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National Project ASIRI+ Task 8.4 – Benchmark N°1 – Study of the lateral behavior of a footing on reinforced soil with rigid inclusions

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ABSTRACT: As part of the design and execution of soil reinforcement using rigid inclusions, all the technical recommendations implemented under ASIRI in 2012 are used as references. However, during the feasibility study of the National Project ASIRI+, which aims to complete the initial technical recommendations, a state-of-the-art review highlighted the need for further research in various applications of soil reinforcement using rigid inclusions. ASIRI+ was then structured around three main areas: the study of load transfer platforms, the behaviour of structures under vertical static loads and inclined and excentred pseudo-static loads and the behaviour of structures under dynamic and seismic loads. Among the many defined tasks, task number 8 – "Numerical modelling" aims to assess and improve the common numerical methods. This task led to the emergence of benchmarks. Benchmark No. 1 focuses on predicting the behaviour of a footing on rigid inclusions subjected to static and pseudo-static loads. The studied foundation rested on a geological horizon composed of two compressible silt layers and a deeper sandy-gravelly layer, where the rigid inclusions are anchored. In direct connection with the objective to better understand phenomenon and influence of load transfer platforms (LTP), three different LTP thicknesses were successively modelled between the rigid inclusions head and the foundation base: 0 cm; 25 cm; 50 cm. The main objectives were to assess the transverse behaviour of a footing on a reinforced soil and refine the accuracy of current conventional analytical methods such as MH2 analytical model from the ASIRI guidelines by comparing them with finite elements modelling results.

KEYWORDS: Soil reinforcement, rigid inclusions, load transfer platform, static and pseudo-static loads, modelling, transverse behaviour, MH2, finite elements.

1 INTRODUCTION

The first technical recommendations published under the ASIRI name in 2012 sought to define, guide and interpret the experimental campaigns and modelling efforts required to improve the understanding of the mechanisms governing the innovative rigid inclusions foundation system (ASIRI, 2012). Structured into several chapters, these recommendations included the presentation of analytical calculation methods. Over the subsequent decade of practical application, it became evident that certain technical aspects of the rigid inclusion solution remained insufficiently clarified. This observation led to the initiation of the ASIRI+ project, within which new objectives were established. Among the various themes and research tasks, one was specifically dedicated to numerical modelling of the behaviour of structures subjected to vertical static loads and inclined and excentred pseudo-static loads.

In this context, Benchmark No. 1 of Task 8.4 of the national ASIRI+ project aimed to predict the behaviour of a footing on rigid inclusions subjected to both static and pseudo-static loading. The benchmark had a primary objective: to assess footing design, first under a centred vertical load then inclined and applied in a pseudo-static manner.

The benchmark also aimed to verify the continued relevance of the first analytical approaches established in the ASIRI recommendations by assessing their consistency with contemporary finite element modelling results.

2 BENCHMARK STATEMENTS

2.1 *Geotechnical and structural disposition*

The selected geotechnical profile comprised four distinct geological strata: an initial 3 m-thick silty layer overlying a second silty layer of 4 m thickness, underlain by a sandy gravel deposit extending to a depth of approximately 20 m below the natural ground surface, and finally resting on a marno-calcareous bedrock. The groundwater table was located at the interface between the two silty layers, which together form the compressible horizon and are therefore primarily responsible for the anticipated settlements.

Regarding the structural configuration, the system consisted of a 3.0 m × 3.0 m embedded footing supported by four rigid inclusions, each with a diameter of 0.40 m and spaced at 1.60 m. The footing embedment depth was taken as equal to its thickness, i.e. 0.50 m. The rigid inclusions were anchored 0.50 m into the sandy gravel layer. A Load Transfer Platform (LTP) replaced the existing soil, with an over-width of 0.50 m, and three LTP thicknesses were considered in the analyses: 0 m, 0.25 m, and 0.50 m.

The Figure 1 illustrates the geotechnical configuration provided in the Benchmark statement.

