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Soil-Structure Interaction Analyses Using Cone Models

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ABSTRACT

The modeling and analysis of structures subjected to earthquake loading are well studied and understood. During an earthquake, however, the behavior of the soil under the structure plays an important role in determining the superstructure response. In most cases, the soil is not modeled and is ignored. This is due to the reason that the soil, contrary to the structure, is an infinite domain and can not be treated with the conventional models as used in structures. Cone models to represent the soil, have been developed for practical engineering applications during the last ten years. Cone models can be utilized for sites with general layering and embedment conditions, capturing all degrees of freedom. Cone models provide sufficient engineering accuracy with physical insight. Cone models can be used both in force-based methods as response spectrum and time history analyses and in displacement-based methods such as push-over calculations. In these models, the soil is represented with a series of bars and beams as one uses in the analysis of superstructures. In this paper, the development of cone models is reviewed. Further, the application of the cone models in two actual seismic retrofitting projects is demonstrated. In both cases, the retrofitting costs were reduced substantially after modeling the soil with cones.

Keywords:
Soil-structure interaction analysis; Cone models; Azadi hotel; Seismic retrofitting; Finite element models

1. Introduction

Despite radical technological advancements in recent years and the enormous computational capabilities currently available to model soil, soil-structure analyses are rarely carried out on a regular basis, in a typical engineering office.

Cone models, successfully developed over the past ten years, can be applied to model soil for practical engineering applications, in regular design offices. In this paper, we outline the history and theoretical background of cone models and conclude with several applications from our experiences in Switzerland and abroad.

2. Outlining the Problem

In earthquake engineering, the modelling of superstructures is well understood. There are established methods to model the superstructures with finite elements such as beams, shells and plates. Analytical methods such as response-spectrum analyses, time-history calculations (linear or non-linear) are also well established and widely used. Commercial software is currently being successfully applied in design offices for modelling structures subjected to earthquake loads.

The modelling of the soil, however, has not been well researched, and in regular design offices, is often neglected. Including soil in seismic analyses is consistently beneficial. In our experience, including the stiffness of the soil and the corresponding damping effect, the resulting shear forces and moments during an earthquake can be reduced up to 30%. This can lead to substantial cost reduction in seismic retrofitting.

3. Historical Background

There are several methods for soil modelling such as the boundary-element method; sophisticated finite-element methods such as the thin-layer method, and the scaled-boundary finite-element method, see Figure (1). However, despite the enormous computational capabilities which exist today, using the above methods is very time consuming and thus expensive.

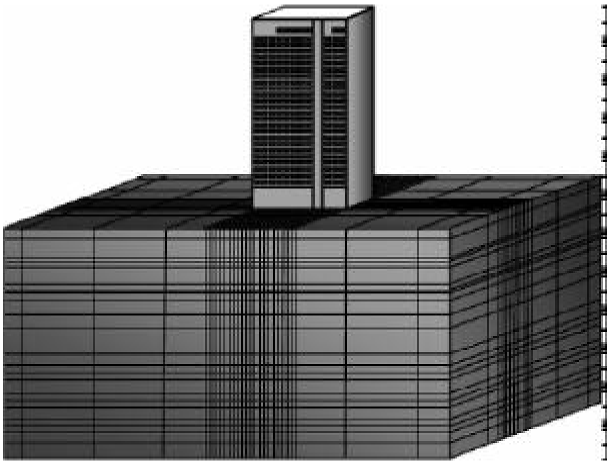


Figure 1. Finite element model of soil structure system.

In order to utilize such models, one needs excessive data preparation time, and experience, to evaluate the results. These rigorous methods should be only used for critical facilities such as nuclear power plants or dams.

For conventional use, the seismic analyses of buildings using rigorous methods can however become very expensive, and simplified procedures must be applied in these cases.

There are various simplified analysis procedures such as:

- Springs, dashpots and masses with frequency-independent parameters
- Formulations based on one-dimensional wave propagation theory
- Cone models

Cone models will be described in detail in this paper.

