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Application of a static surrogate model for the seismic analysis of multiple interconnected deep shafts, a case study

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ABSTRACT: The computational requirements for detailed modelling of large and complex geotechnical structures under seismic loading make a full dynamic analysis prohibitive. In tunnel seismic design, static surrogate models based on the deformation method are often considered to overcome high computational costs and estimate internal forces and deformations of the structure. This paper explores the application of the deformation method to a case study of multiple interconnected deep shafts embedded in soft saturated soils located in a seismic prone area. A geometrically simplified version of the structure was modelled, and a fully dynamic simulation was performed under multidirectional seismic loading. By investigating the structural response, in particular the main 3D deformation modes and internal forces (i.e. bending, shear, axial), a set of prescribed displacements was calibrated to be used as boundary conditions at the edges of a surrogate model under static loading. This set of prescribed displacements was then applied to the geometrically complex full design model. This case study describes the procedure and highlights the challenges encountered in the analysis of deep shaft structures in the framework of a large-scale hydropower project. It presents the application of an existing method to a different field. The aim of this study is to assess the applicability of this approach as a preliminary seismic design strategy and to derive meaningful results for further investigation.

KEYWORDS: Finite elements, seismic loading, static surrogate, shaft, underground structures.

1 INTRODUCTION

The incorporation of computers into the calculation and modelling of structures in the last decades has greatly improved their analysis, allowing engineers to develop complex numerical simulations. However, even though computational capabilities have increased exponentially in the last years, the time required for running complex numerical models – or even dynamic simulations – can last over several weeks and even months, which may render this approach unfeasible.

Underground structures, mainly tunnels, subjected to seismic action are often analysed with the Seismic Deformation Method (SDM). This method seeks to measure the deformations on a soil mass induced by the seismic action, and to replicate them with a set of prescribed displacements applied to the model boundaries (Hashash et al., 2001; Wang & Munfakh, 2001; St. John & Zahrah, 1987). Underground structures are principally subjected to the imposed soil deformations triggered by the seismic loads. This approach differs from the pseudo-static analysis used for structures over the surface, which are exposed to the inertial forces caused by the seismic loads at ground level. Gaspari et al. (2011) applied the aforementioned method via a set of prescribed displacements to analyse the seismic tunnel response in the Istanbul metro line. Pescara et al. (2011) followed their research with analyses of the tunnel body under different seismic conditions. They evaluated the soil's shear deformations under a free field condition, which was used to estimate the ovalisation of the lining for dimensioning purposes.

The calculation of large and complex, even dynamic, Finite Element Models (FEM) requires significant time and computational resources. As such, the ability to perform e.g. additional sensitivity analyses to evaluate different model parameters, might become unfeasible. The use of simplified, smaller versions of the initial model, known as surrogate model, has become a popular technique among engineers to perform several low-cost simulations, which can later be used as inputs for complex models (Liu et al., 2024; Zheng et al., 2023; Asher et al., 2015). These models can be built via simulation and interpolation of parameters (probabilistic analysis and optimisation algorithms, e.g. Liu et al., 2024; Meier et al., 2009; Zheng et al., 2023) or by simplifying the structure and model conditions (Robinson et al., 2008). One of the simplifications might be as straightforward as to reduce the number of elements in the mesh, or the amount of system variables (e.g. a reduction of the amount of material types).

This paper presents the seismic analysis of a highly complex structure based on multiple interconnected shafts embedded in soft saturated soils. Therefore, a surrogate simplified model of a single deep shaft excavation is implemented, for which a time history analysis of a design earthquake is conducted. The seismic-induced deformation results are then calibrated to a series of prescribed displacements on the boundaries of the model via the SDM. This set of prescribed displacements containing the worst-case shear (seismic) response was then used for a pseudo-static analysis of the complex FEM.

Driven by the computational limitations in numerical modelling, this study proposes the application of an existing method, originally developed for tunnel engineering, to a new field: the study of embedded shafts in soft saturated soils. It applies the SDM for seismic analysis and it presents modelling techniques to overcome complex geometries via surrogate modelling. The proposed methodology serves as an initial design strategy for complex structures exposed to seismic loads.