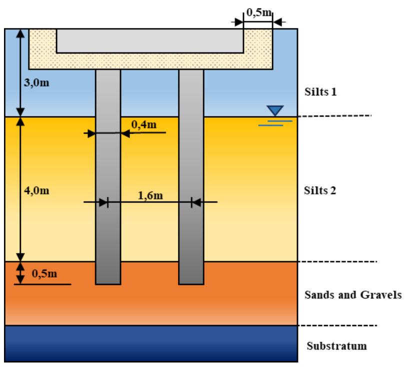

Figure 1. Geotechnical configuration of Benchmark No. 1.

Following Table 1 summarizes the geotechnical parameters provided for each layer of the soil profile. Essential parameters were the pressuremeter modulus E_M, the limit pressure p_l and the unit weight γ.

Table 1. Geotechnical parameters of the Benchmark No. 1.

	Name	γ [kN/m³]	E_M [MPa]	α [-]	p_l [MPa]
	LTP	20	-	-	-
	Silts 1	18	4	1/2	0.4
	Silts 2	19	2	1/2	0.25
	Sands & Gravels	19	20	1/4	2
	Bedrock	20	> 50	-	> 5

2.2 *Studied load cases*

As mentioned previously, two load cases were considered:

- Static load case with a vertical centred load V = 1800kN
- Pseudo-static load case, with a ratio H/V = 25% (with H the horizontal load) and an eccentricity e of 1 m of the vertical centred load

Figure 2 below illustrates both load cases.

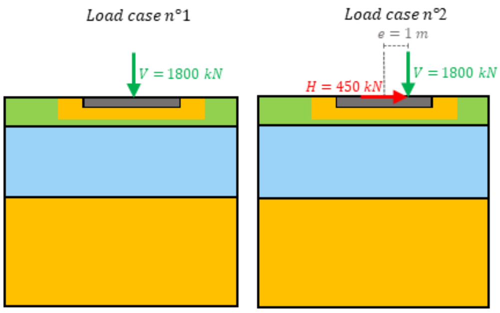

Figure 2. Static and pseudo-static load cases studied in Benchmark No. 1.

3 WORKING APPROACHES

3.1 *Static load case*

The modelling approach enabled the definition of the deformation modulus for each layer by accounting for the observed strain level, according to the relation: $E_y = k.\ E_m$ where k is a coefficient directly taken from Appendix J.2.1 of the French standard NF P 94-261.

To refine the results, several calibration steps were carried out:

- First, a vertical calibration of the footing without rigid inclusions was performed using the conventional pressuremeter method.
- Then, following the approach described in (Racinais, Maucotel, Varaksin, Hamidi, 2017), we calibrated the rigid inclusions in both the vertical and horizontal directions.
  For the vertical calibration, a single inclusion was modelled and subjected to a load test. Comparing the behaviour of the rigid inclusion in the FE model with the conventional Frank and Zhao formulations enabled us to refine the soil bearing parameters at the column toe.
  Subsequently, still using a single inclusion, a horizontal load test was performed by applying an increasing load at the inclusion head, and direct comparisons were made with analytical P–y curves.

After completing the calibration steps, the finite element modelling results of the footing over rigid inclusions were compared with the MV2 analytical approach described in the ASIRI recommendations. The MV2 algorithm for CMC calculations under vertical loading relies on a biphasic representation dividing the system into two domains: soil and column. To ensure consistency between both domains, two boundary conditions are imposed:

- Force equilibrium law: $Q = Q_{soil}(0) + n.Q_{col}(0)$
- Settlement compatibility at footing base: $w_{soil}(0) = w_{col}(0)$

Interactions between the two domains (soil and column) are modelled using transfer laws, accounting for: lateral skin friction along the column shaft and end-bearing resistance at the column toe.

The analysis of the results focused on the settlements observed at the footing base and on the distribution of the load within the rigid inclusions (Figure 3).

