Vibration Response of Multi Storey Building Using Finite Element Modelling

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Abstract. Interaction between building, type of foundation and the geotechnical parameter of ground may trigger a significant effect on the building. In general, stiffer foundations resulted in higher natural frequencies of the building-soil system and higher input frequencies are often associated with other ground. Usually, vibrations transmitted to the buildings by ground borne are often noticeable and can be felt. It might affect the building and become worse if the vibration level is not controlled. UTHM building is prone to the ground borne vibration due to closed distance from the main road, and the construction activities adjacent to the buildings. This paper investigates the natural frequency and vibration mode of multi storey office building with the presence of foundation system and comparison between both systems. Finite element modelling (FEM) package software of LUSAS is used to perform the vibration analysis of the building. The building is modelled based on the original plan with the foundation system on the structure model. The FEM results indicated that the structure which modelled with rigid base have high natural frequency compare to the structure with foundation system. These maybe due to soil structure interaction and also the damping of the system which related to the amount of energy dissipated through the foundation soil. Thus, this paper suggested that modelling with soil is necessary to demonstrate the soil influence towards vibration response to the structure.

Keywords: Natural frequency, finite element modelling, vibration.

1. Introduction
Excessive floor vibrations have become a greater problem for the occupants. These issues had become one of the most significant challenges produces by the traffic and occupants. Structure-borne sound and vibrations from traffic in dense urban environments can cause annoyance to the inhabitants of surrounding buildings besides being disruptive to the operation of manufacturing facilities, medical facilities, and research laboratories. Individuals can detect building vibration values that are well below those that can cause any risk of damage to the building or its contents. In addition, soil structure interaction is certainly a typical subject but nevertheless still new in it applicative aspects. The interaction may leads to an increment of the fundamental period of the structure compared to the
fixed-base solution. In this study, the 3D finite element model in LUSAS was developed to perform the vibration analysis on the interaction of structure and foundation.

2. Reviews on Ground Vibration Theory
Some common sources of ground-borne vibration are trains, buses on rough roads, and construction activities such as blasting, pile-driving and operating heavy earth-moving equipment [1]. Ground borne vibration can be a serious concern for nearby neighbour of a transit system route or maintenance facility, causing buildings to shake and rumbling sounds to be heard. It is unusual for vibration from sources such as buses and trucks to be perceptible, even in locations close to major roads. The vibration being produced by the traffic propagated through the foundation of the floors and walls of a building will create resonance frequencies to the building. Hence, it will produce perceptible vibration, rattling of items such as windows or dishes on shelves, or a rumble noise. This will create the room surfaces act like a giant loudspeaker causing so called ground-borne noise. It will make the occupants in the building felt uncomfortable with the sounds in the room.

Ground borne vibration is a creation of man-made over decade ago due to the developments of road, highway and rail networks. Vehicles move on the road and the train on the railways will produce vibration to the ground. The vibration will propagate through the ground and into buildings, resulting in uncomfortable vibration and unacceptable levels of noise in the building. This is clearly investigated at the Wellington Hospital in London [2]. The building lies directly above two mainline railway tracks and within only a few metres of four underground railway tunnels and the main road. The problem related to this matters are the multiples sources of vibration produced by the train and cars propagates along the surfaces of the ground, and influenced the internal noise and vibration.

3. Soil Structure Interaction (SSI)
High vibration and unacceptable dynamic settlements could disturb sensitive devices and people and even be the cause of structural damage. The structural response to ground excitation depends on the soil response to waves propagated from the source, soil and structure [3]. Soil structure interaction is certainly a typical subject but nevertheless still new in it applicative aspects. Further studies are necessary for converting the research highlights in practical tools to be used in routine structural analysis [4]. In general, building-soil interaction consists of two parts; kinematic and dynamic (or inertial) interaction. In the inertial interaction, there are two types of dynamic analysis of soil structure interaction can be done [5]. The analyses are direct method which the soil and structure are modelled together in a single step accounting for both inertial as illustrated in Figure 1(a) and kinematic interaction. Inertial interaction develops in structure due to own vibrations give rise to base shear and base moment, which in turn cause displacements of the foundation relative to free field. Kinematic interaction develops due to presence of stiff foundation elements on or in soil cause foundation motion to deviate from free field motions as shown in Figure 1(b).

