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Impact of Groundwater Level Change on Natural Frequencies of RC Buildings

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Abstract: Structural health monitoring (SHM) provides an opportunity to assess and predict changes in the technical condition of structures during the operation of a building. Structural damage, as well as several operational and environmental conditions, causes changes in modal parameters. Temperature is the most popular environmental condition which is used for research. However, to the authors' knowledge, this is the first investigation that highlights the effect of groundwater level change on the natural frequencies of the buildings and the impact of possible damage detection features. Groundwater level change can influence structural health monitoring measurements and cause faulty structural damage identification using vibration-based methods. This paper aims to analyse the impact of the groundwater level changes on the modal parameters of mid-rise reinforced concrete buildings. The modal parameters of mid-rise reinforced concrete buildings are determined using finite element (FE) models. Three different FE models of structural system types of nine-storey reinforced concrete (RC) buildings with shallow foundations are used to determine the impact of groundwater level fluctuation on the values of the buildings' natural frequencies. Changes in the groundwater level have an impact on the natural frequencies of the mid-rise reinforced concrete buildings. This research proposes a new environmental condition that has to be considered to identify the structural damage using the vibration-based method. It is found that groundwater level rise causes a decrease in the natural frequency value. In this research, it is established that the influence of the groundwater level on the natural frequencies of the buildings can change abruptly, and there is a non-linear correlation between groundwater level change and natural frequencies of the buildings. The natural frequencies of the buildings can change under varying environmental conditions as well as in the case of structural damage. To identify structural damage in the long-term structural health monitoring measurements, it is recommended to select features which are sensitive to structural damage but are not affected by groundwater level change. Data normalisation and elimination using linear correlation methods can be used for short-term SHM under varying seasonal groundwater level change.

Keywords: finite element method; environmental impact; reinforced concrete buildings; natural frequencies; groundwater level; structural health monitoring

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1. Introduction

Structural safety is one of the most important issues during the designing and operation of a building. Structural damage can be defined as changes in the properties of the materials, structural changes, or changes in boundary conditions that affect structural element performance and operational life.

The structural monitoring includes observation of structure technical condition by periodic measurements at a specific time and the determination of damaged structures to

assess the technical state of the existing building structures. In the long term, structural monitoring provides periodically updated information on the ability of structures to continue their intended function, taking into account the inevitable aging of structures and damage caused by the operating environment [1].

The development of structural health monitoring (SHM) is closely related to the development of digital computing equipment. Developments in structural monitoring have been observed in the last 30 years. In the investigations of [2], a growing interest in identifying construction damage is demonstrated. Meanwhile, these studies identified many technical challenges for adapting SHM in practice.

Structural damage causes changes in modal parameters. These changes are different for each modal parameter. Structural monitoring [3] most frequently investigates changes in frequencies, mode shapes, and damping ratios. In order to use vibration-based methods [4] in the monitoring of building structures, it is important to know the modal parameters of the structures.

In [5], Salawu presented an overview of the use of modal frequencies in the identification of structural damage. The observation that changes in structural properties causes changes in frequency was an incentive to use modal methods to identify damage.

However, modal parameters of the structures during construction and operation of the building are also affected by several environmental factors. These factors may vary depending on the type of building structure, location of the building site, and other aspects. Temperature, humidity, geological features, as well as non-bearing structures affect the modal parameters of the structures and may cause incorrect identification of the damage. Suppose the impact of these variables is greater than or comparable to the impact of the structural damage on the modal parameters. In that case, it is difficult to accurately identify the structural damage.

Worden et al. [6] points out that natural frequencies provide an effective indication of structural damage; however, one of the disadvantages is that the frequencies may vary due to environmental or operational conditions.

The study, which obtained data on the modal parameters of a 22-storey reinforced concrete (RC) building every day for a period of one year, determined the environmental impact. The study observed a high correlation between natural frequencies and ambient temperature. The differences between the minimum and maximum natural frequencies in mode shapes were 15.8%, 11%, and 7.13%. The paper also determined that relative humidity is a factor influencing natural frequencies [7].

