PROMOTING EFFICIENCY OF NLTHA USING AN INDIRECT SOIL-STRUCTURE INTERACTION MODELLING APPROACH

Huan HE¹, Sander J.H. MEIJERS², René A. VONK³

ABSTRACT

Nonlinear time-history analysis (NLTHA) of Dutch masonry buildings in the Groningen area demands a lot of efforts of modelling work but also tremendous computational capacities. Convergence is another challenge, which needs to be highly concerned in the calculation. As the most objects involve an enormous number of elements in the calculation, simplification of modelling and improvement of calculation efficiency become the big challenges for the project. Using an indirect excited structural model but considering the soil-structure interaction (SSI) seems a feasible method for the improvement. The basic idea of this method is to improve the calculation efficiency of NLTHA by reducing the nonlinearity or the size of model. The concept of this method and verification cases are presented in this paper. Meanwhile, the advantages and limitations of the method are also discussed.

Keywords: NLTHA; SSI; nonlinearity; seismic response

1. INTRODUCTION

Nonlinear time-history analysis (NLTHA) can provide inelastic seismic structural response in a moderate or strong earthquake. The material degradation caused nonlinearity as well as the geometric nonlinearity can be directly considered by this method. It, as an advanced analysis method, has been generally adopted by the major seismic codes such as Eurocode 8 (CEN, 2004), FEMA 356 (BSSC, 2000) and the new Dutch code NPR 9998: 2017 (NEN, 2017). However, extra efforts are required by this method due to the intrinsic complexity. As a result, it is still not widely adopted by the design offices.

The seismic risk in Groningen area of the Netherlands is man-made induced (by gas extraction). The frequency of the shallow earthquakes is generally increased year by year (over 20 times per year recently), which is also largely concerned by the society. Therefore, the design office Royal HaskoningDHV and the contractor Visser & Smit Bouw joined forces in a framework (called VIIA) for the seismic assessment and retrofitting design of structures in the Groningen region. NLTHA was one of the approaches utilized for the project. The majority building models in the NLTHA include 3D masonry structures supported by the 3D soil blocks. The nonlinear time-history analysis (NLTHA) of building objects in the VIIA project demands a lot of efforts of manual work but also a large numerical occupation. The unreinforced masonry structures reveal high nonlinear dynamic responses due to the high slenderness, larger openings, weak connections, etc. Meanwhile, the behavior of soil shows also significant nonlinearity under strong ground excitations. Soil-structure interaction (SSI) is a dynamic effect between foundation and soil beneath the structure. It describes the phenomenon that the response of the soil influences the motion of the structure and the motion of the structure influences

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the response of the soil. It is generally believed that SSI has a beneficial effect on the structural performance due to its flexibility and energy dissipation. However, it is not always safe to neglect the SSI in the NLTHA (Mylonakis and Gazetas, 2000). Less conservative conclusions can be possibly drawn in a NLTHA neglecting the SSI in some cases. Therefore, the whole structural model, including superstructure, soil, the interface between foundation and soil (F-S interface), is preferable in the NLTHA of the VIIA objects. However, it is hardly evitable to have a huge model in the NLTHA. Convergence is another problem concerned a lot in the calculation. As most objects involve enormous number of elements in the calculation, simplification of modelling and calculation is a big challenge. Using indirect excited model but considering the SSI effects seems a feasible method for the improvement. The recent Dutch code NPR 9998:2017 (NEN, 2017) shows an indirect SSI method for the NLTHA, which is illustrated in Figure 1. Winkler spring and dampers are added for each degree of freedom of the base of the structure. The rotational spring can be added to simulate the rocking behavior. Nonlinear site response analysis is needed for the assessment of the surface ground motion histories, which are used for the input signals for the model. However, the complexity of SSI and element properties assessment are not clearly described by this method. Furthermore, input excitation is added at the end side of spring-damper element (see Figure 1), which could also be discussed.