![Figure 1](image1.png)

**Figure 1.** (a) Direct method of soil structure interaction, (b) Substructure method for inertial interaction analysis [5]
According to Ceroni et.al. [4], soil structure interaction leads to an increment of the fundamental period of the structure compared to the fixed-base solution. It is also because of the damping of the system due to the amount of energy dissipated through the foundation soil (radiation damping). Cai et.al [6], Chore et.al [7] and Pulikanti and Ramanchurla [8] found that three-dimensional (3D) nonlinear finite element subsystem were developed to study the seismic soil-pile-structure interaction effects in which the plasticity and work hardening of soil have been considered as shown in Figure 2(a). Chore et.al [7] performed a methodology for the comprehensive analysis of building frame supported by pile groups embedded in soft marine clay using the 3D finite element method too as illustrated in Figure 2(b). In this study, the 3D finite element in LUSAS will be developed to perform the vibration analysis on the interaction of structure and foundation.

![Figure 2](image)

**Figure 2.** (a) Example of structure and pile foundation developed using FEM [6], (b) Typical building frame supported by group of piles [7].

4. Application of Finite Element Modelling by LUSAS software

Finite element method is a numerical method to find out an approximate solution variable in a problem which is difficult to obtain analytically [9][10]. The high-speed digital computer nowadays helps a lot in running and analyzing complex problems in continuum mechanics. A study on finite element method enable users to understand the synthesis of analysis, material behaviour, and constructability, environmental, social and economic realities that influence solutions in the practice of engineering.

LUSAS is finite element analysis software that can analyse all types of complicated models using linear or nonlinear analysis. It is an associative feature based Modeller. This means the model geometry is entered in terms of features which are then sub-divided into finite elements in order to perform the analysis. Increasing the number of elements usually increases the accuracy of the analysis but the time for the analysis to be done will also increased. In LUSAS, every element of concrete and soil must be assigned with material constant to define structure properties in term of mass density, poison ratio and modulus of elasticity. Details step by step in LUSAS are applied in this study to obtain the required natural frequency and mode shape and listed as follows [11]:

- Creating a new model
- Defining the geometry and groups
- Defining the mesh-reinforcement bars and mesh-concrete
- Defining the geometric properties and material properties
- Assigning attributes to the bars and concrete
- Assigning supports and loading
- Set the eigenvalue control and running the analysis
- Viewing the results of reformed shape and creating a load versus displacement
- Principal stress contour plots
- Viewing crack patterns and animating the results

5. Case Study: Multi Storey an Office Building
Registrar Office is a five storey building located in Universiti Tun Hussein Onn Malaysia (UTHM) campus. This office managed in the human resources and facilities for the staff [12]. UTHM campus area is surrounded by soft soil type which is low in shear strength, bearing capacity and suffers large settlements when subjected to loading. Referring to the index properties of the soil, it can be categorized as CH (Inorganic Clays of High Plasticity) according to Unified Soil Classification System [13]. The soft clay layer in the UTHM campus extends to a depth of 40m. The soft clay has high moisture content, low permeability, high compressibility, shrinks when dried and expands when wetted. Problem arises when structures are built on these soils, where under large superimposed load, significant settlements can occur if the soil is not being improved. A details structure and soil property for this model is listed in Table 1.

| Type                        | Structure with rigid base | Structure with soil considered |
|-----------------------------|---------------------------|--------------------------------|
| Beam size                   | 200x600 mm                | 200x600 mm                     |
| Column size                 | 400x400 mm                | 400x400 mm                     |
| Slab thickness              | 150 mm                    | 150 mm                         |
| Young’s Modulus             | 28 N/mm²                  | 25 N/mm²                       |
| Poison Ratio (concrete)     | 0.2                       | 0.2                            |
| Mass density (concrete)     | 2500 kg/m³                | 2500 kg/m³                     |
| Poison Ratio (soft soil)    | -                         | 0.3                            |
| Mass density (soft soil)    | -                         | 1.75 x 10³ kg/m³               |

The building has an estimated size about 54m long x 32.5m wide x 20m high. Figure 3 shows the different view of this office, which is the side view of office building, the view of the building with rigid base and also the view of the building considering the soil underneath the building. LUSAS software is used to model the existing structure using the original plan and perform the modal analysis to obtain the natural frequency and the mode shape.

