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Soil-Structure Interaction: The New Frontiers of Interoperability

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Abstract: The paper illustrates, through the design of a reinforced concrete tall building on a mat foundation, the new interoperable methodology between the geotechnical calculation environment Flac3D (Fast Lagrangian Analysis of Continua) and the structural calculation environment Midas Gen. This methodology is aimed at calculating settlements and defining the foundation system. The paper deals with a complex case history that requires a sophisticated global analysis of the interaction between the soil, foundation structure and superstructure.

Key words: soil-structure interaction, interoperability, settlements

1. Introduction

In recent years, interest in the topic of soil-structure interaction has significantly increased within the scientific community. The difficulty of this type of analysis lies in choosing a single physical-mathematical model that appropriately describes the overall phenomenon from both structural and geotechnical viewpoint. The evolution of deformations in foundation soil under the action of the superstructure, potentially leading to failure, induces relative and absolute displacements that alter the internal stress state of structural elements, both in elevation and in the foundation elements directly in contact with soil. The need for determination of this effect represents one of the most significant conceptual challenges concerning the delicate boundary between geotechnical engineering and structural engineering.

The solution lies in *direct interoperability*, i.e., the ability to enable communication between the geotechnical and structural calculation environments. The aim of the project under examination is to assess the effects of soil-structure interaction with reference to the detail design of the foundation system for a tall reinforced concrete building. This communication is ensured through the link between Midas Gen, a leading tool supporting structural engineering, and Flac3D, a general-purpose software for continuum numerical analyses in the geotechnical field [1]. Due to structural complexity, the case is emblematic of the importance of interoperability for the design of the foundation system, ensuring an accurate settlement estimate, which ultimately led to the decision to improve foundation soil with jet grouting columns.

2. The Case Study of Tower Buildings on a Two-Storey Underground Parking Basement

The project involves the construction of four new residential tower buildings in Milan, lying on an underground volume designated for parking spaces, storage rooms, and technical rooms. Specifically, two separate, structurally independent lots are planned, each consisting of two towers and their corresponding underground areas. The four residential towers have varying heights, ranging from 55 to 80 meters above ground, with three underground storeys (Fig. 1).

2.1 Structural Modeling

Taking advantage of symmetry, a single tower has been chosen for this project. The tower is a high-rise

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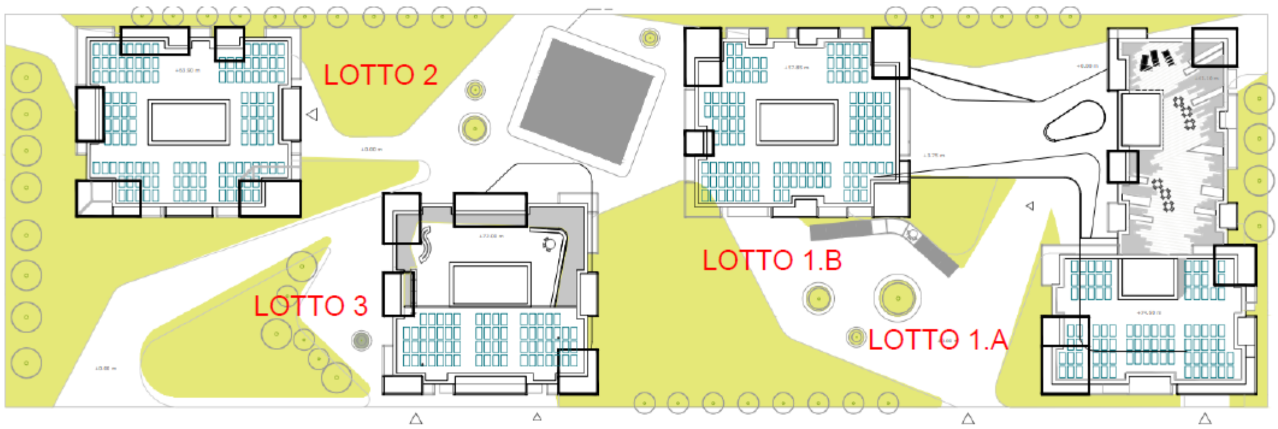

Fig. 1 Configuration of the intervention area with the position of the individual lots.

residential building made of reinforced concrete, comprising twenty-six floors supported by a mat foundation. The structure features a frame system with an elevator core consisting of earthquake-resistant reinforced concrete walls.

