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Foundation system optimization of a high-bay warehouse using finite element modelling

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ABSTRACT

An automated high-bay warehouse with a floor area of approximately 37 m x 170 m and a total height of 36 m is being built as part of the extension of the LEGO plant near Nyíregyháza, Hungary. In this paper we present the design-optimization process of the building's foundations. In this type of system, the formerly separated structural and storage functions are cost-effectively combined in a single structure. The shelving system itself provides the support of the planned warehouse. In such structures, the focus is more on geotechnical and foundation issues. Taking into account both technical and economic aspects, 2D and 3D geotechnical finite element models were used to investigate the possibilities of slab foundations, rigid inclusion soil improvement and pile-supported slab foundations. The very strict deformation requirements can only be verified by such advanced modelling. In this study we emphasize the essential cooperation of the fields of structural and geotechnical engineering.

KEYWORDS

finite element modelling, deep foundation, automated warehouse

1. INTRODUCTION

Our design task was the foundation of the automatic high-bay warehouse that was built as part of the expansion of the LEGO plant in Nyíregyháza. Our company was involved in the construction of the LEGO factory as technical inspector, and in the current expansion project as a geotechnical designer. For this purpose, we used the previously completed soil investigation report and additional field tests carried out for the detailed design.

In the framework of the expansion, we prepared the execution plans of three building called MLB, Raw Material and PHB. The MLB and Raw Material buildings will be constructed using pile foundations widely used in the Hungarian practice. From a geotechnical point of view, the design of the foundation system of the PHB, i.e. the high bay warehouse building, was a challenge. The new building is an automated warehouse for palletised goods, 37 m wide, 170 m long and 36 m high (Figure 1).

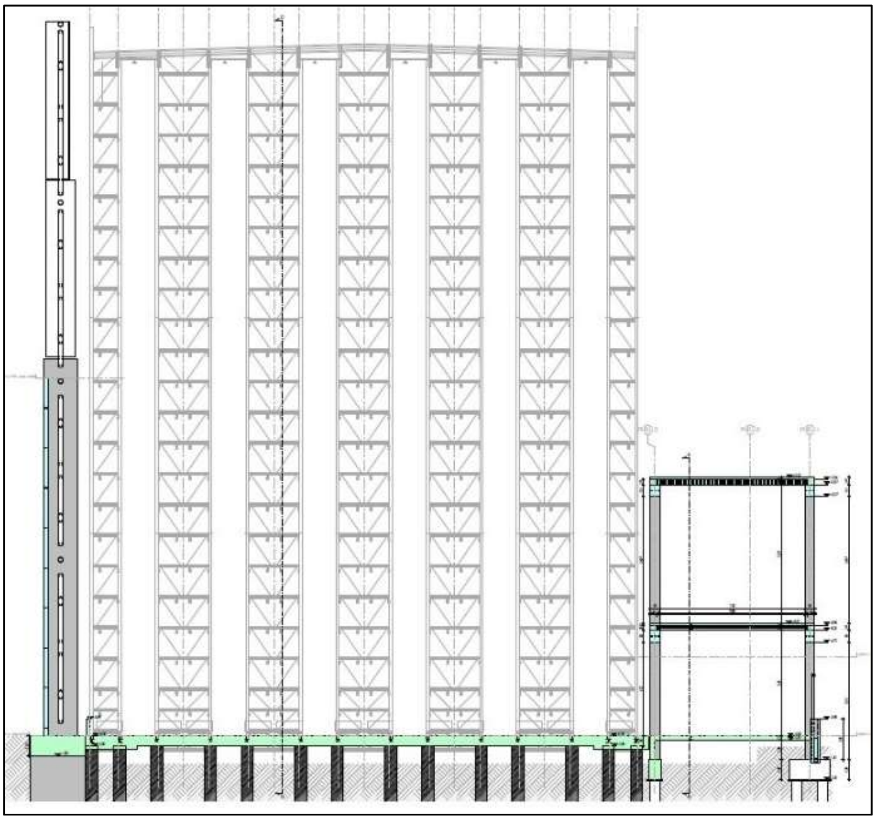

Figure 1. Typical section of the planned high-bay warehouse (firewall on the left, service building on the right)

