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m-PISE: A novel numerical procedure for pile installation and soil extraction.

Application to the case of Leaning Tower of Pisa

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Abstract

This article introduces a new procedure to model two cases related to the simulation of the movements of the Tower of Pisa: installation of micropiles and soil extraction. Standard FEM requires geometry definition in the initial configuration. In this case the initial configuration is much different from the final one. m-PISE procedure overcomes this limit. Previous models based these two simulations on a back-analysis procedure. In m-PISE the volume changes are the same as the extracted or injected in-situ, providing a forecasting of the movements. The results obtained through this new procedure show very good agreement with the measured data.

Keywords

Leaning Tower of Pisa; FEM; soil extraction; pile installation; micropile; m-PISE

1 1 **Introduction**

2 In finite element analyses, discretisation of entities that are relatively small in size
3 compared to the extents of the overall finite element model can be a challenging task.
4 Examples for such rather small entities are rebars in reinforced concrete or piles,
5 anchors and nails in soil and rock. In the past, large numbers of such objects were
6 usually modelled by smearing their strength and stiffness over a larger volume. This
7 rather crude modelling approach was later superseded by embedded elements, that is
8 rebar elements in reinforced concrete design and embedded piles in geotechnical
9 engineering [1,2]. These special purpose elements allow the user to define rebars, piles,
10 anchors and nails mesh independently: the end nodes of the embedded elements do not
11 need to coincide with nodes of the overall model. Yet, the position of the embedded
12 elements has to be defined in the reference configuration of the model. In most cases,
13 this is straightforward. Sometimes, however, for example when piles are installed after a
14 certain deformation has readily taken place, it is cumbersome to define their initial
15 configuration in respect to the undeformed mesh. For such cases, the paper at hand
16 presents m-PISE, a novel numerical procedure that allows the user to introduce piles at
17 any time in the (deformation) history of a model. Furthermore, the method can be used
18 to model soil extraction. The merits of the method are demonstrated within an analysis
19 of the Leaning Tower of Pisa.
20 Several Finite Element analyses were published in relation to the Leaning Tower of Pisa
21 [3], [4], [5]. The latter authors carried out a series of updated and improved Finite
22 Element analyses through the years 2002 and 2010. Beside the improved constitutive
23 models used in their studies, their analyses benefitted also from the technological
24 progress made at the time of the study: more accurate and reliable predictions of the

Tower rotation and settlement could be obtained due to an improved discretisation of the problem. However, two events that highly affected the Tower in its recent history have not yet been modelled in previous studies: first, micropiles installation in 1995 and secondly, the soil extraction procedure started in 1999 as a remedy to the problem of leaning instability. The accurate modelling of these two events is a crucial step in defining the reliability of a numerical model of the Leaning Tower of Pisa. This article introduces a new numerical procedure that can be used to model these two events. Previous models based the simulations on a back-analysis procedure assuming an equivalent volume change that would produce the same effect as the real micropiles installation or the soil extraction. In m-PISE the input volume changes are the same as those resulting from the injection or extraction operations. The computed movements simply represent the effect of the input data.

2 Finite element model and soil profile

Figure 1(a) shows the geometry and soil profile at the location of the Tower. High quality in situ and laboratory data are available in literature for the soil characterization [6]. Studies and accumulated experience [7] [8] [9] [10] show that the silt layer (in grey) is responsible for the tilting of the Tower towards south. The soft clay layer (in brown) is the main reason for the settlement of the Tower. Figure 1(b) shows the Finite element mesh used in the analysis consisting of roughly 240.000 tetrahedral linear stress elements. Material models and parameters for the subsoil used in this study have been adopted from [6] and [11]. The tower is modelled as a rigid body. The soil-structure interaction is modelled by introducing horizontal interface elements with elastic-

perfectly plastic behaviour. Strength and stiffness parameters of these interfaces are inherited from the surrounding soil.