The structural model was developed using the finite element software Midas Gen, developed by Midas IT, and includes approximately 49,000 elements comprising beams, trusses, plates, and walls. Gravity loads, permanent structural and non-structural loads, as well as accidental loads, were applied using pressure loads on slabs and beam loads on beams and trusses, respectively.

2.2 Geotechnical Modeling

The high-rise tower is founded on predominantly sandy-gravelly granular soils with increasing properties with depth, interleaved with some weakly silty sandy lenses. The geotechnical model of the subsurface was constructed using Flac3D 9.0, developed by ITASCA Consulting Group. This software addresses continuum mechanics problems, determining stress and deformation states in a three-dimensional domain. The soil characteristics are defined by elastic or plastic constitutive laws and boundary conditions, utilizing the finite difference method.

The three-dimensional model encompasses lots 1A and 1B, portions of terrain extending 90 meters east of lot 1A, and 70 meters north and south of both lots. It also includes the soil beneath the foundation extending to approximately 70 meters depth below the foundation's base level, which represents the top of the model.

The boundary between lot 1B and lots 2 and 3 is modeled as a symmetry plane to maximize differential settlements.

The stratigraphy is shown as reported in Table 1.

The water table is found at a depth of approximately -15 meters from ground level, and for initial geostatic analysis, the perfect rigid-plastic Mohr-Coulomb constitutive model was adopted.

For subsequent settlement analysis, the soil model used was the Plastic Hardening model [2], specifically developed for addressing the deformation behavior of granular soils undergoing phases of unloading (excavation) and reloading (new construction, re-excavation, etc.). This model is capable of numerically simulating the nonlinear behavior of soils using plasticity theory and hardening.

Table 1 Reference stratigraphy.

	Thickne	Friction	Young's
Layer 1	2	32	70e6
Layer 2	20	35	110e6
Layer 3	38	33	120e6

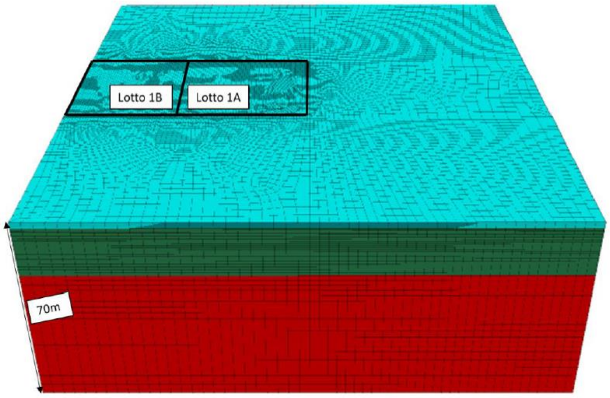

Fig. 2 Geotechnical model.

Specifically, the Plastic Hardening model allows for simulating strain-hardening mechanical responses of the soil both in shear and volumetric terms.

It considers stiffness variations under both unloading/reloading conditions and low deformations.

3. FLAC3D-MIDAS Gen Link

Once completed in Midas Gen, the structural model was transferred to the geotechnical program Flac3D using a tool developed by the Digital Transformation department of Harpaceas. This achievement was made possible, on one hand, by the capability of Midas IT products to export model description through a formatted numerical file. On the other hand, it uses the built-in programming language available in all ITASCA-developed software (FISH language). Additionally, part of the code was optimized by also working in the Python environment, directly accessible from within Flac3D [3].