4. Cone Models

The development of cone models can be divided into three phases [1]:

- Phase I included the pioneer work up to the mid-1970s. In this phase, a surface foundation resting on a homogenous half-space was analysed.
- Phase II was from the 1970s up to the mid-1990s, with major developments in the mid-1990s. In this phase, the reflection and refraction of waves on material discontinuities, as exists in the case of a layer on a half-space, was addressed. Surface and embedded foundations on a layer, resting on a homogenous half-space, were modelled.
- Phase III spans from the mid-1990s to the present. In this phase, foundations resting on multi-layered sites were addressed. A general method with sufficient accuracy for a large range of practical cases was developed.

Pioneer work on cone models dates back to 1940s, based on the work done by E. Ehlers, published in the journal “Beton und Eisen” [2]. In this publication, cones were used to model a foundation on the surface of a homogenous half-space for vertical and horizontal motions. Rocking motion was explained in 1974 by Meek and Veletsos (simple models for foundations in lateral and rocking motions, *IAEE* paper [3]). Later, torsional motion was examined by Veletsos and Nair [4]. The treatment of material discontinuities at the interface of a layer to a half-space was explained in the 1990s by Meek and Wolf in the Journal of Geotechnical Engineering of *ASCE* [5] and in the 9*th* European Conference on Earthquake Engineering [6]. Reflected and refracted waves at the boundaries of layers to a half-space were traced by their own cones with cross-section properties increasing in the direction of the wave propagations. Further, an embedded foundation was also treated using stacks of embedded disks modelled with double cones.

5. Concepts of the Cone Model

The vertical, horizontal, rocking and torsional dynamic stiffnesses of a soil layer or a half-space can be captured using cone models. For example, the calculation of the vertical dynamic stiffness of a disk lying on a half-space is performed using a bar whose area increases with depth, see Figure (2). The dilatational waves propagate along the bar axis from the surface to infinity. The opening angle of the cone can be determined from the static-stiffness coefficient of the disk lying on a half-space.

The equilibrium equation for an infinitesimal element can be solved both directly in time and frequency domains. Consequently the equivalent spring stiffness and damper constants can be determined. The soil will be then replaced by a spring and a damper in the vertical direction. Detailed information is provided in Wolf and Deeks [1], Meek and Wolf [7-10], and Wolf and Meek [11-12].

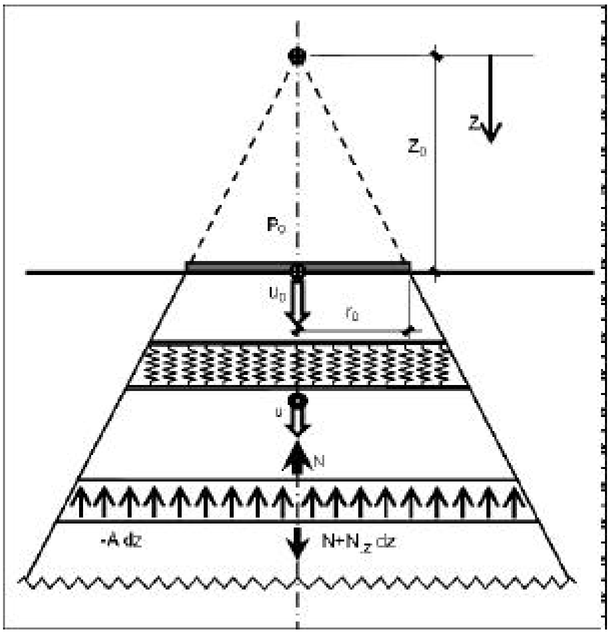


Figure 2. Soil model based on cone model.

Figure 3. The Azadi hotel.

