robotic packing structures.

This paper references two case studies to explain key geotechnical aspects of high-bay facilities including site selection, developing a geotechnical model of existing ground conditions, numerical analysis of the foundation system and economic design of ground improvement to achieve differential settlement limits. The paper also includes analysis for a site where the original earthworks were not designed for tight tolerances. Design moduli for the site were verified by in service performance and measured deformations. These projects have highlighted the importance of an effective site investigation in order to understand existing ground conditions prior to commencement of design.

1 INTRODUCTION

Recent high-bay facility developments with fully automated storage retrieval systems (ASRS) have significantly improved the overall efficiency of many supply chain and logistics operations. High bay facilities are developed to occupy a limited footprint and maximise storage capacity. They consist of narrow racking aisles with high density storage units that are typically up to forty metres high. Developments in robotics technology has enabled machinery to store, select and move the product to distribution channels without the need for human-operated forklifts that are synonymous with standard warehouses. Benefits of high bay facilities compared with typical warehouse operations include greater storage capacity, reduced labour costs, 24-hour operations, increased work-place safety and improved flow at all stages of the distribution process.

Due to storage heights, the ASRS system needs a flat level platform to operate safely and effectively. As such differential settlement limits of 1V:2000H, that is less than 0.5 mm in service vertical settlement over 1 m horizontal length, are often imposed on the slab supporting the ASRS. Depending on the racking supplier, these requirements are often adopted from European codes, i.e. Federation Europeenne de la Manutention (FEM) 9.81 and 9.82.

In general, the differences between high-bays and standard warehouse facilities are summarised in Table 1.

Two case studies are presented to briefly discuss key geotechnical aspects of ASRS. These include site selection, understanding existing ground conditions, foundation analysis and economic design of ground improvement to achieve stringent differential settlement limits.

Table 1. Comparison between high-bays and standard warehouse facilities

Parameters	**High-bays and ASRS facilities**	**Standard light-weight warehouse facilities**
Building height (m)	40 (up to 25 pallets high)	10 (5 or more pallets high)
Storage load (UDL – kPa)	Up to 60-80 kPa	Up to 25-30 kPa
Post Load (kN)	350	75
Operation	Automated	Manual (forklift and labour)
Floor tilt requirements	1V:2000H to 1V:3000H	1V:100H to 1V:300H
Project cost	$200 million to $300 million	$10 million to $30 million

2 CASE STUDY 1

The first case study is for a project in Queensland. This site is located in Brisbane and was previously undeveloped (a “green” field).

2.1 *Geotechnical investigation*

A geotechnical investigation was undertaken for ASRS. The investigation locations were chosen to provide good coverage of the ASRS area. The investigation comprised drilling of boreholes and seismic dilatometer testing (SDMT). The dual approach was chosen to economically capture accurate information for soil and rock. SDMT results were interpreted to better understand soil properties, particularly initial constrained modulus. Results for SDMT testing are reproduced as Figure 1. Drilling (with coring) was completed to “prove” bedrock level.

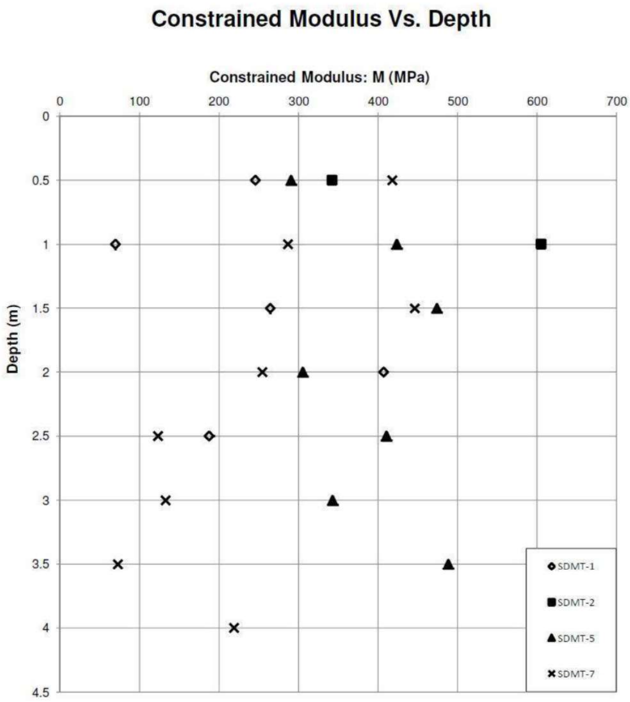

Figure 1. SDMT results

The geotechnical investigation indicated favourable conditions for ASRS. Depth to bedrock was relatively shallow (e.g. within the top 2 m of the finished bulk earthworks level), and bedrock surface was essentially “flat”. A 3D ground model for the ASRS area was developed following the investigation.