Structural details, such as Catino wall-Tower foundation connection, are modelled with so-called *node-to-node anchor* elements [2], providing an elastic link between the end nodes. Their elastic stiffness was set to a value derived from the resulting stiffness of the metal tubes connecting the foundation mass to the Catino floor. Moreover, the variation in water table depth throughout the deformation history of the Tower is also modelled. A summary of the construction phases of the Tower is shown in Table 1. The detailed description of the simulation of the modelling of these phases is out of the scope of this article. The focus is on the modelling of the micropiles installation and the soil underexcavation stages.

Table 1. Construction history

Time Line	Description
1173 to 1178	Construction of the foundations and the first four levels, reaching the height of 29m
1178 to 1272	Construction pause
1272 to 1278	Construction of the tower to the seventh level, reaching the height of 51m
1278 to 1360	Construction pause
1360 to 1370	The Tower was completed with the bell chamber to its final height of 58m
1838/1839	Excavation of the Catino
1934	Impermeabilization of Catino floor and foundation mass
May 1993	A pre-stressed concrete ring is constructed around the base of the tower above Catino floor
July 1993	The inclination reaches 5.5°. Start of application of a counterweight of 6MN in four phases
January 1994	The last lead ingot of the first series is placed
Aug – Sept 1995	Installation of micropiles through the South Catino wall, second series of counterweights
1999	First soil extraction under the North side of the tower
2000	Second soil extraction

61

62 **3 Micropiles installation and soil extraction**

63 In 1995, it was decided to install 30 micropiles through the Catino wall at the southern
64 side of the Tower. The configuration and distribution of the micropiles are shown in
65 Figure 2(a, b). The initial diameter of each micropile was 0.13 m. After installation, the
66 final diameter reached the value of 0.25 m, since their installation was controlled on
67 volumetric basis. Therefore, the expansion resulted in a local volumetric strain of about
68 270%. Their installation aimed to reduce the influence of Catino weight on the south
69 side of the Tower. Unfortunately, the operation did not give the expected result.
70 In fact, the Tower started to accelerate its southward rotation, which required urgent
71 installation of temporary lead counterweights on the northern side of the Catino.
72 Meanwhile many permanent stabilization alternatives were discussed. As a final
73 measure, a soil extraction procedure on the northern side of the Tower started in 1999.
74 A carefully defined amount of soil was extracted underneath the Tower. The extraction
75 was carried out using extraction tubes, and it was undertaken through two distinct
76 phases. The first is the so-called “preliminary underexcavation”, where cautiously a
77 small amount of soil was extracted from higher depth and far enough from the
78 foundation mass, as it was clear that the Tower is very sensitive to what happens nearby
79 its footing. Considering the promising results obtained with the preliminary
80 underexcavation, the second phase, called “full underexcavation”, took place in 2000.
81 This resulted in a total extraction of 44.61 m³ of soil. The configuration of the tubes for
82 the preliminary and full underexcavation are shown in Figure 3 and Figure 4.

83

4 Numerical challenges in modelling the micropiles installation and underexcavation

Both the micropiles installation and the underexcavation are difficult to be modelled with the finite element method. A major concern here is the excessive number of rather small volume elements needed to properly model extraction tubes and micropiles. This number can easily reach values that are very difficult to be handled nowadays. In addition, the small elements in micropiles and soil tubes regions could suffer high distortions during loading and hence, lead to convergence problems. A remedy to these difficulties could be the use of embedded elements which are readily available in commercial software packages [1, 2].

However, FEM codes usually require problem definition in the initial configuration. This is not a serious practical problem in the case of small deformations. However, in the case of the Pisa Tower, in which case the ascertained settlement is at least three meters, the modeller will be facing the difficult task of determining the initial configuration of micropiles and extraction tubes in the year 1173, keeping in mind that both, micropiles and extraction tubes are installed in the deformed geometry in late 20th century.

To avoid the complexity of the problem, all previous analyses of the Pisa Tower that aimed for modelling micropile installation and underexcavation used a smeared approach [5], [12]. The stiffness and induced strain of micropiles and extraction, respectively are distributed on a volume that approximately resembles the micropiles and the underexcavation regions, but the approximation is far from acceptable. To better approach the modelling of the micropiles and extraction tubes, [11] proposed to work at Gauss (stress integration) point level without the need to define new special

108 volume elements for the tubes or the micropiles. The m-PISE procedure described
109 below follows this idea.