![Figure 1. An indirect SSI modelling method in NPR: 9998: 2017 (NEN, 2017)](image)

In this paper, an indirect SSI method for NLTHA is discussed and verified by several example applications, especially by two real VIIA objects. Some limitations and possible improvements of the method are also investigated in the report. The conclusions drawn in the study would be beneficial for the further application of the indirect SSI method and improvement of the calculation efficiency of the NLTHA for VIIA objects.

2. CONCEPT

DIANA FEA has introduced a method to incorporate the indirect SSI effects in the NLTHA (DIANA FEA, 2016). The basic concept can be illustrated by a two-step calculation workflow as Figure 2:

- Step 1: calculation of the linear superstructure with nonlinear soil blocks generally similar as the direct SSI method (the full calculation).
- Step 2: calculation of the non-linear superstructure with the achieved boundary time histories excitations from the Step 1.

![Figure 2. Concept illustration introduced by DIANA FEA (2016) for the NLTHA with the indirect SSI method](image)
In the first step calculation, the internal force-time responses of master nodes at the tyings between soil and foundation (F-S tying for a shallow foundation) or tyings between embedded pile and pile beam (P-B tying for a pile foundation) are evaluated and calculated (illustrated in Figure 3). Nodal force, nodal damping force, nodal inertia force and nodal velocity histories are extracted from the first step calculation. The calculated total force-time loading by Equation 1, will be applied for every master node of the F-S tying (for a shallow foundation) or the P-B tying (for a pile foundation) as the new excitation histories for the second step calculation.

\[
F_{X_i} = F_{X_i}^{nt} + F_{X_i}^{d} + F_{X_i}^{m} + F_{X_i}^{damper}
\]

\[
F_{Y_i} = F_{Y_i}^{nt} + F_{Y_i}^{d} + F_{Y_i}^{m} + F_{Y_i}^{damper}
\]

\[
F_{Z_i} = F_{Z_i}^{nt} + F_{Z_i}^{d} + F_{Z_i}^{m} + F_{Z_i}^{damper}
\]

\[ (1) \]

In which, \( F_{X_i}^{nt} \) is the total nodal force (by element and reinforcements) extracted from the results NODFOR TOTAL in the first step; \( F_{X_i}^{d} \) is the nodal element damping force extracted from the results NODFOR DAMPIN in the first step; \( F_{X_i}^{m} \) is the nodal element inertia force extracted from the calculation results NODFOR INERTI in the first step; \( F_{X_i}^{damper} \) is the soil damping force from the boundary soil layer, which can be calculated from the Equation 2.

\[
F_{X_i}^{damper} = c_s \cdot A_i \cdot v_{X_i}
\]

\[
F_{Y_i}^{damper} = c_s \cdot A_i \cdot v_{Y_i}
\]

\[
F_{Z_i}^{damper} = c_p \cdot A_i \cdot v_{Z_i}
\]

\[ (2) \]

In which, \( v_i \) is extracted from the nodal velocity results of VELOCI from the first step; \( A_i \) is the soil area averaged to the node \( i \); \( c_p \) and \( c_s \) are the distributed damping coefficients of shear wave and pressure wave of the surface soil layer, which can be calculated by Equation 3 and 4, respectively (NEN, 2017).

\[
c_p = \rho \sqrt{\frac{(K + \frac{4G}{3})}{\rho}} = \frac{\rho(K + \frac{4G}{3})}{\sqrt{\rho}}
\]

\[
c_s = \rho \sqrt{\frac{G}{\rho}} = \sqrt{\rho G}
\]

\[ (3) \]

\[ (4) \]

where, \( G \) is the shear modulus \( (G = \frac{E}{2(1+\nu)}) \) and \( K \) is the bulk modulus \( (K = \frac{E}{3(1-2\nu)}) \); \( \nu \) is the Poisson’s ratio; \( E \) is the Young’s modulus and \( \rho \) is the density of the soil.
3. A SIMPLE MASONRY BUILDING