2 CASE STUDY

2.1 *Structure*

This paper is based on a case study of a hydropower infrastructure consisting of two principal shafts (49 m in diameter and 59 m of excavation depth) and two logistic shafts (19.5 m in diameter and 56 m in excavation depth). All shafts are built using 1.5 m thick rectangular sections of diaphragm walls (D-wall) with different embedment depths, depending on their distance to the bed rock. Below the foundation slab of both principal shafts, a series of 1.5 m diameter piles is added for additional support and foundation of the future structure. The principal shafts are connected to the logistic shafts via two small-diameter tunnels (7 m) each. These small-diameter tunnels are planned to be built using the soil freezing technique, once the four shafts are finalized. Figure 1a shows the 3D model of the structure and their principal components.

2.2 *Hydrogeology*

The soil consists of four major layers: a plastic silty clay, a medium dense silt, a dense sand, and a volcanic weathered rock. The three soil layers comprise the first 55 m depth of the site, while the rock can be found below this depth in an inclined plane between 55 to 118 m (Figure 1b). The plastic silty clay and silt have considerable weak mechanical parameters (Table 1). The water table is located 7 m below the ground level, as this infrastructure seeks to pump seawater from a lake to an uphill reservoir.

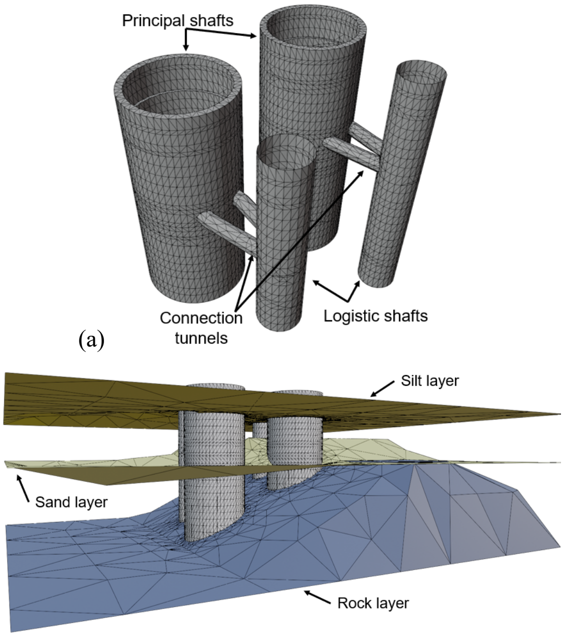

Figure 1. 3D model of the hydropower infrastructure: (a) structures of interconnected shafts and (b) soil layers.

Table 1. Soil parameters (estimated).

Soil	γ_{sat}	E_{oed}^{ref}	E_{ur}^{ref}	c'_{ref}	φ'
	kN/m^3	kN/m^2	kN/m^2	kN/m^2	°
Plastic clay	20	5E2	2E3	5	15
Silt	20	2E3	5E3	10	18
Sand	21	15E3	45E3	5	26
Rock	23	300E3	900E3	50	25

2.3 *Seismic loads*

The hydropower facility is planned to be constructed in a seismic active region of Southeast Asia. The dynamic analysis was performed for the following seismic input motions and corresponding return periods: Construction Earthquake (CE, 50 years), Operating Basis Earthquake (OBE, 145 years), and Design Basis Earthquake (DBE, 475 years). For the CE analysis, the structure consists of the D-walls forming the shaft and stiffened with ring beams, the foundation piles, and a fully excavated pit without the foundation slab. This construction stage is the worst-case situation during construction with the weakest structure. In the final construction stage, the structure is stiffer due to the foundation slab, but it is subject to higher seismic loads (OBE and DBE). These different seismic events are intended to cover different hazard levels during construction (CE), and for the final stage (OBE, DBE), addressing the serviceability and ultimate conditions respectively. The present paper focuses on the representative results of the DBE analysis.

The seismic input motion for the time history analysis is a spectrally matched accelerogram of the Landers earthquake (Figure 2). To reduce computational costs, only the first 40 seconds of the time history input were applied, reaching 95 % of the Arias intensity (Figure 3). This ratio is generally considered a conservative yet sufficient assumption.