111 ***4.1 The m-PISE procedure (m-PISE: material-Pile Installation and Soil*** 112 ***Extraction)***

113 To simulate micropiles installation or soil extraction effects, it is here proposed to
114 define mesh independent virtual volumes representing piles or extraction tube volumes.
115 All globally defined Gauss points that are inside a virtual volume are assembled.
116 Stresses at the assembled Gauss points are then calculated independent of the global
117 material definition by a (user defined) constitutive routine. In the example of the Pisa
118 Tower, micropiles are modelled as poroelastic material, with stiffness parameters
119 (swelling index κ and Poisson ratio ν') equal to the corresponding values in the original
120 soil model, listed in Vermeer et al. [13]. The soil extraction effects are obtained by
121 imposing a volume strain at the Gauss point level in the constitutive routine. The entire
122 procedure can be implemented in a user defined constitutive routine. Prerequisite is that
123 the hosting finite element code offers an interface that passes the actual deformed
124 coordinates to the user defined routine.
125 The m-PISE procedure assembles volumes of Gauss points regardless if the element to
126 which they belong is fully included in the virtual volume or not. Particle methods that
127 use a calculation grid, as for example the Material Point Method, initially define
128 structures in a similar way. Same as these methods, m-PISE may lead to high stiffness
129 differences between the Gauss points of a single element and thus, to sometimes slower
130 convergence.

Figure 5 clarifies the idea, where the virtual tube is in grey while the collected Gauss points are in green. The assigned volume strain represents the real extraction or expansion in the field. The light-grey lines represent the contour of the employed Finite Elements, which can be fully or only partially involved by the soil extraction depending on how many of their stress integration points fall in the virtual volume.

Although the proposed approach overcomes the difficulty inherent in the definition of an explicit cluster of extremely reduced size compared to the average element size in the rest of the model, the mesh should be fine enough to collect an appropriate number of Gauss points that represent a certain tube.

This idea was then applied to the case of Leaning Tower of Pisa after its implementation as User Defined Model in PLAXIS 3D [2] and its thorough validation [12]. The input data for m-PISE include:

1. the number of tubes/micropiles;
2. the x, y, z coordinates of the start and end point of each tube/micropile;
3. the radius of each tube/micropile;
4. the applied volumetric strain for each tube/micropile.

Working at Gauss point level saves the need for an excessive number of finite elements for each tube. The input parameters are also straightforward and very efficient. Yet, for the optimization of the procedure, a good estimation of the initial configuration of the extraction region is required. For the latter issue, the authors have developed a special numerical procedure for optimizing the cluster assigned to the extraction/expansion region, as described in 4.3.1.

4.1.1 Verification of the m-PISE numerical procedure

To verify that the User Defined Model is extracting the correct amount of soil volume, a cube with unit dimensions as shown in Figure 6 is subjected to a contractive volumetric strain of 50%. Normal displacements are constrained on three adjacent faces. The used input data are shown in Table 2. The extraction tube is designed in a way it selects all Gauss points in the cube mesh as it clear in Figure 7(a). The selected Gauss points are subjected to a volume strain of 50%. The output in Figure 7(b) shows a uniform volume strain of -0.5, which verifies the correctness of the implementation of the m-PISE model, as one gets the same volume strain that is prescribed in the input.

Table 2. Input file data to verify the m-PISE procedure correctness.

Input data	Value	Unit
Number of tubes	1	[-]
Start Point coordinates of the tube $(x, y, z)_{\text{start}}$	(0.5, 0.5, 1.0)	[m]
End Point coordinates of the tube $(x, y, z)_{\text{end}}$	(0.5, 0.5, 0.0)	[m]
Radius of the tubes	$\sqrt{2}/2$	[m]
Applied volumetric strain	- 0.5	[-]

4.2 Simulation of micropiles installation using m-PISE

After identifying the coordinates of the start point and the end point of each micropile in the current configuration, the algorithm (described in 4.3.1) identifies the involved Gauss points for each micropile, which have then been subjected to the corresponding volumetric strain (Figure 8a, b, d). To avoid the need for an excessively dense mesh, the micropiles are given a virtual initial radius of 0.15 m. The applied volumetric strain is calibrated in a way it produces the same volumetric strain as imposed by the real micropiles. Figure 8(c) shows the

involved Gauss points in the expansion process. The Gauss points exactly represent the micropiles.

