Transient Dynamic Analysis of a Machine Foundation
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Appendix A Additional Information
1 Description

The purpose of this tutorial is to model and analyze a concrete machine foundation positioned on stiff overconsolidated silty sand. The frame type foundation with concrete base raft is supporting a high pressure compressor (HPC) of 60000 kg and a low pressure compressor (LPC) of 40000 kg. Both compressors are rotating at a low speed of 100 rpm. Forces are generated due to the unbalance in both machines [Fig. 1]:

\[ F = m \cdot e \cdot \omega^2 \] (1)

where \( m \) being the rotating mass of each compressor, \( e \) being the eccentricity between the center of mass and center of rotation, and \( \omega \) the angular velocity of the rotating machinery. The permissible vertical amplitude at the base of the foundation is 80 micron \((80 \times 10^{-6} \text{ m})\).  

Figure 1: Frame type machine foundation for two compressors

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2 Material Properties

The foundation is made from normal weight C30/37 concrete with quartzite aggregates as specified by Eurocode 2 EN 1992-1-1. The soil on which the foundation is placed can be characterized as stiff overconsolidated silty sand and will be modeled as Mohr-Coulomb material. The machinery supported by the foundation will be modeled as two point masses for the high pressure compressor (HPC) and the low pressure compressor (LPC) on a massless stiff steel frame. Between the soil and the foundation a stiff no-tension interface will be placed to model the soil-structure interaction (SSI).

The relevant material properties for the transient dynamic analysis can be found in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Material properties</th>
<th>Concrete</th>
<th>Soil</th>
<th>Steel</th>
<th>HPC</th>
<th>LPC</th>
<th>SSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (E)</td>
<td>32837</td>
<td>160</td>
<td>210000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio (ν)</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (ρ)</td>
<td>2400</td>
<td>2200</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mass (m)</td>
<td>60000</td>
<td>40000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean uniaxial tensile strength (f_{utm})</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean compressive strength (f_{cm})</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction angle (φ)</td>
<td>35°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilatancy angle (ψ)</td>
<td>2°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cohesion (c)</td>
<td>25 kPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral pressure ratio (K_0)</td>
<td>0.47</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal stiffness modulus-z</td>
<td>1E+6 MPa/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear stiffness modulus-x</td>
<td>1E+4 MPa/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear stiffness modulus-y</td>
<td>1E+4 MPa/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3 Finite Element Model

For the modeling session we start a new project for structural analysis. The dimensions of the domain for the three-dimensional model are set equal to 100 m. We will dominantly use linear hexagonal elements.

![Figure 2: New project Dialog](https://dianafea.com)
3.1 Units

We choose meter for the unit Length, kilogram for the unit Mass, newton for the unit Force, second for the unit Time, and degree for Angle.

Geometry browser ➔ Reference system ➔ Units  [Fig. 3]
Property Panel  [Fig. 4]
3.2 Geometry Definition

3.2.1 Concrete Machine Foundation

We start the modeling of the concrete machine foundation with the rectangular base raft slab.
The next step will be the modeling of the six columns by defining one column [Fig. 8], copying it once in Y direction [Fig. 10], and copying those two columns twice in X direction [Fig. 12].

Main menu ➔ Geometry ➔ Create ➔ Add block

Figure 7: Geometry - Add block
Figure 8: View - Isometric view 1
Main menu → Geometry → Modify → Array copy [Fig. 9] [Fig. 10]

Figure 9: Geometry - Array copy

Figure 10: View - Isometric view 1
Main menu ➔ Geometry ➔ Modify ➔ Array copy ➔ [Fig. 11] [Fig. 12]

Figure 11: Geometry - Array copy

Figure 12: View - Isometric view 1
The top part of the concrete machine foundations is created by a rectangular slab [Fig. 14]. The square openings are being created by subtraction of two square blocks [Fig. 20].
Main menu ➔ Geometry ➔ Create ➔ Add block ➔ [Fig. 15] [Fig. 16]

Figure 15: Geometry - Add block

Figure 16: View - Isometric view 1
Figure 17: Geometry - Array copy

Figure 18: View - Isometric view 1

Main menu ➔ Geometry ➔ Modify ➔ Array copy  📈 [Fig. 17] [Fig. 18]
Main menu ➔ Geometry ➔ Modify ➔ Subtract shapes

[Fig. 19] [Fig. 20]

Figure 19: Geometry - Subtract shapes

Figure 20: View - Isometric view 1
We can now assign the properties to all concrete parts. The material is modeled as Eurocode 2 EN 1992-1-1 normal weight C30/37 concrete with quartzite aggregates. The concrete machine foundation will be modeled with structural solid elements.