The investigation was fundamental to being able to reliably analyse the foundation system. The targeted approach led to improved understanding of material properties and thickness of geotechnical units. Without a good understanding of the existing site conditions it is likely a more conservative solution would have been recommended leading to higher overall project costs, e.g. more ground improvement work.

2.2 *Foundation analysis*

Numerical analysis of the foundation was completed using FLAC3D and Strand7. The model consisted of two stages representing the staggered installation of the ASRS system. Loading magnitude and spacing was adopted based on the racking manufacturer’s installation guide. Each individual post load was modelled.

The centre aisle for one aisle width was modelled parallel to the aisle and perpendicular to the aisle in FLAC3D. The full 3D model was run in Strand7. A cross section of the FLAC3D model is shown in Figure 2. An isometric view of the Strand7 model is shown in Figure 3.

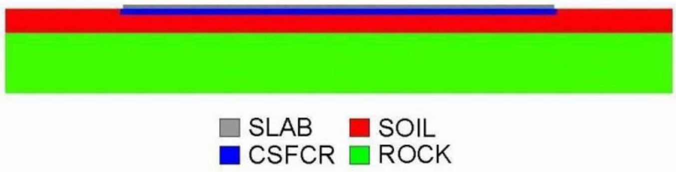

Figure 2. FLAC3D model cross section

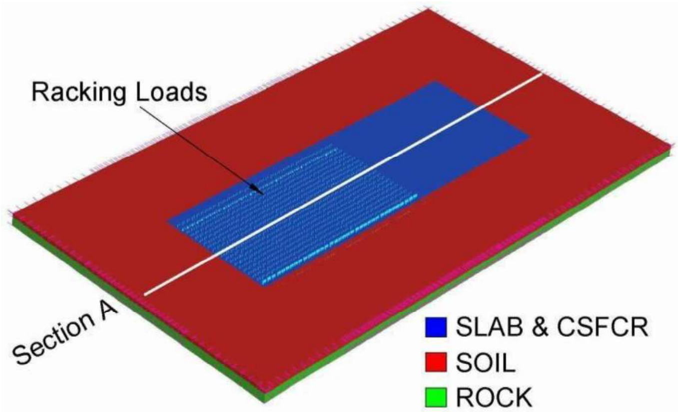

Figure 3. Strand7 model

2.3 *Ground improvement*

For this site various ground improvement strategies were analysed. It was considered that the most economic strategy would be to remove the existing soil to a specified depth and replace with a 500 mm thick layer of cement stabilised fine crushed rock (CSFCR) underlying a 300 mm thick concrete slab. This was assessed based on the foundation system achieving a settlement limit of 1V:2000H with the exception of the ASRS perimeter and a boundary between stages.

Figure 4 presents the estimated displacement and tilt following ground improvement for Section A shown on Figure 3. The section is taken perpendicular to the racking aisles.