The calculation result shows a very good agreement with the measured data as presented in Figure 9. The overall southward rotation induced by the micropiles installation is about twenty seconds of arc.

Embedded-pile elements [2] have been used to simulate the properties of the micropiles after expansion. The embedded pile allows to simulate the stiffening effect related with the rigid inclusions, whereas the radial stress increase simulates the installation effect. Figure 10 shows the activated micropiles after installation.

4.3 Simulation of soil extraction using *m-PISE*

The procedure enables to exploit the available data of soil extraction for a real input for the numerical model. Figure 11 shows the available data for the final soil extraction phase. Each square in Figure 11 represents an extraction segment of dimensions 0.5 m. The bold number inside each square represents the extracted amount of soil in dm^3 (10^{-3} m^3). The whole data represents 41 extraction segments. The total length of these extraction segments ranges from 4.0 m to 5.0 m. As a first trial, the intent was to use the same distribution in the numerical model. However, during the preparation of the input file it turned out that some tubes should be exposed to a very high-volume strain to account for the real extracted values. Such a high-volume contraction strain poses numerical difficulties that make the convergence extremely difficult especially in the case of large deformation calculations. To avoid the numerical problems, it was decided to assemble each two adjacent extraction tubes into one tube.

Moreover, each assembled tube was divided into a front part and a rear part. The final distribution of the tubes is shown in Figure 12 where rear tubes are in white and the front tubes are in the darker colour.

The coordinates for the start-point and the end-point of each tube are derived from the geometry of the problem in the current configuration. The imposed contraction on each tube is calculated by summing up the amount of extracted soil within that tube and dividing it by the volume of the tube.

4.3.1 Numerical procedure to determine the elements involved in soil extraction

In order to use the implemented numerical procedure, it should be assigned as a material model to the cluster where the soil will be extracted. This cluster should be designed and determined in the initial configuration. As it is almost impossible to guess the initial location of such a cluster, a numerical procedure is developed to overcome this problem and to optimize the number of element involved in the extraction phase. The procedure consists of four steps:

1. the material model will be activated at the soil extraction phase using the provided coordinates and data as described in the preceding section, Figure 13(a);
2. the material model locates the Gauss point that are inside the contraction tubes in the deformed (current) configuration, Figure 13(b);
3. the finite elements containing these Gauss points can be filtered and then shown in the initial undeformed configuration, Figure 13(c);
4. using the filtered elements in the initial configuration, a suitable envelope can be drawn to form the optimized cluster as it is clear in Figure 13(d).

1 219 The proposed procedure, in combination with the new model for the identification of
2
3 220 Gauss points to be strained, overcomes the difficulties in pre-defining in year 1173 the
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5 221 cluster enveloping the extraction tubes used eight centuries later. Even though a mesh
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7 222 refinement is applied to that cluster, this is definitely more efficient than modelling each
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9 223 tube individually.

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12 224 The performance of the procedure is shown in Figure 14 for the case of the preliminary
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14 225 underexcavation phase and in Figure 15 for the case of the full underexcavation phase.

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17 226 The resulting rotations for preliminary soil extraction are shown in Figure 16. The
18
19 227 numerical results agree with the measurements from a qualitative point of view, and
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21 228 only slightly overestimating them quantitatively.

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24 229 The positive outcome is confirmed for the final soil extraction as shown in Figure 17,
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26 230 where the numerical simulation matches the rotation measurements.

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29 231 Finally, Figure 18 shows the vertical displacements at the last step of the calculation
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31 232 phases for the preliminary soil extraction and the final underexcavation, respectively.

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34 233 The colour map testifies the correct location of the extraction tubes in the numerical
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36 234 model at the time of the operations.