**Main menu** ➔ Geometry ➔ Assign ➔ Properties 🍃 [Fig. 21]

**Properties** 🍃 ➔ Material ➔ Add material 🍃 [Fig. 22] ➔ Edit material 🍃 [Fig. 23]

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**Figure 21:** Assign properties

**Figure 22:** Add new material - Concrete

**Figure 23:** Concrete material properties
3.2.2 Machinery

The two machines, a high pressure compressor of 60000 kg, and a low pressure compressor of 40000 kg, are not modeled explicitly. The two compressors will be modeled as point mass elements which are placed on a stiff massless frame to position the centers of mass correctly. The dynamic loading is modeled with nodal forces with attached time-load factor functions to mimic the unbalance forces due to the rotating machinery. First, the stiff massless frame is being modeled.

Main menu ➔ Geometry ➔ Create ➔ Add polyline

Figure 24: Geometry - Add polyline

Figure 25: View - Customized view
Main menu ➔ Geometry ➔ Modify ➔ Array copy  

[Fig. 26] [Fig. 27]

Figure 26: Geometry - Array copy

Figure 27: View - Customized view
Figure 28: Geometry - Add line

Figure 29: View - Customized view
Main menu ➔ Geometry ➔ Modify ➔ Array copy ➔ Array copy  

Figure 30: Geometry - Array copy

Figure 31: View - Customized view
The stiff steel frame will be modeled with three-dimensional Class-I beam elements, which have a pipe cross-section of 0.5 m and a wall thickness of 0.1 m. Keep in mind that this frame is only used to get the correct positions of the high pressure compressor (HPC) and the low pressure compressor (LPC) without modeling the actual machinery!

**Figure 32: Assign properties**

**Figure 33: Steel - Element geometry properties**
The steel frame will be modeled without any mass, because the mass of the machinery will be concentrated in two point mass elements. Therefore, the density will be set to zero for the linear elastic steel material [Fig. 35].

![Figure 34: Add new material - Steel](image)

![Figure 35: Steel material properties](image)
Next, two point bodies are being created for the high pressure compressor (HPC) and low pressure compressor (LPC) with a mass of 60000 kg and 40000 kg respectively.

Figure 36: Add point body - HPC

Figure 37: Add point body - LPC
First, the properties are assigned to the high pressure compressor, which will be modeled with a point mass element with a mass of 60000 kg.
Secondly, the properties are assigned to the low pressure compressor, which will also be modeled with a point mass element, but has a mass of 40000 kg.
3.2.3 Soil

The stiff overconsolidated silty sand on which the machine foundation is placed, is modeled by a block which has a length of 23 m, a width of 18 m, and a height of 10 m.
A Mohr-Coulomb material is being used to model the stiff overconsolidated silty sand.
The material forms for the Mohr-Coulomb material will be filled with the properties as specified in Table 1.

Figure 48: Soil material properties

Figure 49: Soil material properties

Figure 50: Soil material properties
The soil block will be supported in global $X$, $Y$, and $Z$ directions to perform an eigenvalue analysis later.

**Main menu → Geometry → Assign → Supports**  
[Fig. 51] [Fig. 52]
Main menu ➔ Geometry ➔ Assign ➔ Supports 📃  [Fig. 53] [Fig. 54]

Figure 53: Attach Support

Figure 54: Supports soil Y
Main menu ➔ Geometry ➔ Assign ➔ Supports [Fig. 55] [Fig. 56]

Figure 55: Attach Support

Figure 56: Supports soil Z
3.2.4 Interface

Between the concrete foundation and the soil an interface will be placed with no-tension behavior in normal direction and constant shear stiffness. The interface can easily be created without imprinting the floor slab on the soil.

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**Figure 57: Connection property assignments**

**Figure 58: Interface - Add new material**
The material forms for the soil-structure interface (SSI) will be filled with the properties as specified in Table 1.
In case the interface results need to be checked, it may be helpful to explicitly define the element axes to make sure all interface elements are oriented the same way.