6. Advantages of Cone Models

Cone models provide sufficient accuracy for engineering designs. A maximum difference of 20% to the results of rigorous methods can be expected using cones. Considering the vast uncertainties in determining the dynamic properties of the soil, this deviation can be accepted for practical engineering problems. Cone models satisfy physical features. For example, for a layer fixed at its base, no radiation damping occurs below the cut-off frequency. Cone models can be used for sites with general layering. They can be used for a surface foundation and an embedded foundation for all degrees of freedom. Cone models can be used for various foundation shapes. Cone models utilize simple physical and exact mathematical solutions. In many cases, when using cone models, the dynamic soil stiffness can be calculated using simple hand calculations or with a *MATLAB* Program. The cone models have postulated the wave pattern clearly. The wave reflections and refractions at the material discontinuities such as of a layer on a half-space are captured using cones.

7. Seismic Retrofitting of the Azadi Hotel in Tehran (Case Study, Example 1)

The 28-storey Azadi Hotel was built during the 1970s by a German engineering company from Stuttgart, see Figure (3). In order to determine the seismic resistance of the Azadi hotel, the lateral-force-resisting system was first identified [13]. The building is made of concrete and the preliminary resisting units for the seismic loads are the shear walls.

The building has extensive walls from the 2^{nd} floor to the 28^{th} floor. These walls partition the rooms and are made of reinforced concrete. However, the walls stop at ground level, introducing a discontinuity to the lateral load resisting system. This results in a structure with a soft storey floor.

The owner has set the seismic performance level of the building to immediate occupancy for earthquakes with a 475 year return period (*FEMA* 356). This means that the post-earthquake damage state should include very little structural damage. The basic vertical and lateral-load-resisting systems of the building should retain nearly all of the pre-earthquake strength and stiffness.

The seismic hazard due to the ground shaking is defined by the acceleration time history and response spectra. The Iranian code of practice for seismic resistance design of buildings, Standard No. 2800, prescribes a response spectrum for all Iran. The building is considered to be in a very high seismic zone.

Soil class II, according to Iranian Seismic Code 2800, has been assumed for the Azadi site in Tehran. However, a local site investigation was performed by the International Institute of Earthquake Engineering and Seismology (*IIEES*) in Tehran and a site specific spectrum was determined for the Azadi hotel.

The spectrum is applied in both translational directions for the calculation of the Azadi hotel.

For the final design, non-linear analyses with acceleration time history were performed, see Figure (4). The input time histories were provided by *IIEES* Tehran.

The columns in the lobby, which were introduced to create a commercial space in the first story, are highly critical. Such designs are not allowed in seismic zones, because a high demand is placed on these columns during earthquake loading. In buildings built in the 1970s, columns usually only have standard vertical and transverse reinforcement. In order for these columns to survive severe earthquake loading, they must have tightly spaced closed ties, which are well anchored.

An extensive finite element model was prepared for the Azadi hotel using *ADINA* software. This model (see the attached figures) includes all the structural elements of the Azadi hotel, without any simplification.

Cone models were used to determine the dynamic stiffness of the soil for the Azadi building, see Figure (5).

The dynamic stiffness of the soil was calculated using *CONAN* software. *CONAN* deals with wave propagation in cone segments, and was developed by the Swiss Federal Institute of Technology. The stiffnesses are frequency dependent. They were inputted to *ADINA* as springs and dampers to model the damping effect of the soil and the flexibility of the underlying soil. Including the soil effects reduces the loads by 17%.

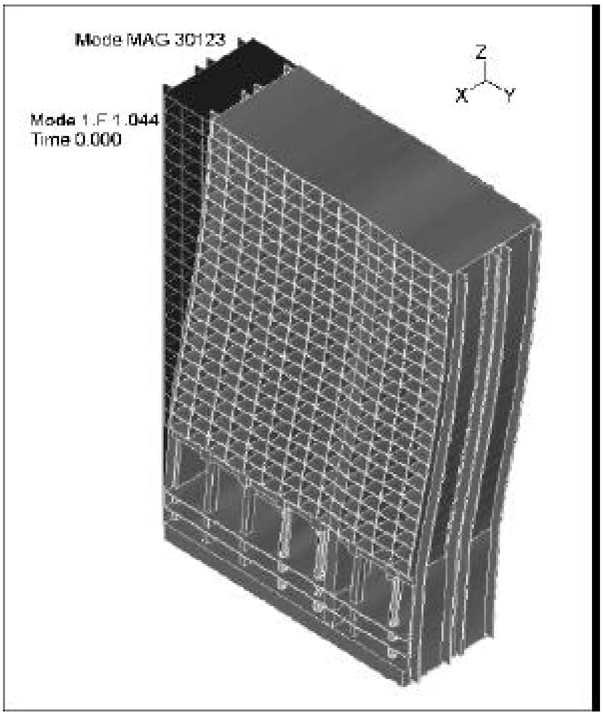


Figure 4. Three dimensional finite element of the Azadi hotel structure.