2. ANTECEDENTS

The superstructure of the warehouse is made by a dutch manufacturer, Vanderlande Ltd. In the design of the shelving system, the structural calculation was carried out by using infinite rigid supports, taking into account the FEM specifications and standards [1]-[3]. In Hungary the general designer who was responsible for the structural design was provided with the loads on the shelf legs in each load case. Their task was to determine the combinations for the ULS and SLS limit states and then to proceed with the design of the floor slab. According to today's state-of-the-art design, the structural and geotechnical models of the floor slab had to be synchronised.

When designing the base plate, the most important task is to meet the rotation and displacement criteria given in the regulations. Without that the storage system might become unusable due to the automatic filling and emptying system's limit of tolerance. The displacement values were influenced by loads from several directions.

The new building will be connected to existing buildings. In these areas, it must be ensured that the construction does not place excessive additional loads on the pile foundations of the surrounding buildings. It was a challenge that the layout of the piles under the floor slab was also affected by the existing foundations on the boundaries of the adjacent buildings. A 36 m high firewall, with an independent foundation, was constructed from the adjacent buildings and match the height of the warehouse in accordance with fire regulations (Figure 1).

The firewall is built as a structurally independent fixed end structure. From the geotechnical point of view the pile cap (which was near the surface) was loaded with an unusual magnitude of moment, about ~4-6000 kNm, as the client's requirement was to assume that the firewall would be built before the warehouse. It is foreseen that the next high storage building will be built on the other side of the firewall. The impact of building this extension also needs to be assessed. On the other side of the warehouse, a two-storey utility building on pile foundations will be constructed. It should be noted that the rotations of the floor slab in SLS limit state are influenced by the loading of the warehouse. Therefore, the aim of the investigations is to optimise the foundation system and the calculations should take into account the directly connected existing and future structures.

3. GEOTECHNICAL CONDITIONS

The study area is located near Nyíregyháza, Hungary. The area is characterised by the presence of loamy, silty soils near the surface. The layers with bearing capacity for deep foundations are found at a depth of 10-12 m. The final geological model, based on field investigations and CPT testing, distinguishes 11 soil layers.

The soil investigation report [4] prepared in the previous design phase analysed the site conditions on the basis of 4 CPT tests. As the design progressed and before construction started, additional tests were carried out, so that a total of 11 CPT tests were used in the final calculations.

The planning area is characterised by heterogeneous stratification; sand, sandy silt, silty sand layers alternate. Between these with a varying thicknesses of fine grained layers occur frequently.

The CPT tests show that the cover of the area is composed of a clayey sand layer up to a depth of 1 - 1.5 m. Below this, sand and silty sand are deposited to an average depth of 10 m. The peak resistance of the cone vary from 4 - 8 MPa initially to 16 - 22 MPa below 5 m. The diagrams clearly show the silty regions where the cone resistance decrease. Overall, the sand layer is moderately dense, with occasional dense settlements.

Deeper, to the bottom of the tests, there is a layer of sand, silty sand, sandy silt with a lower bearing capacity than the previous one, the peak resistance of qc is about ~ 10 - 12 MPa. The layer is moderately dense, with fine grained layers characterized by stiff consistency. At these depths, sand layers also appear in variable thicknesses, with peak resitances of 20 - 24 MPa.

Based on the available test results and the previous geotechnical documentation the level of the groundwater table is near the surface.

4. APPLIED STANDARDS

The design had to consider the load combinations that could occur during the planned lifetime of the warehouse. It is not possible to combine meteorological loads and shelf loads in Plaxis software, this has to be done by the structural designer using their finite element software, AxisVM.