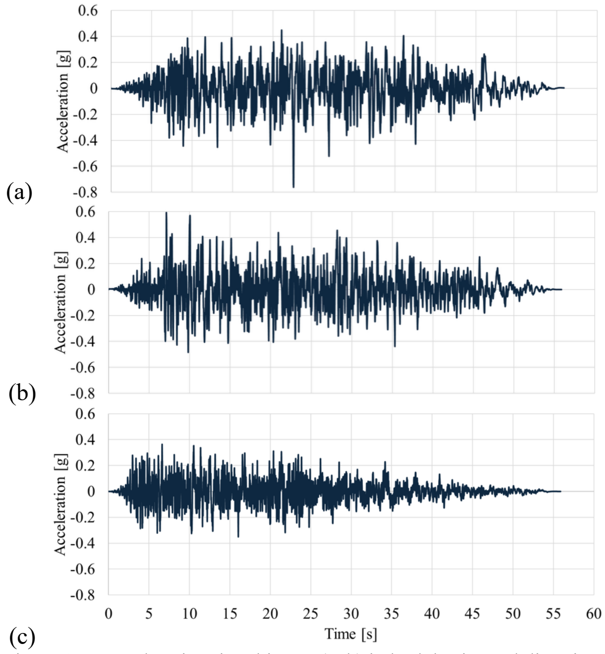

Figure 2. Acceleration time history (a, b) in both horizontal directions and (c) in vertical direction of the DBE seismic input.

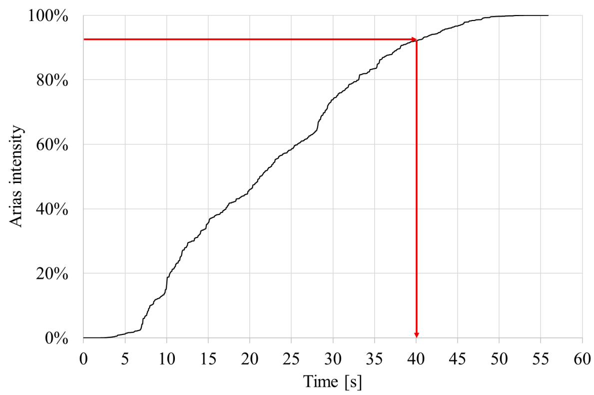

Figure 3. Analysis of the Arias intensity (the red line marks the 40 seconds under consideration and the corresponding Arias intensity).

3 METHODOLOGY

3.1 *General approach*

The first approach to this case study was the development of a full design model with Plaxis 3D. This model covers all construction phases under static conditions. However, the dynamic calculation of this 3D FEM model with its complex geometry, soft saturated soil conditions (Table 1), and seismic multidirectional input motion (Figure 2) would require prohibitively large computational resources. To overcome this constraint, a simplified 3D FEM model was built with one single principal shaft and a simplified geology. A dynamic analysis with the seismic load was performed for this simplified model, which lasted approximately two weeks. Once the structural and soil responses were computed, an analysis of the main deformation modes and internal stresses of the structure was performed. To replicate these results with a static model, a set of prescribed displacements (applied at the boundaries of the model) was iteratively calibrated. Finally, this set of prescribed displacements was applied to the complex full design model to estimate the seismic response of the entire structure, including the four shafts and the connecting tunnels.

3.2 *Complex full design model*

To create the initial static design, a complex full 3D model was developed, using a Hardening Soil Model with Small Strain Stiffness (HSS) for the soil. Each principal shaft consisted of 56 plates that simulated the individual wall sections (thickness: 1.5 m), and six ring beams (thickness: 3 m), distributed at different heights of the shaft (0 m, -14.5 m, -29.5 m, and -47 m below ground level), to increase its structural stiffness. This design considered only ring beams and no other stiffening element (e.g. struts), as they were not feasible due to technical requirements. The foundation slab was modelled with a thickness of 4 m and the foundation piles with a diameter of 1.5 m in a 3 m x 3 m grid below the foundation slab. All wall and beam structural members of the shaft were modelled as plate elements, while the foundation piles were modelled as embedded beam elements. The material type was set as isotropic elastic C30/37 partially cracked concrete (i.e. stiffness calculated as 2/3 of the concrete's nominal stiffness: 22E6 kN/m^2). The size of the model is shown in Figure 4.