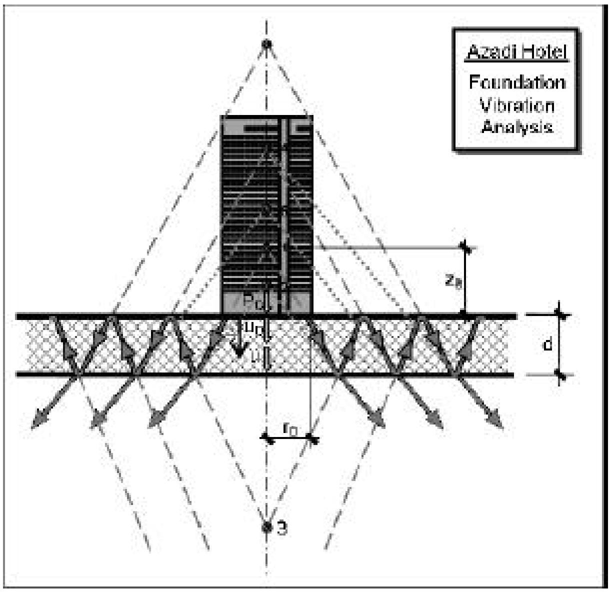


Figure 5. Earthquake waves reflections and refractions.

Column ductility is an important design criterion for the seismic retrofitting of the Azadi hotel in Tehran. Lack of ductility results in failure of the columns even in small earthquakes. The use of *FRP* on test columns has improved column ductility by a factor of eight, meaning that the column is capable of accommodating displacements that are eight times larger than of a non-retrofitted column.

The added benefit of *FRP* is the increased vertical load capacity of the columns, see Figure (6a). Testing has shown that a two-layer application of glass *FRP* on a standard cylinder increases the axial load capacity by 35 percent.

Ease of installation makes the use of *FRP* sheet a very cost-effective alternative in the seismic retrofit of existing buildings, see Figures (6b) and (6c).

The final design was to apply *FRP* along with hydraulic dampers, see Figures (7) and (8a)-(8c).

A thickness of $0.5mm$ for the walls and $0.7mm$ for the columns was assumed for the *FRP*. These layers were modeled as shell elements applied to all columns and walls in the lobby and basements.