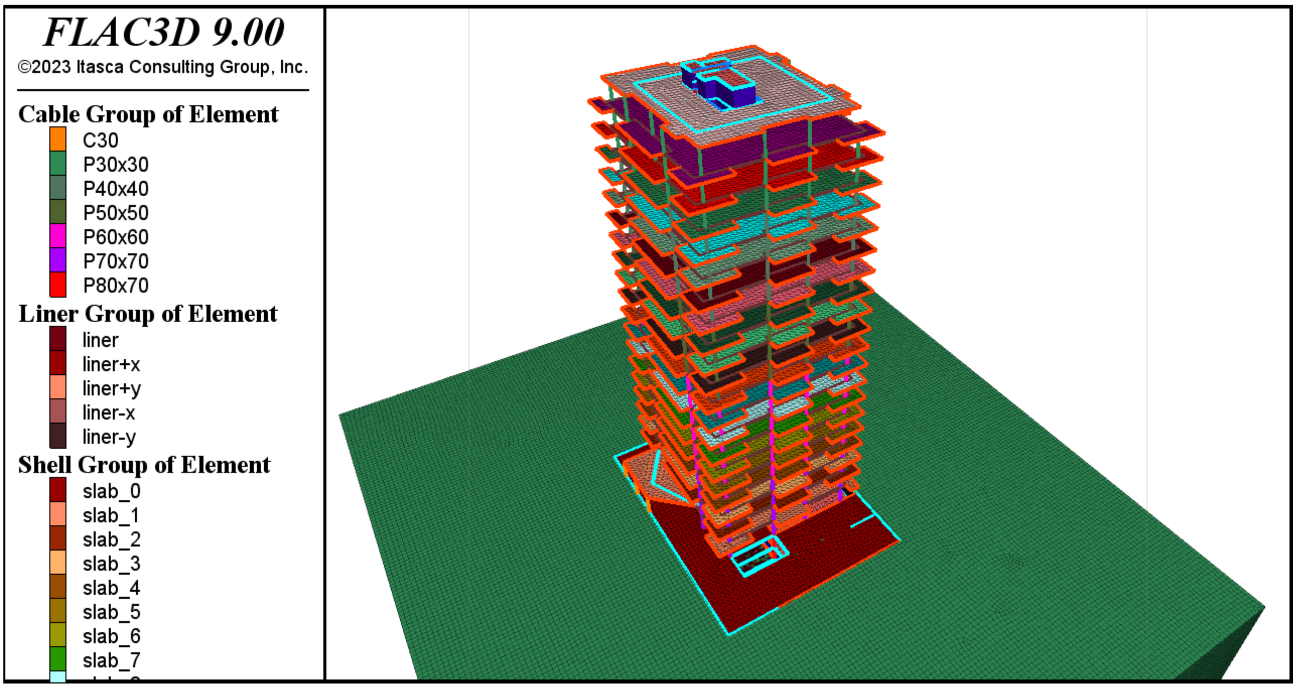

Fig. 3 Import of the model from Midas Gen into Flac3D.

3.1 Results – Direct Foundation on Natural Soil

Below are presented the results of the analysis in terms of vertical displacements. The maximum settlement is recorded at the core of the tower in lot 1A, reaching approximately 6 cm. The average settlement across the building is 4 cm.

It is noteworthy that there is a differential settlement of about 2 cm (as depicted in the section B-B' diagram). These displacements, given the foundation setup of the building's mats and underground areas, do not meet the project requirements, which stipulate differential settlement values in the order of centimeters.