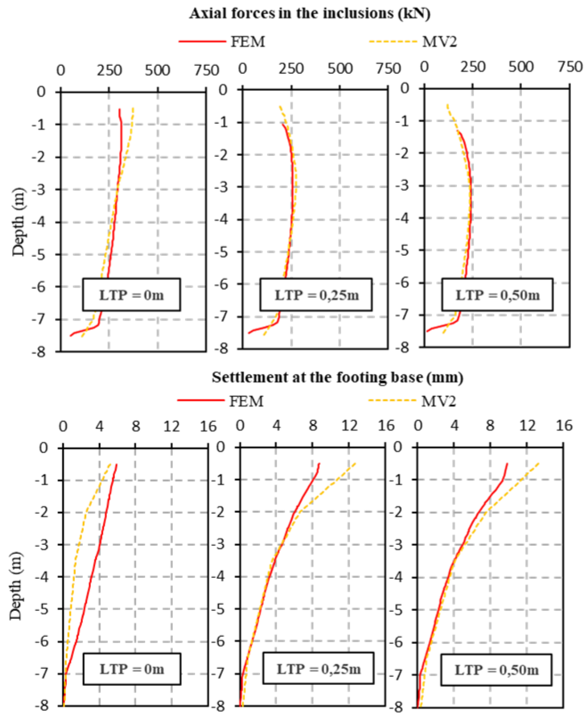

Figure 3. Axial forces in the inclusions and settlement at the footing base as a function of LTP thickness under vertical static loading

The axial forces computed in the finite element analyses show excellent agreement with the MV2 model.

The main conclusion from the static load case was that the MV2 analytical approach shows a high level of agreement with the finite element modelling results. Building on this observation, the analysis was extended to a pseudo-static load case representative of seismic conditions.

3.2 *Pseudo-static load case*

The pseudo-static scenario was defined considering seismic zone 4 conditions, which required incorporating dynamic amplification effects into the modelling process.

According to (AFPS; 2012), the ratio of dynamic to static shear modulus at short term (CT) is:

$$\frac{G_{dyn}}{G_{stat,CT}} = 1.5$$

The short-term to long-term static modulus ratio is:

$$\frac{G_{stat,CT}}{G_{stat,LT}} = 2$$

Therefore, the total amplification coefficient becomes:

$$\frac{G_{dyn}}{G_{stat,LT}} = \frac{1.5 \times G_{stat,CT}}{G_{stat,LT}} = 3$$

This consideration naturally leads to a reflection on the loading phasing of our finite element's models. To better model the transition from a static load phase to a pseudo-static load, we decided to carry out three phases:

Phase 1: Application of the centred vertical load (static phase)
Phase 2: Modification of the soil mechanical parameters to account for seismic conditions
Phase 3: Application of an eccentric and inclined load to simulate the pseudo-static seismic effects.

To ensure consistency across the model, the mechanical properties of structural elements such as the rigid inclusions were also increased by a factor of 3 in accordance with the soil parameter adjustments.

4 FINITE ELEMENT MODELLING

4.1 *Model dimensions*

The model dimensions account for the extent of the studied structure, namely a 3.0 m x 3.0 m embedded footing, ensuring that settlements at the model boundaries remained negligible. The selected dimensions provided both accuracy and reliability of the results while maintaining reasonable computation times.

Regarding the depth of the model, the bedrock layer was not modelled as it was considered incompressible.

4.2 *Soil parameters*

Depending on load case, soil layers were defined using different constitutive laws and deformation parameters. Following Table 2 summarizes model parameters implemented for the vertical static load phase:

Table 2. Soil parameters for vertical static loading phase.

	Name	Behaviour law	k [-]	E_Y [MPa]
	LTP	Mohr-Coulomb	4.5	150
	Silts 1	Linear elastic	4.5	18
	Silts 2	Linear elastic	4.5	9
	Sands & Gravels	Mohr-Coulomb	3	60

For a footing loaded at 200 kPa, the inclusion-based soil reinforcement ensures that the soil remains within the elastic domain. Accordingly, Silts 1 and 2 layers were modelled as linear elastic materials for the centred vertical load case.

Upon transition to inclined and eccentric loading, the corresponding parameters were adjusted in accordance with the approach detailed in section 3.2. Table 3 presents the parameters for the pseudo-static loading phase:

Table 3. Soil parameters for pseudo-static loading phase.

	Name	Behaviour law	E_Y [MPa]
	LTP	Mohr-Coulomb	150
	Silts 1	Mohr-Coulomb	54
	Silts 2	Mohr-Coulomb	27
	Sands & Gravels	Mohr-Coulomb	180

The constitutive behaviour of the Silt 1 and Silt 2 materials was modified to a Mohr–Coulomb model in order to allow plastic yielding under the applied pseudo-static loading.