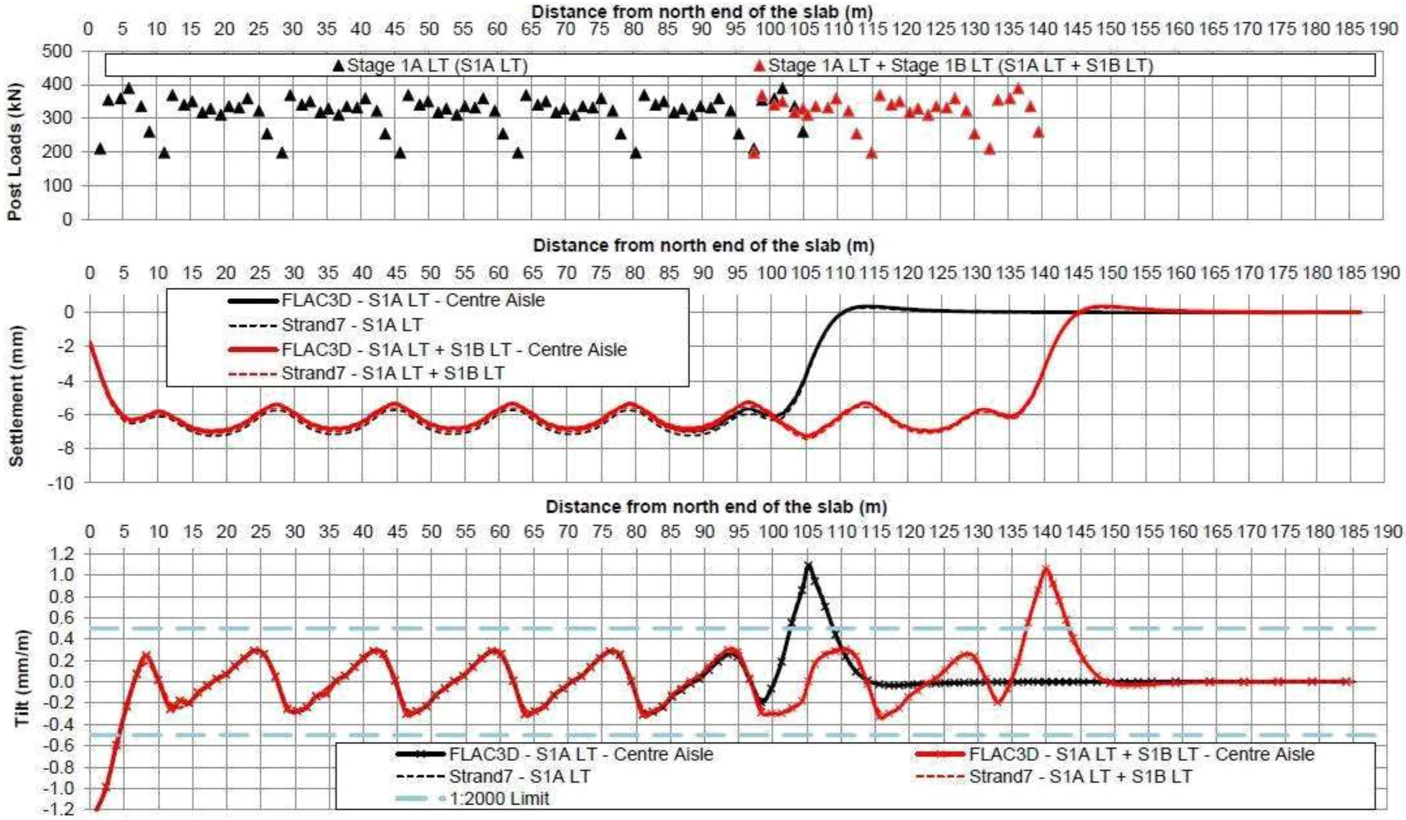

Figure 4. Predicted displacement and tilt for Section A with ground improvement (Case Study 1)

2.4 *Hard edge loading (pattern loading)*

Hard edge loading refers to the load case where bays on one side of a line are fully loaded adjacent to empty bays on the other side of the line. It was understood from the racking supplier that hard edge loading was not expected for this ASRS, e.g. the system has the capability (within the software) to distribute the storage across the bays. However, hard edge loading is generally unavoidable at the perimeter aisles of an ASRS as the full warehouse capacity is generally utilised. As such, engineering solutions are usually required, at least, at the perimeter. Possible solutions include installation of ground anchors (i.e. preloading) or including a softened zone.

A structural solution consisting of void formers installed around the perimeter of the ASRS was designed for this project. Void formers were used to soften the edge of the loading area and gradually smooth the predicted settlements at the edge posts. The solution was modelled with a user defined stress-strain curve for the void formers provided by the structural designer. The model results were found to be within the settlement limits.

3 CASE STUDY 2

The second case study is for an existing warehouse located in Western Sydney that would be upgraded with an ASRS facility. The original earthworks and warehouse slab were not designed for tight settlement tolerances. The authors had been closely involved in the site development including undertaking numerous plate load tests. A detailed study of the site and existing performance during ten years service was required in order to assess the suitability for an ASRS from a geotechnical perspective. This required the development of a geotechnical model, verification of existing performance and numerical analysis of the proposed ASRS.

3.1 *Geotechnical model*

A geotechnical model of the site was developed based on a detailed desktop review of site investigation reports and earthworks construction documentation. A comprehensive 3D ground model was developed. Bedrock was inferred to be at least 8 m below the existing surface and sloping towards the southeast. Depth to residual soil was variable due to the presence of soft alluvial material that was removed during earthworks construction. Engineered fill was placed to varying depths across the extent of the site. The existing slab was 230 mm thick.

A key feature of the site is a 6 m deep backfilled sewer trench. The trench is approximately 25 m wide and runs across the shorter length of the warehouse.