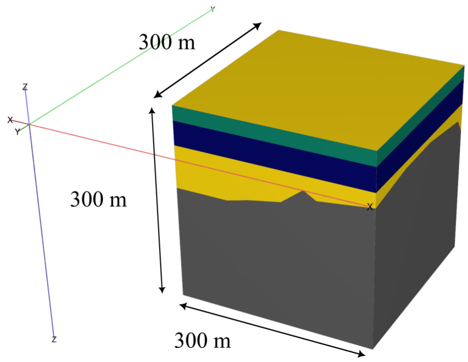

Figure 4. Complex full design model.

The excavation phases were considered in steps of 5 m of depth, until reaching the bottom edge of the foundation slab at -63 m below ground level. The logistic shafts were excavated first, followed by the main ones. Lastly, the connection tunnels were constructed. The construction was divided into a total of 39 phases, with one initial phase for gravity loading of the soil.

3.3 *Simplified model and dynamic analysis*

As mentioned previously, a simplified version of the model, following the low-fidelity approach mentioned by Robinson et al. (2008), was constructed. The geology was simplified into three main soil layers (soft silt/sand, dense sand, and rock), the domain depth was reduced (for computational reasons), and one single principal shaft was considered (Figure 5). The shaft structure (i.e. the D-wall plates, ring beams, foundation slab, and pile elements) had the same material properties and dimensions as in the complex model. The soil parameters for the HSS constitutive model are shown in Table 2Table 1.

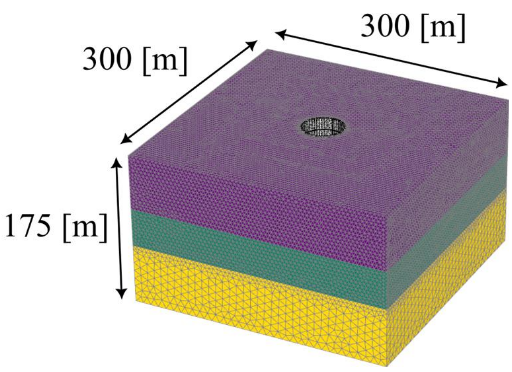

Figure 5. Simplified model (purple & green: soft soils; yellow: rock).

Table 2. HSS soil parameters for the simplified model.

Soils:	Soft silt/sand	Dense sand	Rock	Units
Depth	0 - 63	63 - 107	> 107	m
γ	20	20	20	kN/m^3
E_{50}^{ref}	2E3	15E3	300E3	kN/m^2
E_{oed}^{ref}	2E3	15E3	300E3	kN/m^2
E_{ur}^{ref}	5E3	45E3	900E3	kN/m^2
ν_{ur}	0.2	0.2	0.25	-
m	0.9	0.9	0.5	-
p_{ref}	100	100	100	kN/m^2
G_0^{ref}	7.5E3	6.75E4	1.35E6	kN/m^2
$\gamma_{0.7}$	0.1E-3	0.1E-3	0.1E-3	-
c'_{ref}	10	5	50	kN/m^2
φ'	25	30	25	°
ψ'	0	0	0	°

3.3.1 *Discretization*

To simulate the shear wave propagation in the different soil layers, the maximum length of an element $h_{e,max}$ was chosen following the criteria of $h_{e,max} = v_s / 5f_{max}$, with v_s as the shear velocity and f_{max} as the maximum frequency of the seismic input motion (Bakr & Ahmad, 2018). The shear wave velocity for the softest soil layer (180 m/s) and the frequency of 10 Hz for the seismic input motion were used, obtaining a maximum element length of 3.6 m. A mesh with 540k elements was generated.

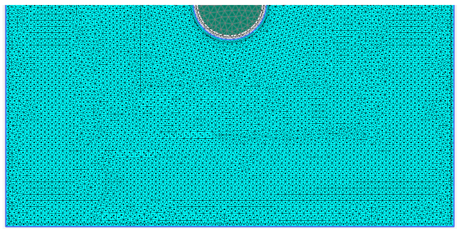

Figure 6. Fragment (domain's symmetric half) of the mesh.