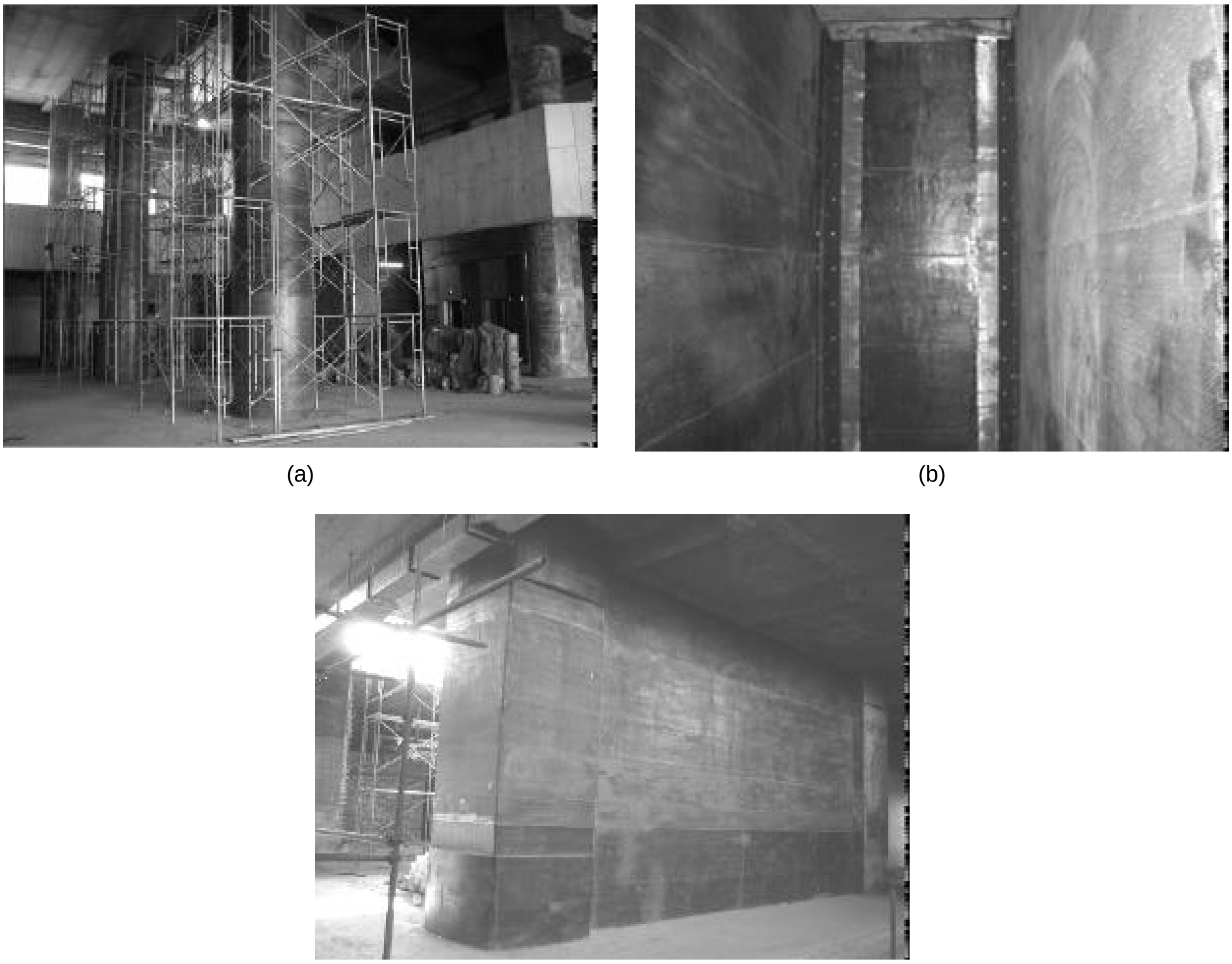
The position of the bracings is shown in the attached figure, see Figure (7). The bracings were introduced between the columns at the lobby level and their position was discussed with the owner on various visits of the site in Tehran.

The retrofitting was as follows:

- Introduction of bracings in the lobby and 1st floor.

- Introduction of hydraulic dampers to the lobby floor and on the 1st floor.
- Strengthening the columns and walls with *FRP* sheets (lobby and underground floors).

The retrofitting of the Azadi hotel was completed in March 2009.



(a)

(b)

(c)

Figure 6. FRP reinforcement of the columns in the lobby.