It is essential to analyse both total and partial loads to calculate the plate rotation and settlement. Total loading would not be expected to result in the largest settlement difference and rotation.

The partial load arrangements should be specified by the shelving system designer in agreement with the Client. This will depend on the further use, especially when using an automatic storage system. As no such information was provided in the data, loading schemes were defined by our company and applied in the calculations after the client has approved. In consultation with the structural designer of the superstructure, a total of 14 loading schemes were established (Figure 2). The settlement and rotation criteria were investigated in the SLS quasi-permanent limit state. The plate stresses were also calculated in the ULS limit state.

Figure 2. Schematic of load schemes

The schemes should be interpreted as the maximum SLS load from the legs of the actively loaded shelves (grey part of Figure 2) to the plate, and only the load from the shelf's self-weight and the meteorological load from the unloaded shelves (white part of Figure 2).

The first load scheme is total load, where the maximum load is applied to all shelves. This condition models the full load of the warehouse. In schemes 02-09, the shelving system is fully loaded longitudinally, while transversally some rows of shelves remain empty. Load conditions 10-13 show the change in the longitudinal fill level of the warehouse. In addition, the total loading in the ULS limit state was also investigated.

5. CONCIDERATIONS BEFORE NUMERICAL CALCULATION

The design of the foundations for the storage facility was started based on three CPT and one SCPT from the previous soil investigation report. The aim of the design was to define a foundation system that would satisfy both technical and economic criteria.

From a construction point of view, the simplest design would be a slab foundation. However, initial calculations made it clear that the structure would suffer from large, uneven settlements due to the compressible soil layers near the surface. A more rigid system could be created by bypassing the near-surface soils with stiffening piles. When rigid inclusion elements are used, the floor slab can be constructed on a compacted bedding. Detailed calculations have also been carried out for possible design options for piled raft foundations. Given the size of the warehouse, it is clear that a small change in the thickness of the large surface area floor slab and the large number of piles supporting it can have a significant impact on costs. Establishing these dimensions was a major part of the design task.

A structural analysis was carried out for the superstructure and the foundations of the shelving system. In Axis software, nodal forces were used in place of the shelf legs and the piles were modelled by nodal supports. The rails running between the shelves were included in the model as line loads. A separate structural calculation was performed for each of the loading schemes presented earlier. The node supports were set to infinite stiffness for the first run, and the stiffness and self-weight of the slab were not included in this model, knowing that it would be included in the geotechnical VEM model, and thus its load-distributing effect would not be included twice in the scheme. Due to the size of the warehouse, the number of shelf supports exceeded 700, and the number of piles was also in this order of magnitude.

Geotechnical finite element modelling was carried out using Plaxis software. The key to the foundation of the warehouse is to determine the final deformations as accurately as possible. With this in mind, the soil model was chosen for HardeningSoilSmall. The parameters of the soil model were taken from the CPT test obtained. By statistically evaluating the peak resistances of the layers identified in the CPTs, the average qc values of each layer were determined and their stiffness characteristics derived. The seismic CPT results were used to determine the parameters describing the small deformation range of the soil model.

6. CALCULATION OF THE CROSS SECTIONS

To investigate the types of foundation, calculations were performed on the cross-section of the warehouse as a starting point. The 2D calculations are approximations, but can be used to quickly analyse different variations. When building the model, we determined the soil stratification for 4 cross-sections based on the 4 CPTs available at the time, so we investigated the expected settlement differences due to stratification variations in 4 models. The result of the structural calculation included point loads, of which the values close to the cross-section were converted to line loads. These models were therefore not designed to provide accurate calculation results but to understand the overall behaviour of the structure. Their results give a reliable indication of the local behaviour of the plate in a given section. From a technical point of view, another major advantage of 2D models was that a smaller number of elements results a faster running time, so that it does not take days to analyse possible variations. It is worth mentioning that while the current latest version of the Plaxis2D software is capable of calculating plate rotations, in the 3D version the same values can be obtained by derivation the displacement function.