3.3.2 *Dynamic boundary conditions*

For the seismic analysis, dynamic boundary conditions (BC) were implemented to simulate the dynamic response of the soil domain. A free-field BC was chosen for the side boundaries, a compliant base BC was chosen for the bottom boundary, and no specific BC was selected for the top boundary. These BC are the ones applicable for dynamic time history analysis in Plaxis 3D (Bentley, 2024). The seismic surface displacement multipliers (following the seismic input motion shown in Figure 2) were applied to the bottom boundary in all three spatial directions.

3.4 *Calibration of prescribed displacements*

Once the results of the dynamic simulation were obtained, an analysis of the most relevant displacements and internal forces in the shaft was performed. Using these results, a set of prescribed displacements applied on the side boundaries was iteratively calibrated by hand. The calibration was performed to achieve a similar order of magnitude of (i) deformations, (ii) internal forces (normal forces and bending moments), and (iii) to reproduce a similar deformation shape (i.e. shearing, bending, or a combination of both) compared to the one computed in the dynamic analysis.

3.5 *Application to the complex full design model*

The calibrated set of prescribed displacements was then applied to the complex model to study the response of the complex structure (the four interconnected shafts) to these imposed prescribed displacements. Therefore, eight combinations (Table 3) were applied to consider the random multidirectional nature of the seismic loading and to take into account the geometric characteristics: a sloped geology and an asymmetric structure. With these sets of prescribed displacements, the determinant internal stresses and displacements of the structure were evaluated and used for preliminary design.

Table 3. Prescribed displacement combinations.

Combination	1	2	3	4	5	6	7	8
x-axis multiplier	-1	+1	0	0	-1	-1	+1	+1
y-axis multiplier	0	0	-1	+1	-1	+1	-1	+1

4 RESULTS

4.1 *Seismic analysis (DBE)*

4.1.1 *Dynamic analysis (simplified model)*

This section presents the results of the dynamic analysis run for the simplified model. The average phase displacements (of all three spatial directions) of the shaft at different depths below the ground was analysed (Figure 7). These results show that the highest average displacements appear at approximately 32 s, with an order of magnitude of 0.4 m. However, these results do not indicate whether these displacements correspond to a shearing, translation, bending, or any other deformation mode. To estimate the most critical deformations for the shaft structure, the ovalisation of the shaft during the dynamic simulation was analysed (Figure 8), which was calculated as the ratio between the minimum and maximum radii of the deformed shaft. The ovalisation in the shaft tends to increase with increasing seismic load, reaching its maximum also at 32 s. Finally, also the vertical deformation gradient was analysed to elucidate the most critical vertical bending deformation mode of the structure.

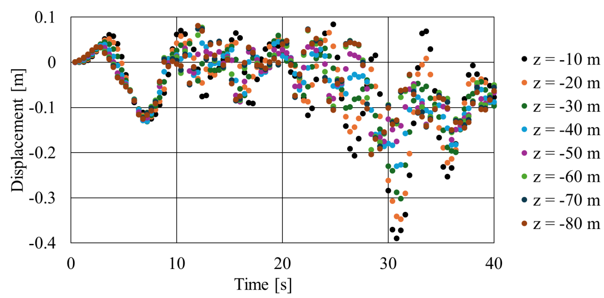

Figure 7. Shaft average displacements at different depths z below ground level.

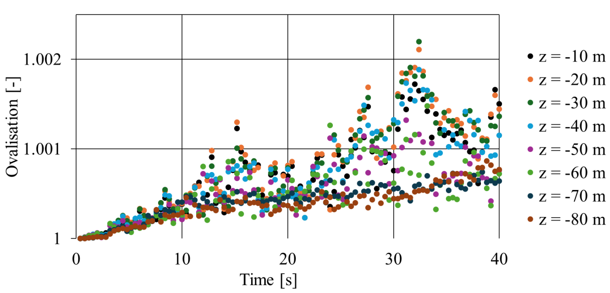

Figure 8. Shaft ovalisation at different depths z below ground level.

The deformation shape and magnitude at the relevant time step of t = 32 s (Figure 9) suggests that the structure's bottom is fixed into the rock, while the top of the structure bends with a peak displacement of 0.5 m. This mode of deformation is thus bending, and it is comparable to a fixed beam loaded at its end.