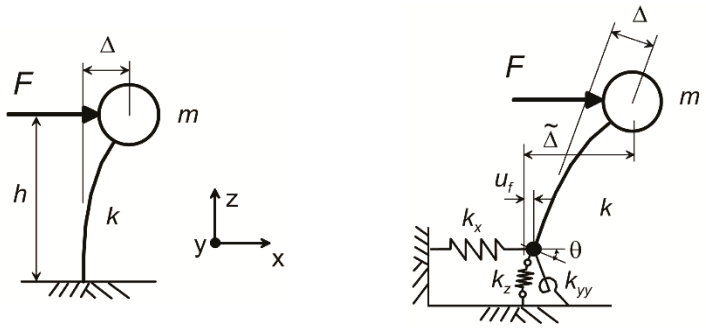
Gargaro and Rainieri [8] present the impact of temperature on natural frequencies in structural monitoring of a hospital building in Campobasso, Italy. The results of the study indicate the importance of reducing the impact of environmental factors to effectively detect structural damage. In fact, the impact of the thermal variation is more relevant to the mode shapes in longitudinal and torsional directions than in the transverse direction.

Butt and Omenzetter [9] investigated modal parameters of buildings, including soil elasticity and the impact of non-bearing structures, and emphasised the importance of soil and non-bearing structure modelling in the calculation model of a building providing quantitative data for the monitoring of the technical condition of structures. Including soil impact [9] in the calculation model, the natural frequencies were reduced by 21%, 25% and 20% of the reference model variant, therefore, indicating a soil impact on the modal parameters. It was found that soft soil affects the mode shapes and even modifies the modal shapes, thus deriving vertical oscillations [10].

The soil impact on the modal parameters is assessed using flexible base analysis. This analysis considers the compliance of both the foundation elements and the soil.

Fixed base structure (Figure 1a) refers to a combination of rigid foundation elements on a rigid base. Then a static force F causes structure with stiffness k and mass m deflection Δ on a fixed base:

$$\Delta = F/k \quad (1)$$



(**a**) (**b**)

Figure 1. Schematic illustrations of deflection caused by applied force to: (**a**) fixed-base structure; and (**b**) flexible base structure [11].

However, a flexible base (Figure 1b) structure is a structure with vertical, horizontal and rotational flexibility at its base representing the impact of soil flexibility. If a force F is applied to a structure resting on a flexible base, then the total deflection [11] with respect to the free field at the top of the structure, Δ_{fl}, is:

$$\Delta_{fl} = F/k + F/k_x + (F \cdot h/k_{yy}) \cdot h \quad (2)$$

k_x—horizontal stiffness in the x-direction,
k_{yy}—rotational spring stiffness, representing rotation in the x-z plane (about the y-y plane),
h—structure height.

Then an expression for flexible base period T_{fl} is given by Veletsos and Meek [10], is obtained as:

$$T_{fl}/T = (1 + 1/k_x + (k \cdot h^2)/k_{yy})^{0.5} \quad (3)$$

Foundation springs depend on the characterisation of the soil stratigraphy—soil types, layer thicknesses, groundwater and rock depth. Shear strength parameters vary depending on the depth. Below the groundwater level, undrained strength parameters are required. Drained strength parameters are generally acceptable above the groundwater level [11].

In 1943 Terzaghi intuitively suggested that when dry sand becomes saturated, the soil stiffness (Young's modulus) reduces by approximately 50%. Effective vertical stress on soil under the water level reduces roughly to half, which reduces the effective confining stress by 50%. This reduction causes the loss of saturated soil stiffness by 50% compared to the dry condition, and settlement of the building in the soil below the water level is doubled [12].

Fluctuations of the groundwater level cause changes in several characteristics of the soil layers. The groundwater level depth from the ground surface affects the bearing capacity and deformation of the soil, and also the stability and solidity of the foundations. Primarily, deformations of cohesive soils are affected by the position of the water level [13].