[Fig. 61]

Connection properties [Fig. 61]

Figure 61: Interface - Element geometry properties
3.2.5 Perfectly Matched Layers

Because no damping is being specified in the concrete or the soil block, special boundary conditions need to be applied to prevent wave reflection at the supports. In this tutorial, perfectly matched layer (PML) boundary conditions will be used to attenuate the waves coming from the rotating machinery. The first PML zone will be placed at the same level as the soil block and will attenuate waves in horizontal directions only. The second PML zone will be placed below the first PML zone and soil block and will attenuate waves in horizontal and vertical direction.

Figure 62: Geometry - Add block

Figure 63: View - Isometric view 1
When subtracting the soil from the first PML zone it is important that the tool is kept, because the soil must remain and not be deleted!
Figure 66: Geometry - Add block

Figure 67: View - Isometric view 1
Now functions need to be defined in all three global directions for the perfectly matched layer boundary conditions. These functions need to be zero where they connect to the soil and equal to one at the supported boundaries.

Figure 68: Function PML X
Figure 69: Function PML Y
Figure 70: Function PML Z
First, the properties to the top perfectly matched layer (PML) will be attached. For three-dimensional models, the perfectly matched layers will be modeled with structural solid elements. The material properties for perfectly matched layers can be found in the soil and rock class.
For the linear elastic properties of the PML zones it is important that these match the linear elastic properties of the connected soil. Differences in properties between soil layers always result in some wave reflections! In the top perfectly matched layer only horizontal waves are being attenuated.

Figure 73: PML 1 material properties

Figure 74: PML 1 material properties
Secondly, the properties to the top perfectly matched layer (PML) will be attached. For three-dimensional models, the perfectly matched layers will be modeled with structural solid elements. The material properties for perfectly matched layers can be found in the soil and rock class.

Figure 75: Assign properties
Figure 76: Add new material - PML 2
Figure 77: PML 2 material properties

Figure 78: PML 2 material properties
The PML zones will be supported at the outer boundaries in global X, Y, and Z direction.

Figure 79: Attach Support

Figure 80: Supports PML X
Main menu ➔ Geometry ➔ Assign ➔ Supports ➔ [Fig. 81] [Fig. 82]

Figure 81: Attach Support

Figure 82: Supports PML Y
Figure 83: Attach Support

Figure 84: Supports PML Z
3.2.6 Loads

For the stress initialization in the soil, a self weight load has to be defined [Fig. 85].

Main menu ➔ Geometry ➔ Assign ➔ Global loads ➔ [Fig. 85]
The unbalance forces originated by the eccentricities of the rotating machinery are defined by four separate load cases. Each of these load cases will have a time-load history diagram attached to mimic the changing direction of the loads during rotation. For the unbalance force of the low pressure compressor, two unity loads are being set up in global $Y$ [Fig. 86] and $Z$ direction [Fig. 87].

**Figure 86: Load - LPC Y**

**Figure 87: Load - LPC Z**
For the unbalance force of the high pressure compressor, also two unity loads are being set up in global Y [Fig. 88] and Z direction [Fig. 89].

**Figure 88: Load - HPC Y**

**Figure 89: Load - HPC Z**
The forces in $Y$ and $Z$ direction as function of time $t$ for the low pressure compressor (LPC) are defined by:

\[ F_{LPC,Y} = A_{LPC} \sin(2 \pi f t) \]  
\[ F_{LPC,Z} = A_{LPC} \cos(2 \pi f t) \]

with $A_{LPC} = 80000$ N the amplitude of the unbalance force of the LPC, and \( f = 100 \) Hz the rotation frequency. These functions will be attached to the unity loads defined earlier.

Figure 90: Load low pressure compressor $Y$

Figure 91: Load low pressure compressor $Z$
The forces in $Y$ and $Z$ direction as function of time $t$ for the high pressure compressor (HPC) are defined by:

$$F_{\text{HPC},Y} = A_{\text{HPC}} \sin(2 \pi f t + \phi)$$  \hspace{1cm} (4)$$

$$F_{\text{HPC},Z} = A_{\text{HPC}} \cos(2 \pi f t + \phi)$$  \hspace{1cm} (5)$$

with $A_{\text{HPC}} = 40000$ N the amplitude of the unbalance force of the HPC, $f = 100$ Hz the rotation frequency, and $\phi = \pi/4$ the angle between the unbalance force of the LPC and the HPC. These functions will be attached to the unity loads defined earlier.