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40 41 42 236 **5 Conclusions**

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47 237 The current analysis extends the Finite Element method probably to the limit of its
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49 238 applicability. The main element of novelty in the analysis presented in this article has
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51 239 been the new procedure used to simulate the micropiles installation and the soil
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53 240 extraction in much more accurate and effective way than previous approaches, where
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55 241 the volume strains were back-analysed based on the measured data. The procedure does
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57 242 not require the definition of clusters of finite elements, which is a typical cause of
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meshing problems when dealing with small clusters in large models. In general, the proposed procedure is suitable for every practical application that involves soil extraction or large displacement. In the case of Pisa Tower, the results obtained through the new procedure show very good agreement with the measured data, using the actual excavated (or injected) volumes as input.

Conflicts of interest

The authors declare no conflict of interest.

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Figure captions

Figure 1. Tower model: (a) Geometry and soil profile; (b) Used finite element mesh.

Figure 2. (a) Micropile (black dots) distribution; (b) Single micropile geometry.

Figure 3. Configuration of the extraction tubes in the preliminary underexcavation phase. After [4].

Figure 4. Configuration of the extraction tubes in the final (massive) underexcavation phase. After [4].

Figure 5. Virtual tubes (in grey) and the collected Gauss points (in green) to be strained.

Figure 6. Geometry (a) and Finite Element mesh (b) of the verification test.

Figure 7. Sampled Gauss points (a) and the resulted volumetric strain (b)

Figure 8. Micropiles modelling: (a) Used FE cluster; (b) Micropiles location; (c) Gauss points activated for the micropiles; (d) Applied volumetric strain.

Figure 9. Measured versus computed rotation due to micropiles installation.

Figure 10. Activation of the embedded piles to simulate the micropile stiffening effect after expansion.

Figure 11. In situ extracted soil data for the final excavation.

Figure 12. Modified soil extraction tubes as used in the analysis.

Figure 13. Numerical procedure to determine the elements involved in the extraction phase: (a) geometry of the condensed tubes; (b) identification of the elements involved through their Gauss points within the virtual tubes; (c) involved elements at their initial configuration; (d) optimized cluster.

Figure 14. Designed cluster for the preliminary soil extraction phase: (a) assembled extraction tubes located inside the cluster; (b) involved Gauss points.

Figure 15. Different views that illustrate the performance of the proposed procedure for the optimization of soil extraction cluster: (a) deformed clusters for final (dark grey) and

1 314 preliminary (light grey) soil extraction; (b) identification of elements involved in the
2
3 315 procedure; (c) involved elements at their initial state (in red); (d) optimization on the
4
5 316 shape of the cluster enveloping the involved elements.
6
7 317 Figure 16. Calculated versus measured rotation after the preliminary soil extraction.
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9 318 Figure 17. Calculated versus measured rotation after the final soil extraction.
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11 319 Figure 18. Incremental vertical displacements: (a) after preliminary soil extraction; (b)
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13 320 after final soil extraction.
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21 322 **Table captions**
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23 323 Table 1. Construction history.
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25 324 Table 2. Input file data to verify the m-PISE procedure correctness.
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Figure 1
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Figure 2
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Figure 6
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Figure 7
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(a)

Phase volumetric strain P_{ϵ_V}
Uniform value of -0.5000

(b)

Figure 8
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(a)

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Figure 9
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Figure 10
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Figure 11
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Distance*	BOREHOLE																																														
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23.3+24.8	29 11	24 10	27 7	22 10	13 8																																										
24.8+24.3	14 10	14 10	10 11	9 10																																											
24.3+25.8	7 10	10 10	7 11																																												
25.8+25.3																																															
Total	1413	1445	1464	1578	1260	902	937	1005	1064	786	678	761	716	801	835	903	946	794	1028	881	937	802	911	724	833	790	737	709	782	833	739	884	881	944	844	850	906	1198	830	909	741						

Figure 12

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Figure 13
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(a)

(c)

(b)

(d)

Figure 14
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(a)

(b)

Figure 15
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(a)

(c)

(b)

(d)

Figure 16
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Figure 17
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Figure 18
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(a)

(b)