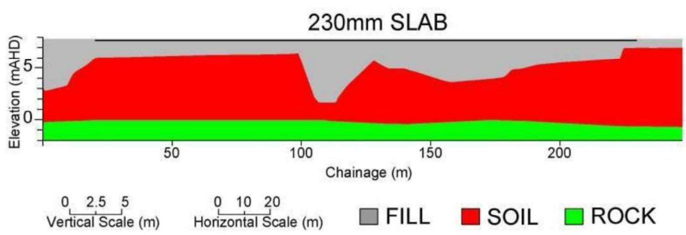

Figure 5. Geotechnical Section B (Case Study 2)

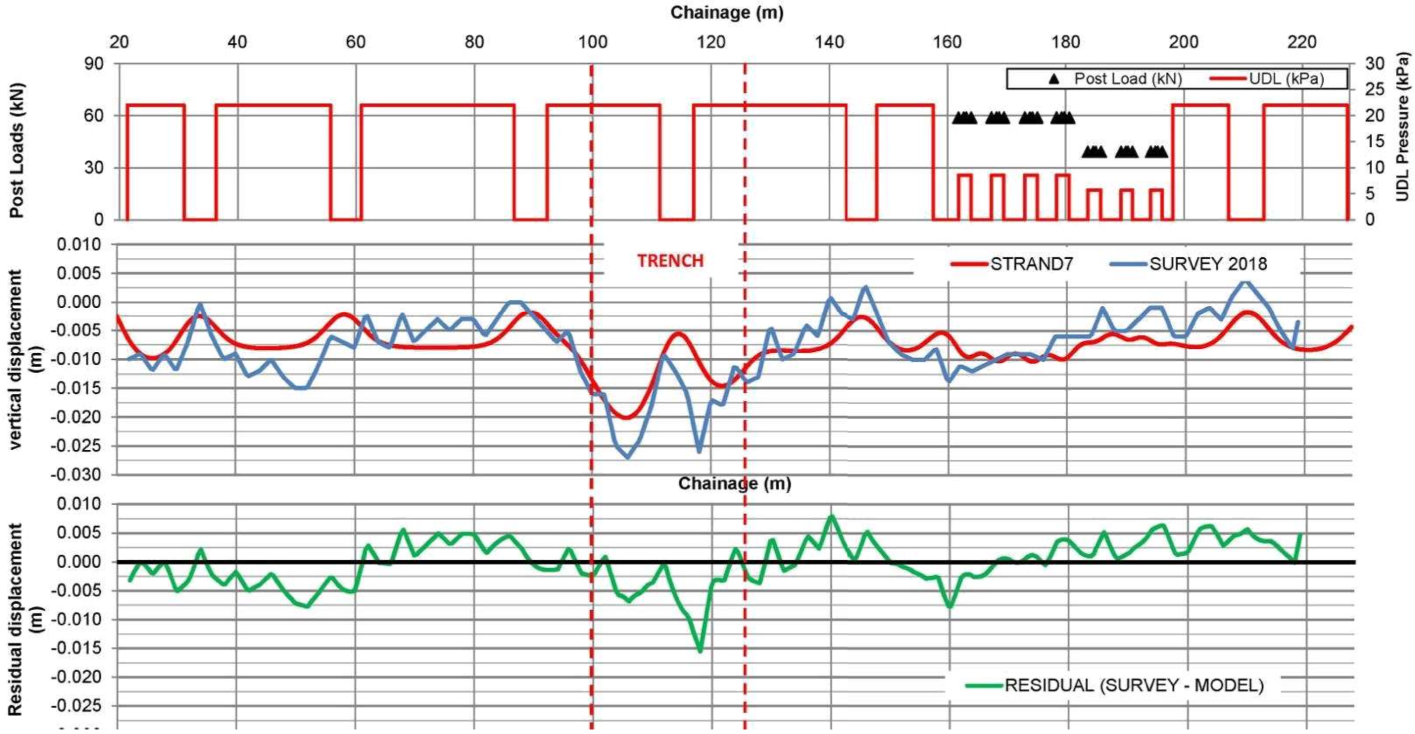

Figure 6. Comparison between predicted and measured displacements for Section B (Case Study 2)

The trench was backfilled with engineered fill with side batters at approximately 1H:1V. Figure 5 presents Section B.

3.2 *Verification of ground model*

The original earthworks were designed for typical light industrial use. Verification of the ground model was completed by measuring slab deflections and assessing against existing loading conditions. Slab de-flections were measured by engineering survey and selective runs using a walking profilometer. A 3D analysis of the existing warehouse slab was completed using Strand7. The model was compared with measured deformations. Figure 6 presents a comparison between settlement predictions and measured deformations. Figure 7 presents existing loading conditions. Displacement contours of existing conditions as predicted by Strand7 are presented in Figure 8.