A nonlinear masonry building with underneath soil blocks is used for the verification test (see Figure 4(a)). The house is based on a shallow foundation, shown in Figure 4(b). All the foundation nodes are separately tied to a number of nodes on the soil surface. Through the soil blocks and SSI effects, the acceleration history of one node in the far field and that of one master node under foundation can be compared in Figure 5. This example shows the SSI has beneficial effects on the NLTH performance of structure. For the indirect SSI method, the procedure described in Section 2 is followed. The force time histories of all the master nodes were extracted from the first step calculation and reused as the excitations for the Step 2 calculation. The displacement responses of one top corner node in two models are illustrated in Figure 6. It shows the responses of this node are almost same by NLTHA with the direct or indirect SSI methods.

![Image of a simple masonry building model for NLTHA with DIANA: (a) full model with soil blocks; (b) tying details between the foundation and soil (nodes in red are the master nodes; nodes in yellow are the slave nodes; the blue lines indicate the tying relationship)](image)

Figure 4. A simple masonry building model for NLTHA with DIANA: (a) full model with soil blocks; (b) tying details between the foundation and soil (nodes in red are the master nodes; nodes in yellow are the slave nodes; the blue lines indicate the tying relationship)

![Image of two nodes selected on the surface of soil and their corresponding acceleration time histories in the X direction](image)

Figure 5. (a) Two nodes selected on the surface of soil and (b) their corresponding acceleration time histories in the X direction

![Image of response at the top corner (Node 36348 in Figure 5(a)) of a masonry wall](image)

Figure 6. Response at the top corner (Node 36348 in Figure 5(a)) of a masonry wall
4. AN OBJECT WITH A PILE FOUNDATION

An combination masonry building of a multifunctional centrum and a primary school is selected for the test with NLTHA. The building is based on a pile foundation and built in 2010 near Groningen of the Netherlands. The full DIANA model and superstructure model can be referred to Figure 7. A nonlinear RC pile beam is added on the top of each pile, and the bottom of it is tied to the head of the pile. Translational nonlinear springs and rotational springs are added between foundation and the pile beam to simulate the shear failures and transfer the moment loading. Some no tension line interfaces are added between inner wall (outer wall leaf) and foundation. More details can be partly referred to Figure 3(b). Based on the concept of the indirect SSI method, the master nodes (bottom node of pile beam) of the tying between pile beams and embedded piles are selected as the key nodes. The force information and velocity histories are extracted from the first step calculation, which are used for the second step analysis. The major calculation performance and results by two methods (Model 1: the direct SSI method; Model 2: the indirect SSI method) are illustrated in Table 1. It shows the total calculation times of these two models are relatively similar. However, step number without convergence is greater in Model 2 compared with that of Model 1. As the calculation of Model 2 has smaller (medially 0.29 times) energy norm compared with Model 1, the calculation quality of Model 2 can still be guaranteed. More detailed comparison on the maximum structural response and damage in the masonries can also be found in Table 1. It shows the most of responses of masonry walls are similar by these two methods.

![Figure 7](image)

Figure 7. An object model in the NLTHA with DIANA: (a) full model with soil blocks; (b) superstructure with piles

<table>
<thead>
<tr>
<th>Performance</th>
<th>Model 1 (Full)</th>
<th>Model 2 (Indirect SSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No conv. steps</td>
<td>13</td>
<td>0+22=22</td>
</tr>
<tr>
<td>Calculation time</td>
<td>2.60 days</td>
<td>1.9+1.8=2.7 days</td>
</tr>
</tbody>
</table>

Table 1. The calculation performance and maximum response of masonry wall

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Maximum relative OOP X

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5
5. AN OBJECT WITH A SHALLOW FOUNDATION

A primary school object in the north of Groningen region of the Netherlands is also selected for the test. It is originally built in 1989 with a shallow foundation. In 2005, an extension of one classroom was performed in one side of building. The object was analyzed using DIANA 10.1, shown in the Figure 8. There are three types of masonries presented in the object: “Clay before 1945”, “CS 1960-1985” and “CS after 1985”. The model was already retrofitted with some measurements on two weak