The results of the first calculations showed that neither the slab foundation nor the rigid inclusion soil improvement can meet the 1/2000 rad rotation criteria specified in the standard (Figure 3). Thus, these foundation methods cannot be used to prepare the foundations for the warehouse. Due to the height of the warehouse, it is exposed to significant wind loads. At the edge of the slab in the ULS limit state, large tensile forces are generated by the wind load, which cannot be absorbed by slab foundations.

With this in mind, we started to investigate deep foundation methods. Pile foundations were not an option due to the site layout and structural design. A possible good structural design is a piled raft foundation.

Two possible designs for piled raft foundations were investigated. One of them is the layout of piles in a uniform grid pattern. A warehouse similar to the present one is already in use on the site and it was built with this pile arrangement.

In the case of a grid layout, the structure can be optimised by varying the length of the piles and the distance between the rasters. In the case of the possible design mentioned above, i.e. piles under each shelf, the allocation is adapted to the support structure. The structure can then be made more economical by varying the length of the piles.

Additional 2D models were created to investigate the two versions in an approximate way. Their results showed that these foundation systems meet the rotation requirements of the standard (0.0005 rad). Based on the results of the models (Figure 3), it was decided to perform 3D testing of two designs, covering the entire warehouse floor area, its surroundings and the connected buildings. In this way, several of the impacts described in the previous chapter could be accurately quantified.

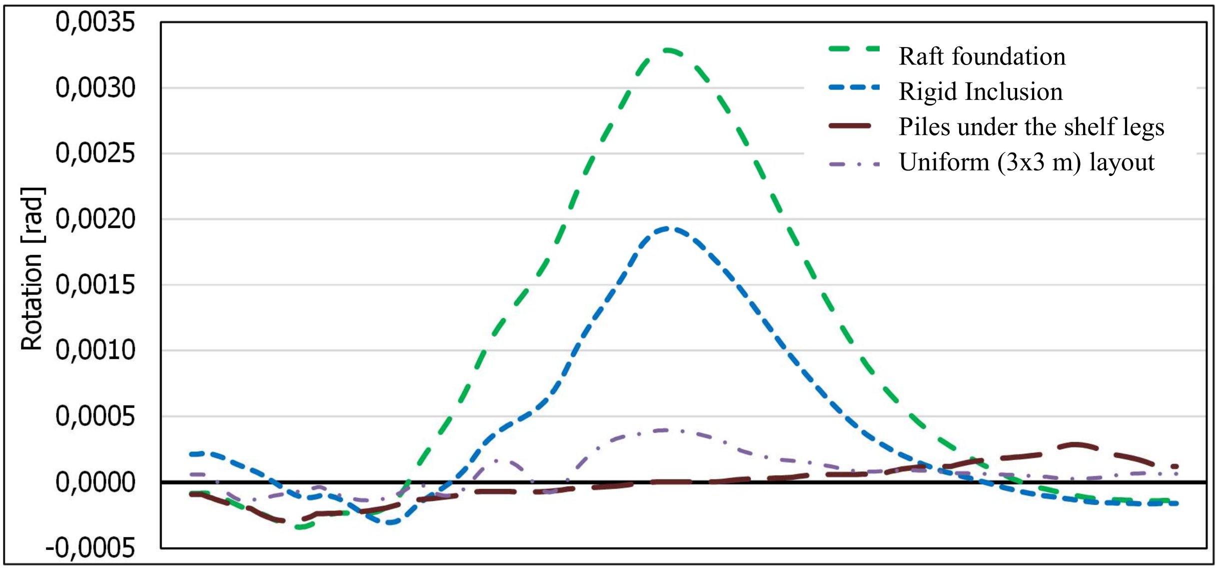

Figure 3 Analysis of the rotations of possible foundation types

7. SPATIAL CALCULATIONS

Using the 3D module of the Plaxis software, calculations were made with a more accurate view of the geometry. In our model, we considered both the floor slab currently being designed and the foundation of the warehouse in the future extension plan, considered as a negative effect. Over 1500 piles were placed under these slab foundations. Also included the foundations of the new firewall sections between the existing buildings and the new buildings, and the pile foundations for the utility building. The 3D model was thus 120 m wide and 230 m long and 40 m deep (Figure 4).