Further numerical analysis was undertaken for the proposed ASRS load (e.g. double the existing storage load). The analysis indicated that even under existing loading conditions the site was not able to achieve the high level of performance required for ASRS within the backfilled trench area. This demonstrates that earthworks originally designed for typical industrial warehouses are likely to struggle to achieve the higher performance requirements for ASRS. This case study also highlights how three-dimensional subsurface effects such as sloping bedrock and trenches can adversely affect foundation structures.

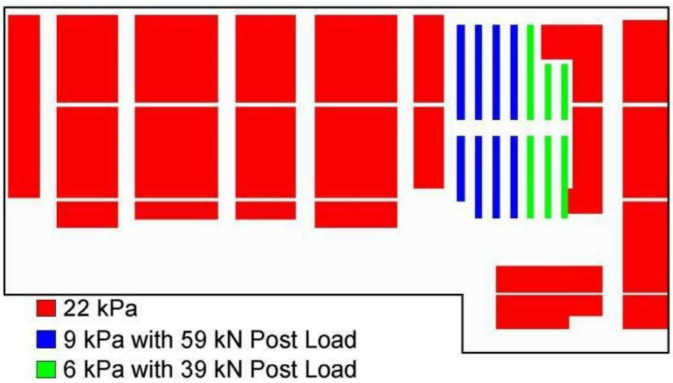

Figure 7. Existing loading conditions

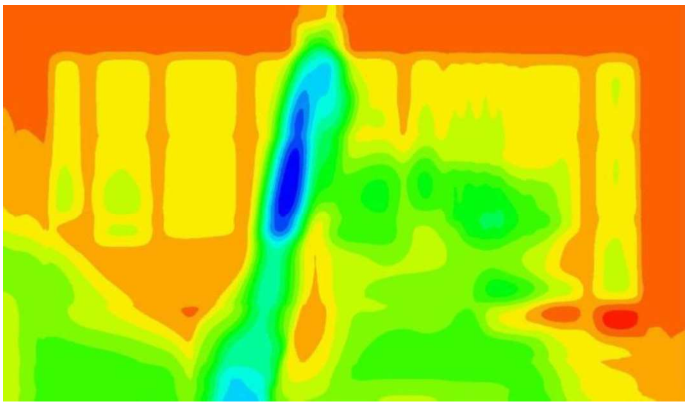
Figure 8. Displacement contours for existing conditions

4 CONCLUSIONS

The key features of each case study are summarized in Table 2.

Both case studies highlight key geotechnical features that influence foundation design. These include depth to bedrock, presence of soft material, slope of geotechnical units, magnitude of post loads in the ASRS area, hard edge loading and load spacing. Ground improvement or engineering solutions will often be required if any one of these factors are unfavourable.

Table 2. Key features of Case Study 1 and Case Study 2

Feature	Case study 1	Case Study 2
Ground conditions	Green field	Existing warehouse
Storage system	High-bay and ASRS	ASRS
Requirements	1V:2000H (achieved)	1V:2000H (achieved with an area of non-conformance)
Solution	0.3 m slab overlying 0.5 m CSFCR	Existing slab and negotiation with suppliers

Both case studies demonstrate that an effective understanding of the existing subsurface conditions is fundamental to foundation analysis and economic design of ground improvement. An effective desktop review and targeted site investigation was crucial in developing a 3D geotechnical model. Numerical analysis was subsequently completed with fewer assumptions leading to greater confidence in settlement predictions.

The second case study shows that earthworks designed for typical industrial warehouses are not necessarily suitable for installation of ASRS. Sites such as this usually require some degree of remediation or ground improvement in order to achieve the higher performance requirements.

Both case studies demonstrate that site suitability for ASRS depends on a number of factors. These include technical and non-technical factors. Important technical factors are:

- Performance requirements.
- Ground conditions (e.g. depth to top of bedrock (after cut and fill), variability, reactivity, etc.)
- Loads (racking layout, spacing and magnitude of the post load).
- Proximity of other warehouse components, e.g. frame footings, hardstand areas, etc.
- Ability to accept performance non-compliance and reset the post following a few years of operations.
- Location (proximity to major arterial roads, existing logistics infrastructure).
- Whether ASRS aligns with the business product mix.
- Cost to build and maintain.
- Other constraints such as real estate, neighbouring site / boundary, aesthetics, legislation, etc.