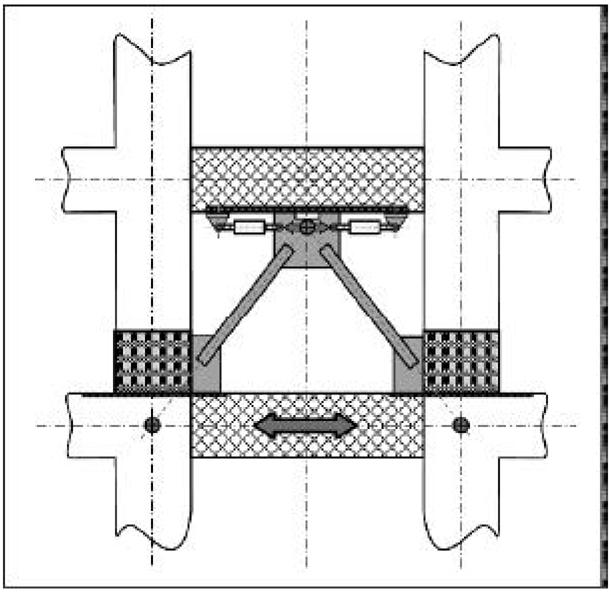
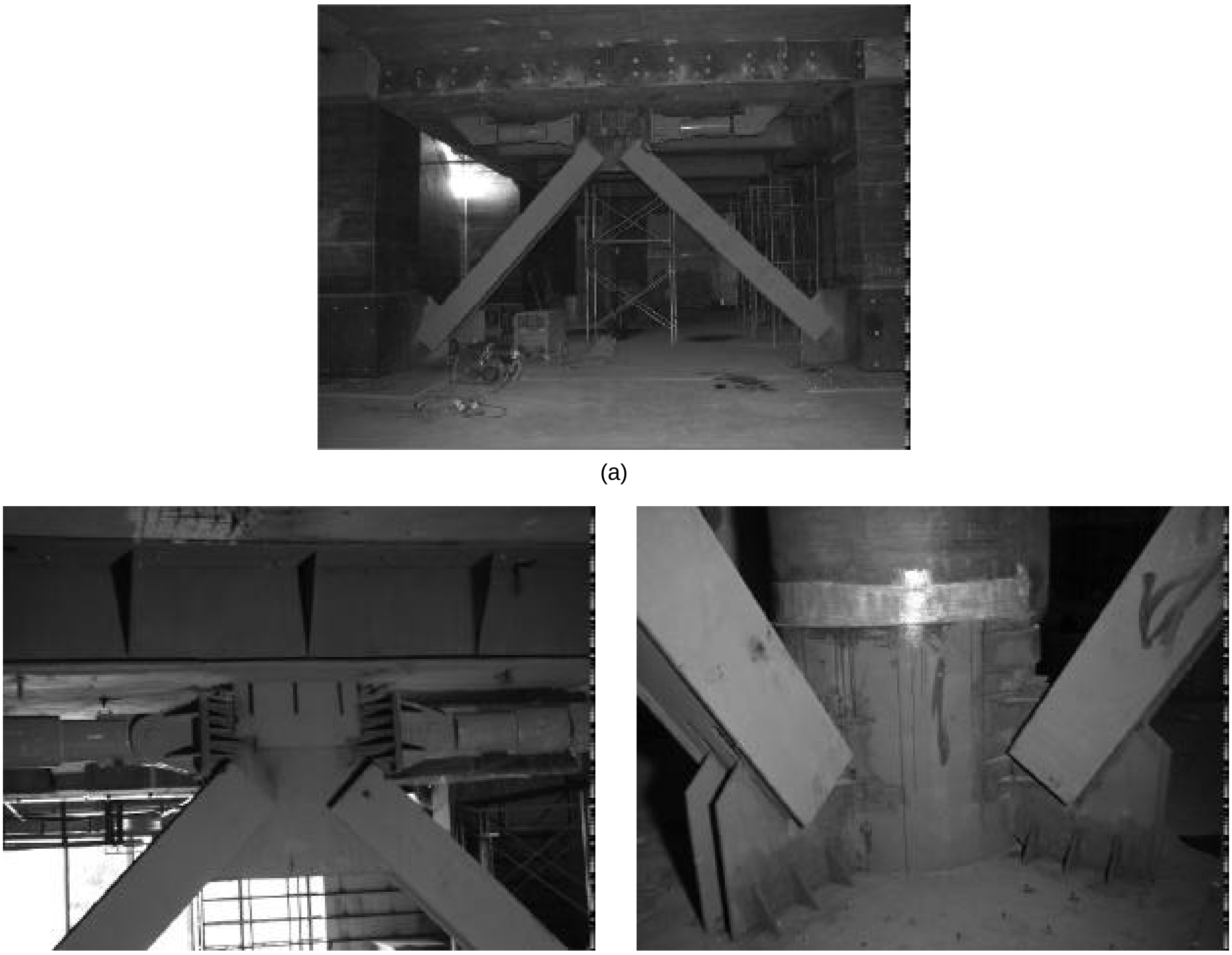


Figure 7. Dampers and bracings in lobby.