![Figure 92: Load high pressure compressor Y](image)

![Figure 93: Load high pressure compressor Z](image)
Figure 94 and Figure 95 display the load signals for the low pressure compressor and the high pressure compressor, respectively.
3.3 Meshing

For the machine foundation itself, the desired element size is set to 0.5 m [Fig. 96]. For the soil a coarser mesh with a desired element size of 2 m is defined [Fig. 97].

Figure 96: Element size foundation

Figure 97: Element size soil
For the perfectly matched layers the element size the desired element size is set to 4 m [Fig. 98]. Figure 99 shows the generated mesh for the entire model.
4 Analyses

4.1 Eigenvalue Analysis

First an eigenvalue analysis is being performed to check the model [Fig. 100]. For the eigenvalue analysis the perfectly matched layers and their supports will be inactive. This can be done by deactivating the corresponding sets in the phased analysis setting [Fig. 101]. The first ten eigenfrequencies will be calculated for the machine foundation and the soil [Fig. 102].
4.1.1 Eigenmodes

Figure 103 to Figure 112 show the first ten eigenmodes of the machine foundation and the soil. Since there are no zero or very small eigenfrequencies and the eigenmodes do not show any unexpected displacements, the model is ready for the transient dynamic analysis.

Figure 103: Mode 1  
Figure 104: Mode 2
Figure 109: Mode 7

Figure 110: Mode 8
Figure 111: Mode 9

Figure 112: Mode 10
4.2 Transient Dynamic Analysis

The transient dynamic analysis will consist of three phases [Fig. 113]:

1. **Stress initialization of the soil.** In this phase, only the soil block and the corresponding supports are active.

2. **Installation of the machine foundation.** In this phase, next to the soil and the corresponding supports, the sets belonging to the machine foundation and the soil-structure interface (SSI) are active. Note that the perfectly matched layers are not activated yet, because no time steps are being performed in this phase.

3. **Transient dynamic analysis of the rotating machinery.** In this phase, all shape sets are active. The support sets of the soil are deactivated while the supports of the perfectly matched layers are activated. The forces from the soil supports remain active as will be explained later.

Figure 114 shows the active shapes, geometry connections, and geometry support sets for each phase. For the model evaluation the default parameters are being used in each phase [Fig. 115].
Figure 113: Transient dynamic - overview

Figure 114: Active sets for transient dynamic analysis

Figure 115: Model evaluation
Further, the nonlinear effects need to be set. Next to the physical nonlinearities, which are needed for the soil, total strain based crack model of the concrete, and the no-tension behavior of the soil-structure interaction, transient effects need to be activated [Fig. 116]. Since a transient dynamic analysis is being performed, the dynamic effects need to be activated. For the perfectly matched layers, damping matrices need to be set up. Euler backward time integration is being used in combination with the perfectly matched layers [Fig. 117]. Note that these settings are applied for all phases, even when the actual transient dynamic analysis is performed in the last phase.

Figure 116: Nonlinear effects

Figure 117: Transient settings
4.2.1 Phase 1: Stress Initialization

In this phase, the stresses of the soils are being initialized [Fig. 118]. The default load step execute block is replaced by a start step output block. The initial stresses will be calculated from the linear elastic self weight load. Since there are no loads from previous phases, the only active load in this phase is the self weight. The load will be applied in a single step [Fig. 119]. The displacements from the calculated equilibrium are being suppressed, i.e. reset to zero [Fig. 120]. Default output is being used for this phase.
4.2.2 Phase 2: Installation Machine Foundation

In this phase, the machine foundation is being installed [Fig. 121]. The default load step execute block is again replaced by a start step output block. In this phase, the self weight remains active and therefore the loads from previous phase is being used. The load will be applied in a single step [Fig. 122]. Since we are not interested in the settlement of the foundation in this tutorial, the displacements from the calculated equilibrium are being suppressed, i.e. reset to zero [Fig. 123]. Default output is being used for this phase.