4.3 *Structural elements*

Rigid inclusions were modelled using solid elements, i.e., cylindrical columns matching the provided dimensions. A dedicated “CMC” material class was defined beforehand. A C20/25 concrete was selected as the material class for the inclusions. The deformation modulus was specified as Ey = 10,000 MPa. The amplification coefficient, previously defined in section 3.2 was likewise applied to the inclusion elements when the loading was excentred and inclined.

An additional Embedded Beam Row element was introduced at the centre of each column to extract forces and deformations observed for each inclusion.

Interactions between the soil and the columns are captured by introducing interfaces around the inclusions. Additionally, enabling the “Layer dependent” feature instructs the software to consider the shear parameters corresponding to the adjacent soils encountered along the inclusions for the soil-structure interactions.

The studied footing was also modelled as a solid element with a deformation modulus assigned sufficiently high to be considered as rigid. To account for potential sliding of the footing under inclined and eccentric loads, interfaces were defined at the footing bottom surface.

Figure 4 illustrates to the final model configuration, including structural and stratigraphic elements.

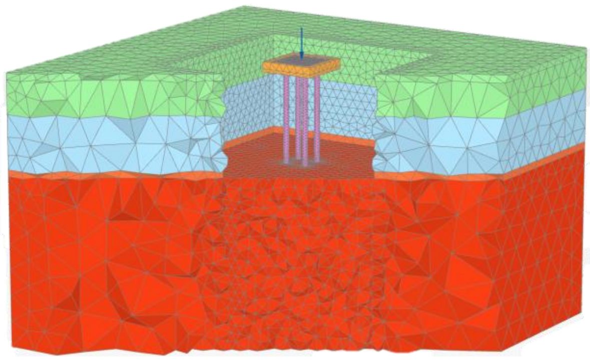

Figure 4. General overview of the finite element model

A refined mesh box was defined around the footing to improve the reliability of the deformation results observed in the high deformation area. The furthest areas were meshed with a coarser mesh. The overall quality of the mesh was satisfactory.

5 ANALYTICAL APPROACHES

Before heading into the comparisons between finite element models results and the analytical calculation approaches MH1 and MH2, it is essential to first present the theoretical foundations of each approach.

5.1 *MH1 analytical approach*

The MH1 analytical model, initially introduced in the ASIRI project, does not account for the shear forces transmitted to the surrounding soil due to foundation displacement. Consequently, soil displacements g(z) is neglected. Instead, a %x of the horizontal load H applied at the footing base is directly transferred to the head of the inclusion H(0), inducing its horizontal displacement y(z) as shown in Figure 5.

This portion of the horizontal load can be estimated using two approaches: either based on the distribution of the vertical load or according to the relative horizontal stiffnesses.

When the approach relies on the vertical load distribution:

$$H(0) = min\ (V(0)/V . H\ ; V(0).\ tan(\delta)) \qquad (1)$$

The first step is to determine the vertical load distribution ratio $V(0)/V$, where $V(0)$ is the axial load applied at the head of a single inclusion and V the total vertical load applied to the footing. This ratio is then used to evaluate the proportion of horizontal load transmitted at the base of the footing.

When the approach is based on the relative horizontal stiffnesses:

$$H(0) = \frac{K_{H;Inclusion}}{K_{H;reinforced\ soil}} . H \qquad (2)$$

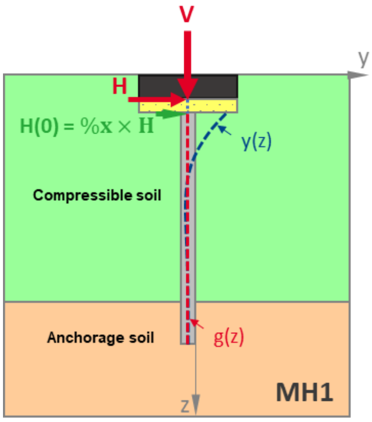

Figure 5. MH1 analytical approach.