From more than 700 shelves, concentrated loads in the order of tens of thousands were applied to the floor slab in 14 different load patterns. When building the 3D model, the command line was used to define the point loads on the floor plate.

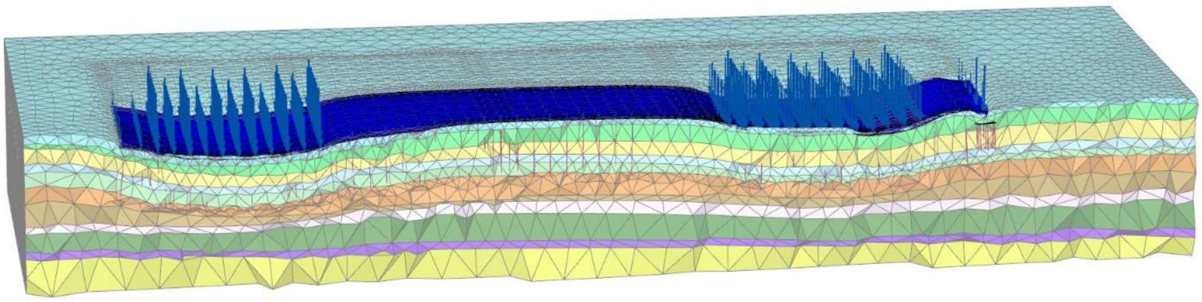

Figure 4 3D finite element model of a high-bay warehouse

The 3D models of the two versions were modified several times and the calculations were carried out. The aim of the tests was to achieve a technically satisfactory, economical structure. During the data processing, the displacements of the cross-section calculated on the plate were read out from the software and the rotations were derived from them. The results were evaluated in cross sections and longitudinal sections taken at the same location.

For the pile layout under the shelf support, we first designed 14 m CFA piles, starting from the piles used in the previous building, (although the shelving system and load of these piles differed slightly from the current structure). Seeing that this solution met the deflection criteria (0.0005 rad) (Figure 5), we reduced the length of the piles and then ran the calculation again. The results for the shorter pile, 11 m, also met the specifications and we were closer to the criterion. The maximum value of the settlement is obtained by the total load in the middle of the pile. However, the maximum deflections are developed in the plate due to partial loading patterns.