8. Seismic Retrofitting of a 4-Storey Building in South of Switzerland (Case Study, Example 2)

The behavior of a 4-storey residential building, see Figure (9), built in the early 1900s (typical of the early 1900s in the south of Switzerland), subjected to the new Swiss earthquake code, was analyzed using cone models. The exterior walls of the building are mostly made of natural stone. The interior walls are made of masonry.



(a)

(b)

(c)

Figure 8. The dampers.

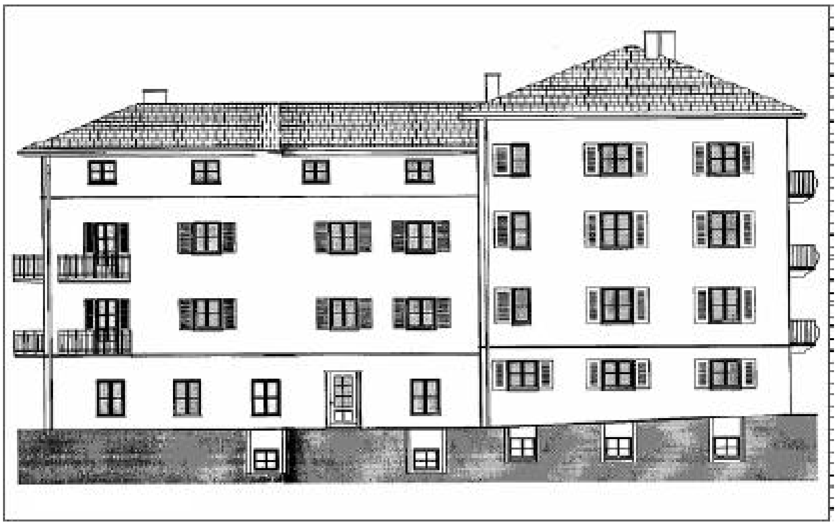


Figure 9. Administrative building.

The slabs are partly made of reinforced concrete and partly of wood. The soil consists of lake deposit, which is mostly sand and gravel. The first period of the building assuming a fixed base is 0.3 seconds. The damping of the structure is assumed to be 5%.

Displacement methods using push-over were used to evaluate the response of the building during an earthquake. Since the structure is relatively stiff, and contains massive walls and slabs, resting on soft soil, there is a strong interactive effect between the structure and the soil.

The soil's dynamic stiffnesses were calculated using cone models, utilizing *CONAN* software. Spring, and dashpot constants were determined from dynamic stiffness. The equivalent damping of the structure including soil is 6.6%. This is an increase of 32% in comparison to the fixed-base structure. Due to the soil's effect, the damping increases substantially. Further, the period of structure, including soil, increased from 0.3 seconds to 0.32 seconds. Due to the higher damping, period elongation of the earthquake load on the structure was reduced by 25%.

9. Summary

In this paper, the historical development of cone models has been addressed. Further, two practical cases have been outlined. Cone models are based on a one-dimensional strength-of-material theory using bars and beams. Cone models duplicate the dynamic behavior of soil during an earthquake using simple models. The waves are assumed to propagate in cones, and all the reflections and refractions at material discontinuities are modelled. The wave amplitude decay and corresponding damping (radiation damping) are correctly modelled using cones. Cone models are based on a simple theory and provide an exact solution for many practical cases.

Cone models can be applied to any site including many layers with surface or embedded foundations. They provide enough accuracy for typical engineering applications in regular design offices [14]. Cone models have been applied by the authors in various retrofitting projects in Switzerland and abroad. More than fifty residential buildings, hotels and industrial buildings in various conditions have been analyzed. In all cases, retrofitting costs were reduced after having modelled the soil with cones.

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