The horizontal load H(0) applied at the inclusion head is determined by applying the ratio between the stiffness of a single inclusion and the stiffness of the reinforced soil to the horizontal load H at the base of the foundation. Horizontal stiffness of the soil is calculated using (Gazetas, 1990) formulations. Then, the stiffness of the reinforced soil is derived from the contribution of the group of inclusions based on the horizontal stiffness of one element plus the contribution of the soil.

In proportion to the horizontal stiffnesses, the LTP thickness has nearly no influence on the results since the LTP thickness is small compared to the soil layers. However, regarding MH1 in proportion to the vertical load distribution, thicker the LTP is, less vertical load is transferred to the head of the inclusion resulting in a lower horizontal load applied to the inclusion.

5.2 *MH2 analytical approach*

In the MH2 analytical approach, introduced as well in ASIRI, the foundation's displacement will generate a soil displacement profile g(z), which will be applied to the inclusion leading to its lateral displacement y(z). However, at the level of the inclusion head $y(0) \neq g(z)$(ASIRI, 2012) therefore recommends adding a shear force H(0) at the head of the inclusion to match both displacements: inclusion and soil.

In contrast to the MH1 approach, the MH2 analytical model is structured in a series of successive steps. The first step consists in estimating the horizontal displacement d_0 of the footing by dividing the applied horizontal load by the horizontal stiffness K_h of the unreinforced soil. The horizontal stiffness can be evaluated using the empirical formulations proposed by (Gazetas, 1990). Next, the soil profile is discretized. Assuming a shear stress diffusion from the footing base at a given angle δ, a shear stress distribution with depth can be derived. With this diffusion angle δ initially prescribed, the shear stress profile is then calculated as a function of depth. For each depth z, the corresponding shear stress is calculated as:

$$\tau(z) = \frac{H}{S(z)} \qquad (3)$$

Where H is the total shear force and S(z) is the area of the shear surface at depth z, which depends on the diffusion angle δ.

In the third step, using the computed shear stress τ(z) and the shear modulus G of the soil, the shear strain γ is determined, allowing the calculation of the lateral displacement of each discretized soil sublayer. By integrating these displacements over the depth, the lateral soil displacement profile g(z) is obtained. The LTP thickness, when present beneath the footing, is included in the calculation of g(z). If the computed displacement at the footing base does not match the initial value d_0, the entire process is iterated with a different diffusion angle δ until convergence is achieved. Otherwise, the diffusion angle is considered satisfactory.

Once the soil displacement profile is validated, it is imposed on the rigid inclusions. An additional shear force H(0) can be applied at the inclusion head to ensure equality between the inclusion and soil displacements at the inclusion head level. The additional shear force H(0) is determined iteratively until equality is reached.

Following Figure 6 synthetizes the MH2 analytical approach.

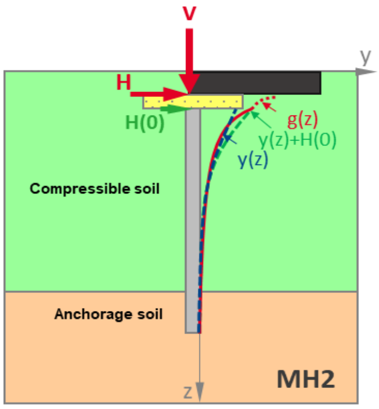

Figure 6. MH2 analytical approach.

6 RESULTS

The following section presents the numerical results and their comparison with the analytical approaches discussed earlier.

6.1 *Clarification of the presentation approaches*

For each LTP thickness configuration (0.50 m, 0.25 m, and 0 m), several Finite Elements Models (FEM) were carried out. The rigid inclusions located on the side of the footing eccentricity were distinguished from those on the opposite side. We analysed and plotted the internal forces in the inclusions namely, the bending moments M, the shear forces H, and the horizontal displacements—across all configurations.

More specifically, the results of the inclusions positioned on the eccentricity side were compared with both MH1 and MH2 analytical results. Analytical calculations (MH1 and MH2) were carried out on a footing reduced to its effective area, considering only the two rigid inclusions located within this zone. In the MH2 model, an additional shear force $H(0)$ was applied at the head of the inclusion. For both analytical models, the footing embedment was considered. Conversely, for the inclusions located on the side opposite the eccentricity, comparisons were made using the MH2 analytical model only, without any additional shear force $H(0)$ at the head of the inclusion.