[Image 0x0 to 1058x595]
4.2.3 Phase 3: Transient Dynamic Analysis

In this phase, the actual transient dynamic analysis of the rotating machinery is being performed. The default load step execute block is again replaced by a start step execute block [Fig. 124]. Also in this phase, the self weight remains active and therefore the loads from previous phase are being used. The load will be applied in a single step [Fig. 125]. The reaction forces from the deactivated supports from the soil block should be remained to keep the static equilibrium after the installation of the machine foundation on the soil in phase 2. This can be done in the properties section of the start steps execute block [Fig. 127]. Since we are not interested in the settlement of the foundation, as done in the previous phase, the displacements from the calculated equilibrium of this start step are suppressed.

Further, a second execute block has to be defined for the 800 explicit time steps of 0.0005 s. The time steps are chosen such that we have 20 steps for each rotation of the machinery.
Further, a second execute block [Fig. 128] has to be defined for the 800 explicit time steps of 0.0005 s [Fig. 129]. The time steps are chosen such that we have 20 steps for each rotation of the machinery. The secant iteration method is being used, which does not set up completely new stiffness matrices every iteration, to reduce the calculation time [Fig. 130].

Figure 128: Phase 3 - transient dynamic analysis
Figure 129: Phase 3 - time steps
Figure 130: Phase 3 - secant iteration
For a transient dynamic analysis with many time steps, choices have to be made with respect to the output results. In general it will not be possible to output all results for all time steps. Therefore, output of displacements, velocities, accelerations, as well as the interface tractions and relative displacements for the soil-structure interaction and the global Cauchy stresses will be output for all steps and for the entire model [Fig. 131]. Further, the following extreme results, i.e. the minimum and maximum values over all the time steps, will be obtained: displacements to check whether the movement of the foundation stays within the prescribed boundaries; the relative displacements of the interface of the soil-structure interaction to check whether the foundation comes loose from the soil; the principal stresses to check whether the concrete of the foundation will crack or crush [Fig. 132].

Figure 131: Phase 3 - output for each step

Figure 132: Phase 3 - output of extremes
4.2.4 Stress Initialization

The first result to be checked is the stress initialization of the soil [Fig. 133 to 135] in phase 1. As expected, horizontal contour bands are visible for the uniform soil block.
4.2.5 Dynamic Displacements

The dynamic displacements at the four corners of the floor slab of the concrete machine foundation are being checked for all time steps to assure that the maximum vertical amplitude remains smaller than 80 micron. The dynamic response shows the forced vibration due to the rotating machinery with a frequency of 100 Hz superposed of the first eigenfrequency of 5.1 Hz.

Figure 136: Vertical displacement SW (node 25)

Figure 137: Vertical displacement NW (node 26)
Figure 138: Vertical displacement NE (node 27)

Figure 139: Vertical displacement SE (node 28)
4.2.6 Relative Displacement of Interface Elements

Figure 140 shows that all maximum relative displacements are negative, which indicates that the machine foundation never comes loose from the soil when the two compressors are operational.

Figure 140: Maximum relative displacements in normal interface direction
4.2.7 Maximum Tensile Stress in Concrete Frame

Figure 141 shows that the maximum occurring principal tensile stress is lower than the tensile strength of 2.9 MPa, which indicates that no cracking will occur when the two compressors are operational.

Figure 141: Maximum tensile stress in concrete
4.2.8 Minimum Compressive Stress in Concrete Frame

Figure 142 shows that the minimum occurring principal compressive stress is lower than the compressive strength of 38 MPa, which indicates that no crushing will occur when the two compressors are operational.

![Figure 142: Minimum compressive stress in concrete](image-url)
4.2.9 PML Displacements

Finally, the displacements in the perfectly matched layers are being checked after the last step, to assure that the PML zone is indeed absorbing the vibrations.

Figure 143: Total displacements TDtXYZ of PML
Appendix A  Additional Information

Folder: Tutorials/MachineFoundation

Number of elements \( \approx 11088 \)

Keywords:
- ANALYS: dynami nonlin phase physic transi.
- CLASS: large.
- CONSTR: suppor.
- ELEMEN: beam class1 hx24l interf l12be mass pipe pt3t pt15l q24if solid struct te12l tp18l.
- LOAD: force node time weight.
- MATERI: concre crack dampin elastis en1992 functi harden isotro mohrco plasti pml rotati soften soil strain struct totstr.
- OPTION: backwa direct newton nonsym regula units.
- POST: binary ndiana.
- PRE: dianai.
- RESULT: accele cauchy displa extern force green moment princi reacti strain stress total tracti veloci.
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