![Figure 3](image_url)

**Figure 3.** (a) Office building with rigid base in LUSAS, (b) Side view of multi storey Registrar office building, (c) Office building considering the soil underneath the building in LUSAS [14].
6. Natural Frequency Analysis

The end results of the modal analysis by LUSAS were produced tenth modes with the natural frequencies and maximum deflection of each mode. The first mode of the structure with rigid base obtained the natural frequency of 1.203 Hz and the maximum deflection is 0.047 mm as shown in the Figure 4(a), while the first mode of structure considering the soil underneath the building has the natural frequency of $0.7850 \times 10^{-5}$ Hz and the maximum deflection is 0.04235 mm as shown in Figure 4(b). The other values of natural frequency and maximum deflection from mode 1 until mode 10 are shown in the Table 2. It can be seen that the natural frequencies are decreased when the structure is modelled considering the soil underneath the building. It shows that the influence of interaction between the structure and the foundation system produce the stiffer structure due to the mass is also increased. This is also due the combined effect of translational and rotational simulating soil deformability as stated by Ceroni [4]. The effect cannot be neglected; however it depends on the characteristics of the structure itself including stiffness, height and also the foundation of soil properties.

![Figure 4](image-url)

**Figure 4.** (a) Mode shape of the structure with rigid base, (b) Mode shape of the structure with considering the soil underneath the building.
Table 2. The first tenth mode for the system.

| Mode | Structure with rigid base | Structure with soil considered |
|------|---------------------------|--------------------------------|
|      | Frequency (Hz) | Max. Displacement (mm) | Frequency (Hz) | Max. Displacement (mm) |
| 1    | 1.203          | 0.0470                  | 0.7850x10^{-5} | 0.04235                  |
| 2    | 1.283          | 0.0324                  | 0.9188x10^{-5} | 0.06152                  |
| 3    | 1.583          | 0.0652                  | 0.9627x10^{-5} | 0.04640                  |
| 4    | 3.297          | 0.1235                  | 0.9783x10^{-5} | 0.04145                  |
| 5    | 3.324          | 0.1242                  | 0.9971x10^{-5} | 0.04863                  |
| 6    | 3.605          | 0.0303                  | 0.1118x10^{-4} | 0.04068                  |
| 7    | 3.623          | 0.0306                  | 0.1128x10^{-1} | 0.01071                  |
| 8    | 3.938          | 0.0596                  | 0.1208x10^{-1} | 0.0001065                |
| 9    | 4.004          | 0.2816                  | 0.1281x10^{-1} | 0.0001611                |
| 10   | 4.269          | 0.4517                  | 0.2232x10^{-1} | 0.0001751                |

7. Mode Shape Analysis

Ten Eigen value are analysed to get the different types of mode shapes, natural frequencies and maximum deflection. Mode shape analysis is used to determine the condition of the floor structure of the building when subjected to different frequency modes. The red area represented the highest peak displacement while the minimum displacement is represented by the blue area. Green areas were experiencing a lower displacement and not so obvious deformed. For areas with the maximum deflection, it is not suitable to accommodate the sensitive equipment and might be annoyed the occupants around this area. Figure 5 indicated tenth mode shape pattern of the building with rigid base and also with soil considered. It can be seen that obvious differences on structure deformation occurred for both systems. For lower modes and natural frequencies, the structure considering the soil underneath the building does not affected too much for the deformation of soil component. However, the soil starts to response and deform up to mode 7 and above, while the structure shows no response. The natural frequencies value also increased starts at mode 7 at 0.01128 Hz.
| Mode | Natural Frequency |
|------|------------------|
| 4    | 3.297 Hz         |
| 9    | 4.004 Hz         |
| 4    | 0.0000098 Hz     |
| 9    | 0.01282 Hz       |
| 5    | 3.324 Hz         |
| 10   | 4.269 Hz         |
| 6    | 0.00011 Hz       |
| 10   | 0.02233 Hz       |

**Figure 5.** The mode shape pattern up to tenth mode of the structure (a) Structure with rigid base, (b) Structure with soil considered.

8. Conclusions

The main aim of this study is to investigate the vibration performance of multi-storey office building considering the soil underneath the building. The comparison of natural frequencies and mode shape pattern also has been done for the structure with rigid base and with soil considered. From the results obtained, it can be finalised that the structure with soil considered are the main factors of the decreased value in natural frequencies upon the structure. The stiffness and mass of the structure is increased after modelling with the soil, hence it is reduced the value of natural frequencies compared to the structure with rigid base. As a structure was modelled and analysed as a one frame structure, it shows that the interaction between structure and foundation greatly influenced the stiffness, mass of the system and also the natural frequencies and mode shapes. Therefore, in conclusion, modelling with soil is necessary to demonstrate the soil influence towards vibration response to the structure.

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