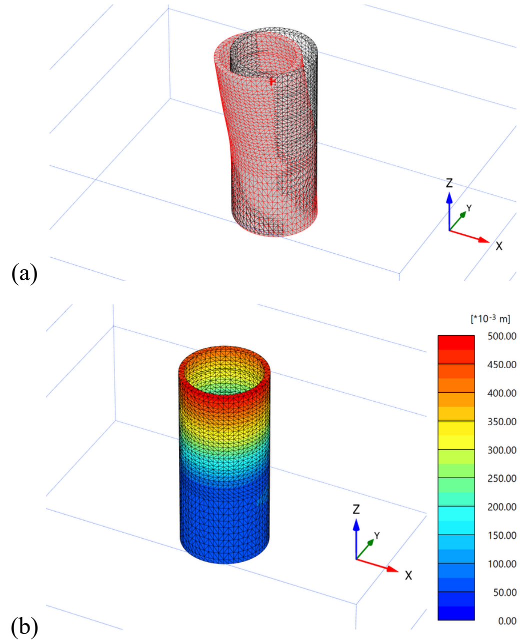

Figure 9. Dynamic results (t = 32 s): (a) shape and (b) displacements.

4.1.2 *Result of the calibration of prescribed displacements*

As previously indicated, the most critical displacement and shaft ovalisation takes place at 32 s. The calibration was carried out for these deformations and internal stresses of the shaft. The calibrated set of prescribed displacements was applied at the side boundaries of the model. The rock will not be subject to substantial deformations (Figure 9), while the softer upper soil layers will be exposed to increasing shearing with decreasing confining pressure. Figure 10 shows the iteratively calibrated prescribed displacements in both directions. It is worth noting that the displacements were left at 0 m at the boundary zone between the rock and dense sand layers to prevent soil failure.

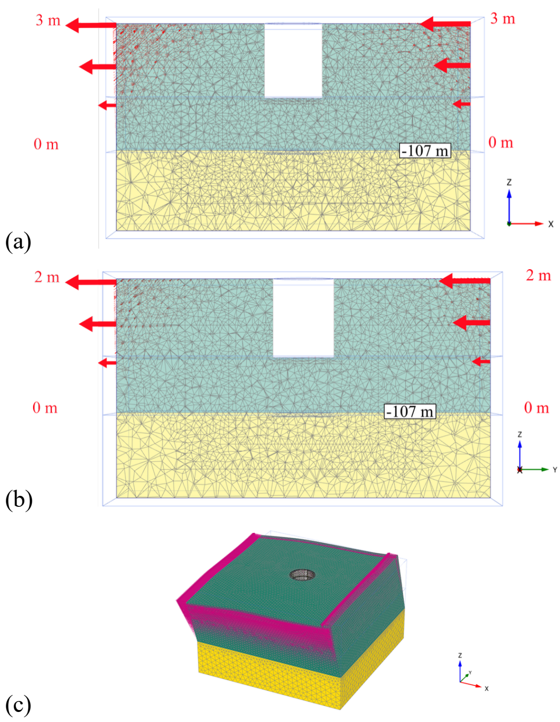

Figure 10. Calibrated prescribed displacements applied to the side boundaries in (a) x and (b) y directions, and (c) deformed model.

Figure 11 shows the results of the shaft structure subject to the prescribed displacements. These pseudo-static results (Figure 11) are similar to those obtained via dynamic modelling (Figure 9) in terms of deformation shape and displacement magnitudes, with an error in the displacements of the pseudo-static simulation of roughly 6 %, which was accepted for a preliminary design stage.

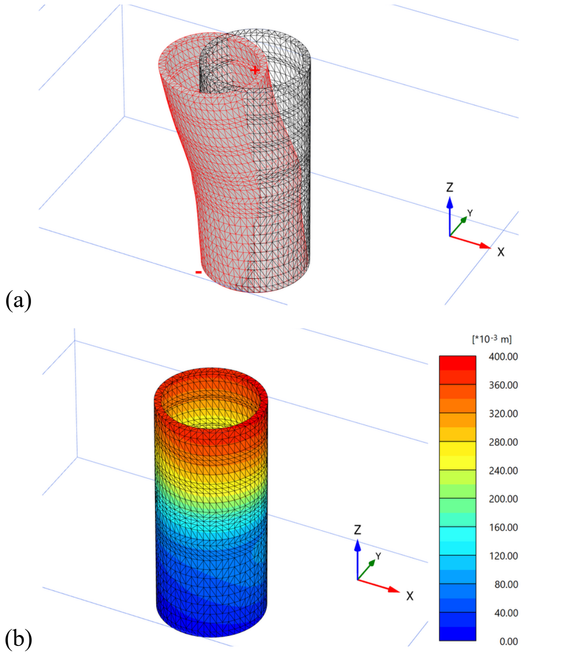

Figure 11. Pseudo-static results (prescribed displacements): (a) shape and (b) displacements.