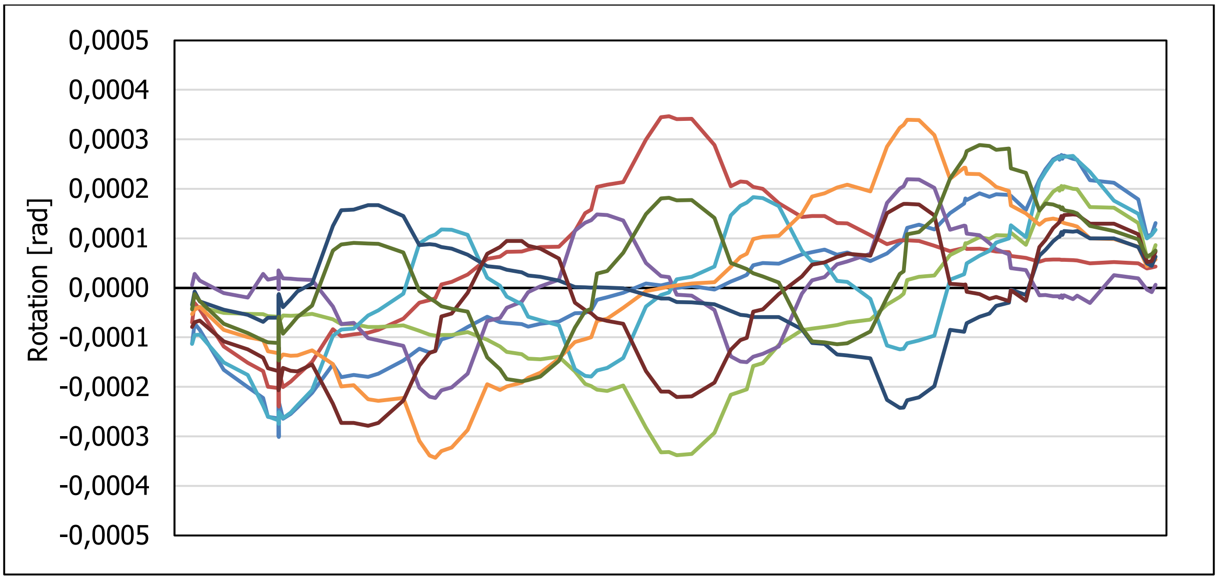

Figure 5 Rotation values in the cross-section of the plate calculated with the under-pole allocation

In the case of even pile distribution, we first examined a rarely distributed 11.0 m long pile in a 4.5x4.5 m grid. Then, as it did not meet the deformation criteria, a 3.0x3.0 m grid was considered. This allocation was at the limit of compliance. A more dense layout would have increased the number of piles significantly, so by increasing the length of the piles to 15.0 m, a technically compliant version was obtained (Figure 6).

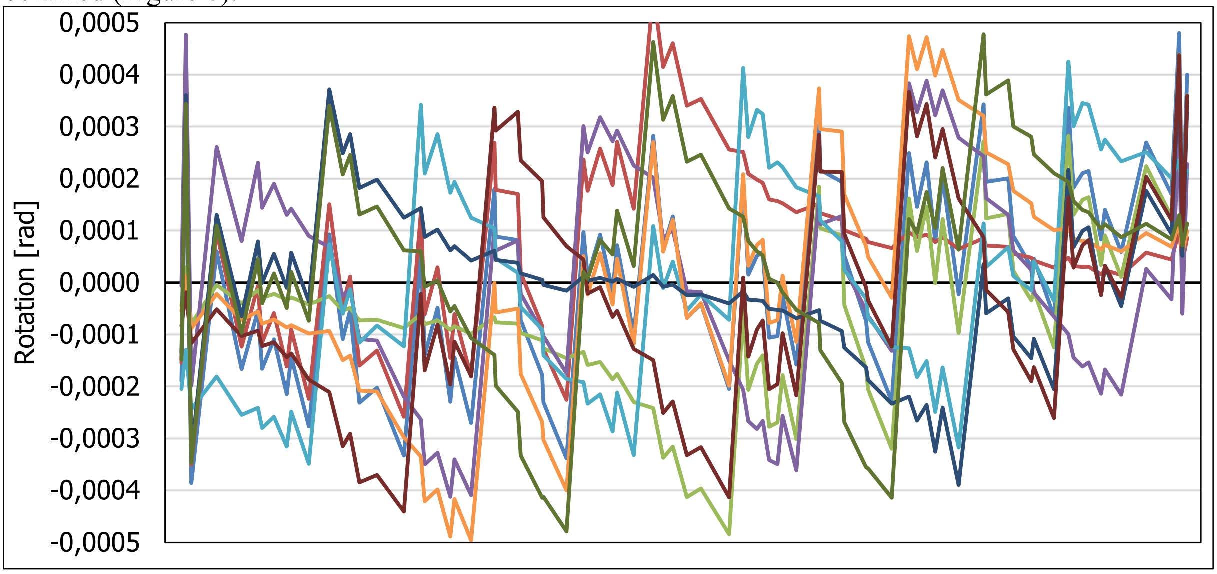

Figure 6 Rotation values calculated with uniform distribution in the cross section of the plate

For both designs, the impact of the foundations of the future building on the existing building was investigated. The results of these calculations showed that the increased load would cause the rise of the displacement towards the planned new building, but the increase in displacement would still be within the 1/2000 rad value.