Figure 8. An school object model in the NLTHA with DIANA: (a) full model with soil blocks; (b) superstructure only model
walls. The connection between foundation and soil is simulated by a non-linear interface. Comparison is also performed for the models using the direct (Model 1) or indirect (Model 2) SSI methods. The key calculation performances, *e.g.* calculation time and convergence performance, are listed in Table 2. It shows NLTHA with the indirect SSI method has its advantages on the calculation time (saving about one quarter calculation time). However, convergence performance of Model 1 is much better.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Model 1 (Full)</th>
<th>Model 2 (Indirect SSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No conv. steps</td>
<td>4</td>
<td>0+52=52</td>
</tr>
<tr>
<td>Calculation time</td>
<td>3.5 days</td>
<td>1.3+1.3=2.6 days</td>
</tr>
<tr>
<td>Maximum relative OOP X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum relative OOP Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum relative dis. Z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum crack width</td>
<td></td>
<td></td>
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</tbody>
</table>

Table 2. The calculation performance and maximum response of masonry wall
than that of Model 2 with the same criterion of energy norm ratio. This is largely due to the greater energy norm in the Model 1, which make criterion be easily satisfied. The energy norm and residual energy for all steps are presented in Figure 9. The median energy norm and residual energy of Model 1 are about 2.9 times and 13.4 times of the ones of Model 2, respectively. The maximum response and crack width contours of two models are also listed in Table 2. It shows Model 1 has larger maximum responses in all directions and crack width than those of Model 2. The response difference between Model 1 and Model 2 majorly located in some significant walls. This can also be illustrated by the displacement response histories of some representative nodes on the masonry walls in Model 1 and Model 2 (see Figure 10). It shows the response histories are quite similar for most locations of walls besides two significant walls (Wall 1 and Wall 2 in Figure 10). Maximum residual forces in two horizontal directions can be checked for the specific walls to illustrate the precision of calculation, shown in Table 3. It shows there are much larger residual forces initiated in the walls in Model 1 compared those in Model 2 (about 2 times greater in the major directions). Therefore, it indicates the calculation in Model 1 for these specific walls is less robust and conclusions can be less reliable. This is a part of limitation of NLTHA with a whole system including soil blocks, superstructure and SSI interface. Any unbalanced residual force (energy) in superstructure will not influence a lot on the convergence of full model. Therefore, there is a possibility that some less reliable results initiated in some specific walls in the full model. Results in Model 2 using the indirect SSI method seems more reliable instead.
6. CONCLUSIONS

The most objects in VIIA projects demand a huge number of elements in the NLTH calculation, which makes the calculation rather cumbersome. Using indirect soil-structure interaction (SSI) seems an applicable method for the improvement of the performance. The basic idea of this method is to improve the calculation efficiency of NLTHA by reducing the nonlinearity or the size of model. The concept of this method and verification cases are presented and discussed in this report. The following conclusions can be drawn based on the study:

1. Simple model applications show the efficiency of the indirect SSI method for NLTHA, which is also the starting point for the study.
2. In the most cases that have been investigated, application of the indirect SSI method in NLTHA reaches similar results compared with traditional NLTHA with the direct SSI method.
3. However, for some masonry walls of some objects with high non-linearity, relatively significant response differences can be found using the respective methods. This can be attributed to the difference in calculation precision. The traditional NLTHA with direct SSI method using a large amount of soil blocks may accidentally allow significant errors in the superstructure. This can be illustrated by the comparison of residual force in specific walls, which indicates that the results obtained by model with the indirect SSI method seems more reliable.
4. The indirect SSI method seems a good solution for the NLTHA of complicated objects. It likely improves the calculation efficiency, especially for the retrofitting validations. However, for objects with a relatively heavy superstructure and large non-linearity, traditional NLTHA with direct SSI is recommended for the reference purposes.

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8. REFERENCES


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