However, not all analytical variants were retained for this benchmark. The MH1 approach based on the proportion of vertical load is not presented in the current analysis. Rigid inclusions are considerably less effective in supporting horizontal loads than vertical ones, particularly when the LTP thickness is low. Additionally, the MH1 approach based on the proportion of vertical load does not allow for the inclusion of the beneficial effect of footing embedment. Regarding the purpose of this benchmark and the inputs statements, we decided to exclude this approach. Based on prior experience, this method is generally not used as a reference, as it significantly overestimates the horizontal forces within the inclusions.

Consequently, the MH1 analytical calculations plotted on the following graphs are based solely on the approach proportional to horizontal stiffnesses. This choice is justified because the stiffness-based method provides a more realistic representation of lateral load transfer mechanisms.

6.2 *Axial forces*

Due to the 1m eccentricity of the vertical load (1800 kN), only two out of the four inclusions contribute to support the load. In the case without a load transfer platform (LTP), the inclusions located on the eccentric side exhibit a vertical efficiency E_V of 33% each, while the two others receive no load at the inclusion head (Figure 7).

The vertical efficiency E_V of an inclusion expresses the proportion of the total load transferred to it. In this case, more than 50% of the total load is borne by only 2 inclusions. As the LTP thickness increases to 0.25m, the vertical efficiency of the loaded inclusions decreases to 25%, and further to 18% with an LTP thickness of 0.50m.

From an analytical standpoint, the calculations performed on the reduced footing show good agreement with the numerical results of the inclusions located on the eccentric side.

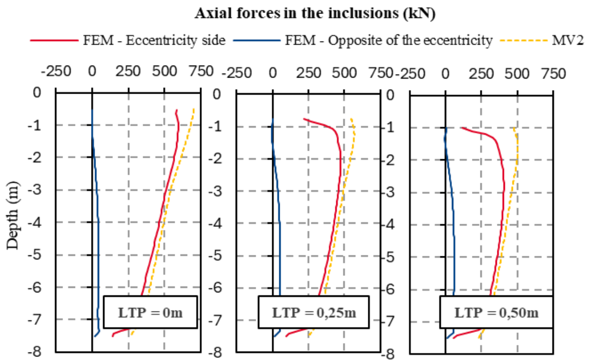

Figure 7. Axial forces in the inclusions as a function of LTP thickness under pseudo-static loading conditions.

6.3 *Horizontal deformation of the inclusions*

An increase in the thickness of the LTP leads to a significant reduction in the horizontal deformation of the inclusions observed in the finite element's models, decreasing from 2.5mm to less than 0.5mm.

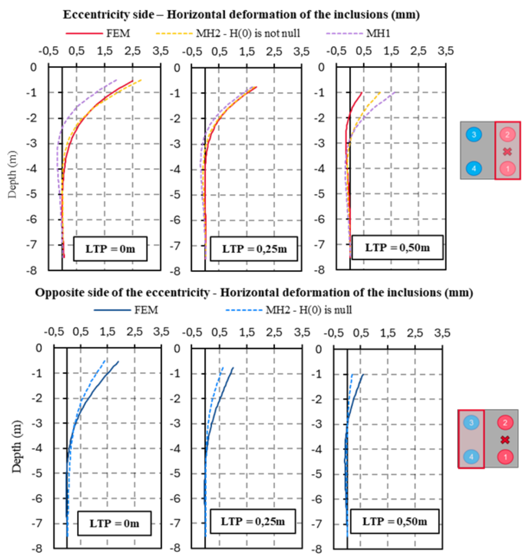

Figure 8. Horizontal deformations of the inclusions as a function of LTP thickness under pseudo-static loading conditions.

In contrast, the MH1 analytical approach, which does not really incorporate the LTP thickness in the stiffnesses calculations, predicts nearly constant horizontal deformations, ranging between 1.7mm and 2.0mm (Figure 8).