The internal forces of the shaft were analysed to compare the results from the dynamic model and the pseudo-static simulation. Figure 12 shows the shaft moments (M22) for both cases. The results are comparable in terms of moment distribution and magnitudes, with an error of 1 to 5 %. Thus, the calibration was accepted and the prescribed displacements were applied to the complex model as described in the next section.

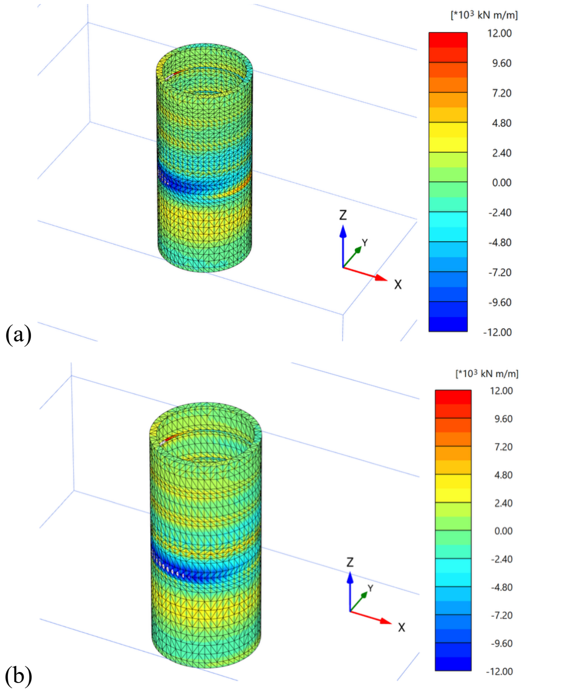

Figure 12. Bending moment in the major axis 22 for the (a) dynamic analysis and (b) pseudo-static (prescribed displacements) simulation.

4.1.3 *Pseudo-static analysis (complex model)*

The calibrated prescribed displacements were applied to the complex model in multiple directions (Table 3). Figure 13 shows the deformation shape, magnitude, and the moments (M22) for the worst-case combination of prescribed displacements (i.e. #7 according to Table 3). These results indicate that the seismic action has a significant effect on the upper part of the structure, with bending and shearing as the principal deformation modes. In terms of the deformation magnitude, the maximum displacement is in the order of 0.47 m, principally affecting the logistic shaft with fewer rock embedment. It is noted that the principal shafts are subjected to maximum deformations of approximately 0.2 m, which are considerably less if compared to the dynamic analysis (in the order of 0.5 m). This is due to the different rock embedment conditions. The dynamic analysis was performed for the shaft with the deepest rock level, to account for the most critical condition. In general, it is observed that the complex structure reacts stiffer (i.e. with fewer deformations) to the seismic load, suggesting a potential stiffening effect of the four interconnected shafts. Moreover, the sloped rock also contributes to a stiffer response.