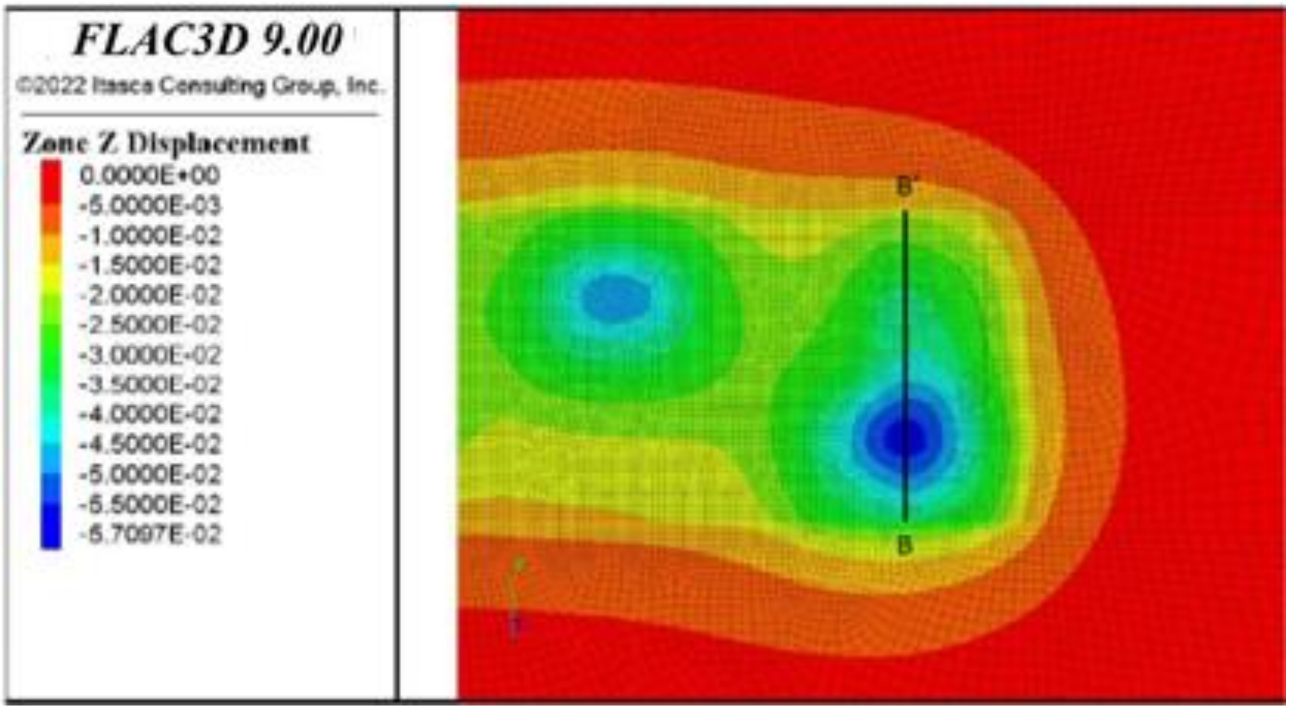

Fig. 4 Vertical settlements.

3.2 Results: Direct Foundation With Soil Consolidation — Jet Grouting Columns

Due to the significant expected differential settlements obtained in the deformation analysis of the shallow foundation, soil consolidation is being implemented. This involves improving soil stiffness by means of jet grouting columns. The numerical analysis conducted follows the same assumptions as previously described, but additionally models the columns as zones (solid elements) characterized by an elastic behavior. These columns are positioned beneath the towers in a 5 m × 5 m grid, with a diameter of 180 cm each.

It is observed that the use of jet grouting columns has reduced settlements by approximately 30% compared to the natural soil case. Consequently, a maximum differential settlement of about 1 cm is estimated. This assessment aligns with the project requirements.

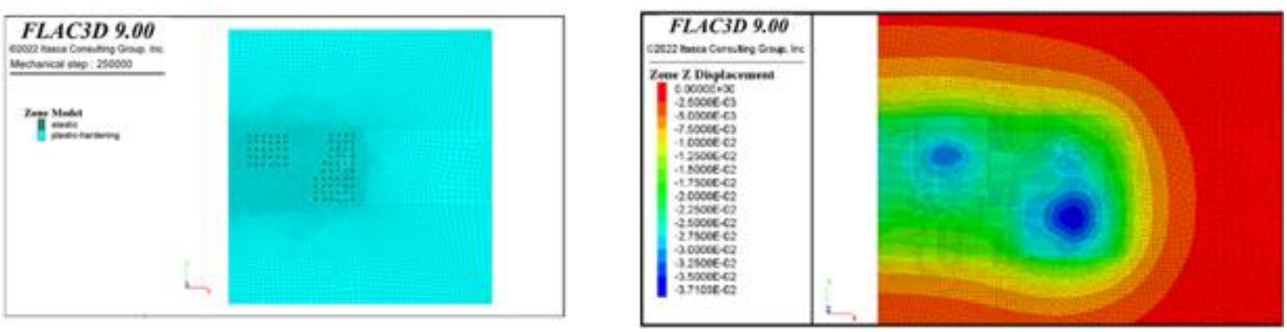

Fig. 6 Vertical displacements at the foundation bearing level: foundations on jet grouting column.

4. Conclusion

An example of interoperability between the structural analysis and geotechnical analysis domains has been shown. The aim of this developed link stems from the need to optimize information obtained through numerical computation by combining functionalities typical of geotechnical analysis (continuum modeling of soils with specialized constitutive relations, groundwater management, and initial stress state initialization) with those typical of structural analysis software, such as finite element modeling, load and constraint definitions. The development was made possible due to the "openness" of the two software tools used: Midas Gen allows data exchange (even partial) through formatted numerical files, while Flac 3D, in addition to having an internal programming language, supports the construction of codes and instructions in Python.

For complex issues, the use of this link is necessary to achieve advanced results that separate models would not allow for, thereby optimizing design choices.

The use of the link between these two environments represents the future direction to take, in order to perform advanced and comprehensive analyses, as increasingly required by regulations. This is why the link also operates in reverse, allowing settlements from Flac3D to be imported into Midas Gen. This capability enables structural verifications based on the actual deformation state of the soil.

The next steps in interoperability development aim to fully integrate all advanced functionalities from the structural analysis environment, such as phased analyses, composite sections, traffic loads, and accelerograms.

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