During the spatial modelling, we also optimised the thickness of the slab, starting from 1 m thickness to 70 cm in the edge band and 50 cm in the middle, which resulted in significant cost reductions.

8. CONCLUSIONS

For this model size, with so many piles and loads, there is no other option but to use the embedded beam and plate element. The results obtained from the 2D model with approximations and the 3D model show that the rotation curves calculated by the 2D program and the rotation curves calculated from the result of the section taken in the 3D model show good agreement (Figure 7).

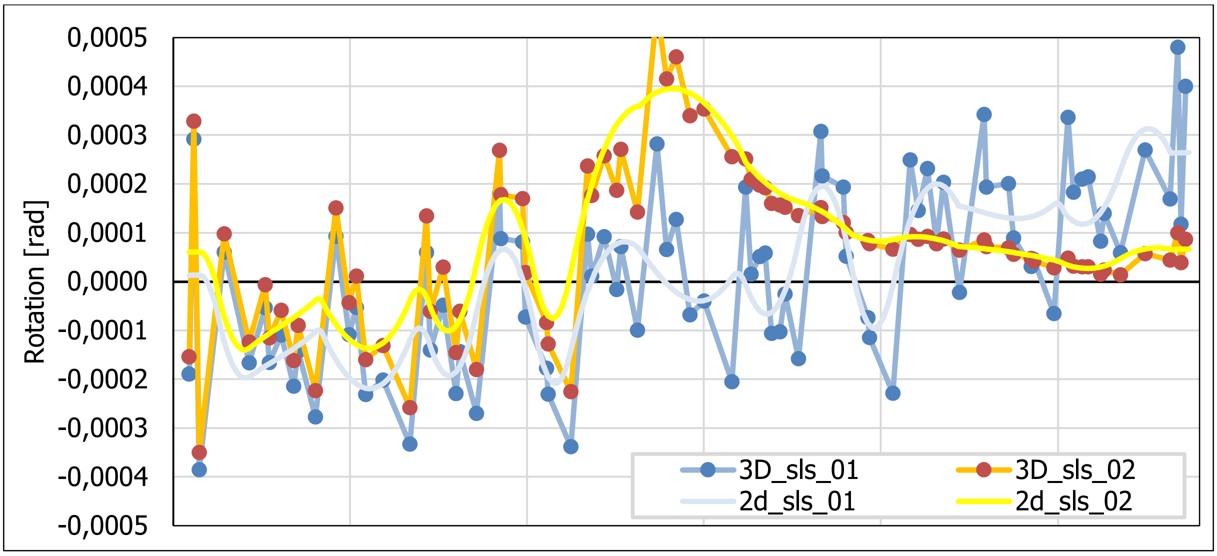

Figure 7 Comparison of 2D and 3D tests

There are fundamental differences in the nature of the rotation curves shown in Figures 5 and 6. By examining the graph of uniform distribution, we can conclude that the deformation of the base plate is fundamentally influenced by the relative positions of the load (shelf supports) and the support (piles). The dashed alternating rotation diagram highlights the approximation of the calculation that the loads and supports are point-defined on the plate. The value of the rotation changes abruptly depending on how close the attack point of the load to the support. From the point of view of piling, this modelling result therefore highlights a real problem. When using uniform distribution, the maximum rotation does not necessarily occur under the action of partial loadings, but can occur under any loading scheme. The amount of deformation depends on the geometric design. This effect can be handled by placing piles under the shelf supports. This eliminates the outward settlement and provides the plate with a stiffer support at the point of force application.
Due to the soft soil layers near the surface and the relatively stiff slab and the dense pile distribution, the calculated bedding under the slab was negligibly small. The plate is supported by the piles, acting as a slab.

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