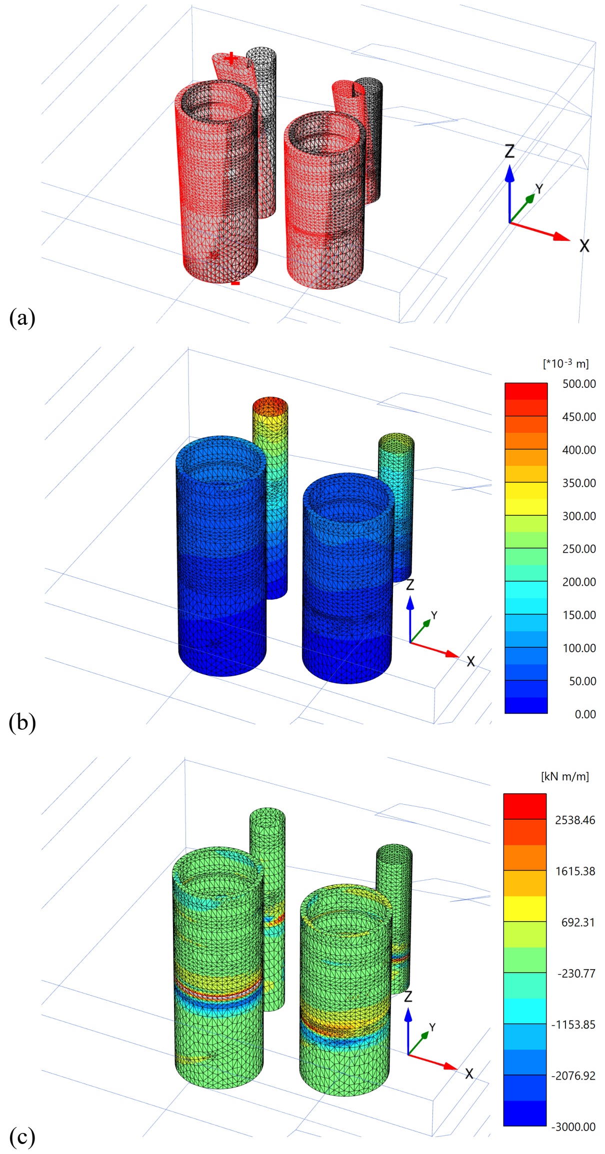

Figure 13. Results of the pseudo-static analysis of the complex model (combination #7): deformation (a) shape and (b) magnitude, and (c) moments (M22).

Regarding the bending moments (M22), it is seen that moment peaks appear in the regions where stresses are transferred between structures: e.g. between the shaft and the foundation slab, between the shaft and the bed rock, and between the shafts and the tunnels.

4.2 *Advantages, limitations, lessons learnt and future work*

The main advantage is that this approach is useful for the analysis of complex structures under seismic loading, which would otherwise be very time-consuming to compute. It is noted that this approach is applicable as a preliminary design strategy to estimate the order of magnitude of deformations, stresses or internal forces. However, for very complex structures or irregular soil layering, the calibrated prescribed displacements on the simplified model (with plain soil layers) are not fully applicable to the more complex model (with sloped soil layers). This is noted as an important limitation, because it may induce some errors when transferring the prescribed displacements from the simplified to the complex model. Moreover, the calibration of prescribed displacements is conducted manually, based on maximum displacements or the ovalisation of the structure. It is intended to capture the worst-case condition; however, due to the nature of manual calibration, this may also induce slight errors.

During the analysis, it has been observed that the domain dimensions of both models (i.e. complex and simplified) need to be chosen as equal to simulate the pseudo-static prescribed displacement application, without inducing errors derived from the soil's nonlinearity. It was noted that for large, prescribed displacements applied on the model boundaries, the stresses were not fully transferred to the structure due to soil failure. Caution is thus asked when defining the parameters subject to simplification during surrogate modelling. Furthermore, it is recommended to verify potential simplifications through sensitivity analyses.

As mentioned previously, the calibration of the prescribed displacements is time-consuming since it is carried out manually, which might be also linked with slight errors. To improve this approach, an automatised calibration will be implemented in future phases, following previous research on automatised calibration via optimisation algorithms as presented in Meier & Pitteloud (2024).

5 CONCLUSIONS

This paper presents the application of an existing methodology, originally developed for tunnels, to different underground structures (i.e. multiple interconnected deep shafts). This methodology consists of calibrating a set of prescribed displacements from a dynamic analysis based on a simplified model. These prescribed displacements are later applied to a pseudo-static analysis of a complex full design model. With this approach, the seismic analysis of complex underground structures and soils (i.e. soft saturated soils) become feasible and achievable in terms of computational power. Based on the example of a case study, this approach has shown that it is effective in estimating displacements and stresses of the underground structures under seismic events. Even though it presents some limitations, this approach is recommended for a preliminary design strategy. Moreover, it should be used as an example of how complex problems in new fields may be solved by applying existing techniques, while keeping the computational demand under reasonable limits.

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