The MH2 approach shows good agreement with the FEM results, particularly for cases with no LTP and with a 0.25m thick LTP. For the 0.50m thick LTP case, however, a complementary analysis of soil deformations revealed a starting sliding mechanism of the footing over the LTP, which likely accounts for the discrepancies observed between the FEM and MH2 horizontal deformation curves of the inclusions located on the eccentricity side.

6.4 *Bending moments*

Since bending moments are obtained from the second derivative of the horizontal displacements of the inclusions, the observed trends follow a similar pattern. Increasing the thickness of the load transfer platform (LTP) leads to a reduction in the horizontal deformation of the inclusions, which in turn results in a logical decrease in the associated bending moments. Notably, the MH1 curves yield the same maximum bending moment within the inclusions, regardless of the LTP thickness.

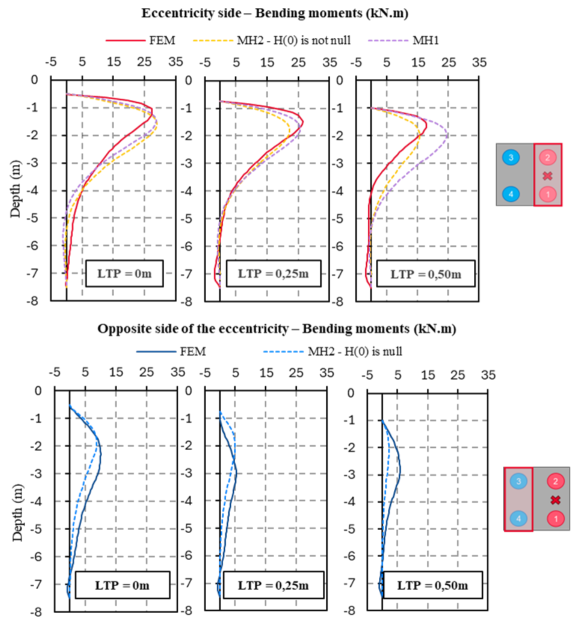

Figure 9. Bending moments in the inclusions as a function of LTP thickness under pseudo-static loading conditions.

Conversely, the MH2 curves exhibit good agreement with the finite element method (FEM) results for both rows of inclusions, whether located on the eccentric or the opposite side of the footing (Figure 9).

7 CONCLUSIONS

As the objective of Task 8 "Numerical Modelling" within the new national project ASIRI+ is to promote the development of innovative numerical approaches, it also provides an opportunity to compare these methods with conventional analytical models. The complexity of finite element analyses does not necessarily guarantee higher confidence in the results. Benchmark No. 1, which focused on predicting the behaviour of a footing on rigid inclusions under vertical static and excentred plus inclined pseudo-static loading, offers valuable insights into the analytical models MH1 and MH2 originally introduced in ASIRI (2012). This benchmark enabled a direct comparison between finite element modelling results and these analytical approaches, highlighting their respective strengths and limitations. Prior to these comparisons, the finite element models were calibrated in both vertical and horizontal directions using pressuremeter data and inclusion load tests, ensuring consistency with analytical assumptions.

The MH1 model, when based on the horizontal stiffness, tends to overestimate the horizontal forces in the inclusions; however, these values remain of a lower order of magnitude compared to those predicted by the MH1 model calibrated according to the vertical load distribution. Since the thickness of the load transfer platform (LTP) is small compared to the thickness of the underlying soil layers in the stiffness calculation, its beneficial effect cannot be accounted for.

The MH2 analytical results, incorporating an additional shear force at the inclusion head for inclusions located on the eccentric load side, and excluding it for inclusions on the opposite side, showed good agreement with the finite element model outcomes for this benchmark case. Additional models and case studies are still required to validate and generalize the approach.

However, as highlighted by Frattini, Alzate et al. (2024), the MH2 analytical model is based on the estimation of the soil's transverse deformation, which is itself inferred from the horizontal displacement d_0 of the footing. This displacement is governed by an analytical expression involving the horizontal stiffness K_h of the foundation, a parameter that can be influenced by multiple factors, including the presence and thickness of the LTP, the embedment depth of the footing, and the stiffness contrast between soil layers (e.g., a stiff layer overlying a soft one, or vice versa).

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