Changes in the groundwater level are determined by the amount of atmospheric rainfall, air temperature, rock lithological composition and the degree of drainage of the site [14]. The level is also affected by intense water exploitation in urban areas, building material careers, water reservoirs, amelioration systems and other objects. However, the groundwater level is slightly affected by these technogen activities, while the meteorological conditions impact the seasonality of groundwater levels. The cyclical nature of feeding changes in groundwater levels is divided into four parts: winter drop, spring rise, summer fall and autumn rise. The ranges of seasonal variation depend on the lithological composition of water-containing sediments. Level changes in sandy and clayey sediments are of a different nature. Fluctuations of the groundwater level are observed faster and are more pronounced in sandy soils with a lower content of clayey sediments.

The study [14] that compiled the data about the difference in groundwater levels of the various observation stations (Figure 2) indicate long-term groundwater level fluctuations—periods with low water levels are replaced by periods with rising levels. Also, groundwater levels in individual wells of the observation stations indicate the different nature of changes. Some observation stations show local changes in groundwater level that have not been explained by changes in atmospheric precipitation but by local influences.

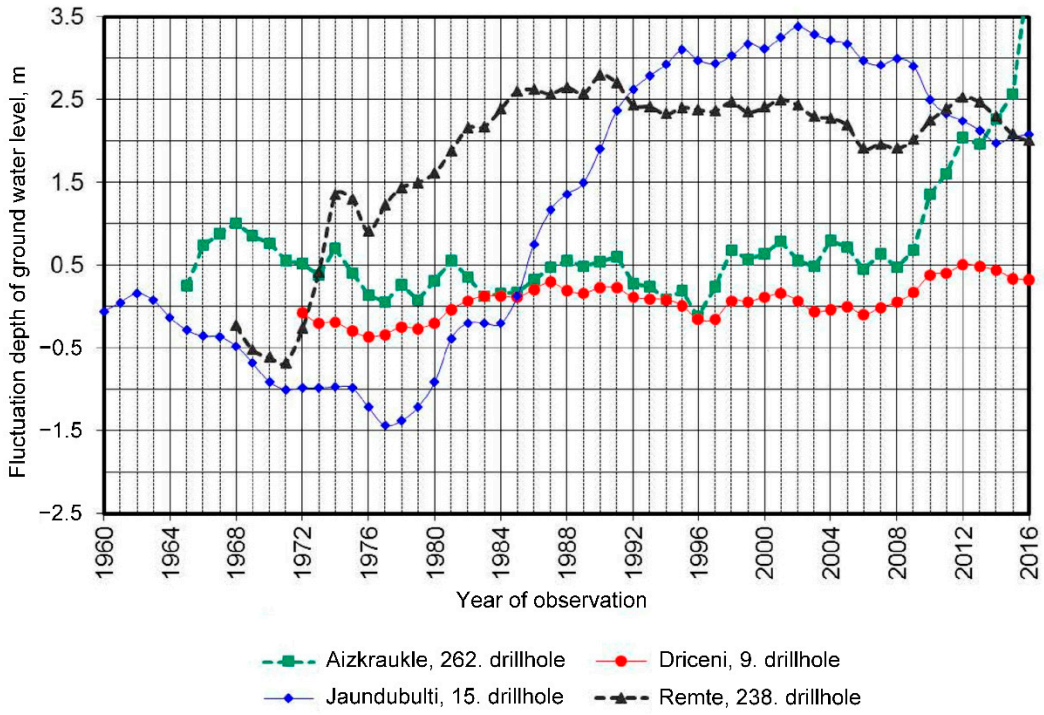


Figure 2. Groundwater level change in the various observation stations during the long-term period [14].

To summarise, it is important to include environmental and operational condition effects in SHM to precisely detect structural damage. Environmental impacts on modal parameters are not static, and they are changing under different circumstances. Also, the impact on the variations on the modal parameters may be higher than in the case of structural damage.

This paper investigates changes in the natural frequencies under varying environmental conditions, for example, fluctuations of the groundwater level.

It is found that the rise of the groundwater level leads to the decrease of the natural frequencies of the buildings. The impact on the natural frequencies depends on the soil structure, and the impact on the structural system of the buildings is different. It was observed that the influence of the groundwater level on the natural frequencies of the buildings could change abruptly, and there is a non-linear correlation between the features.

This research proposed a new environmental condition that has to be considered to identify the structural damage using the vibration-based method.

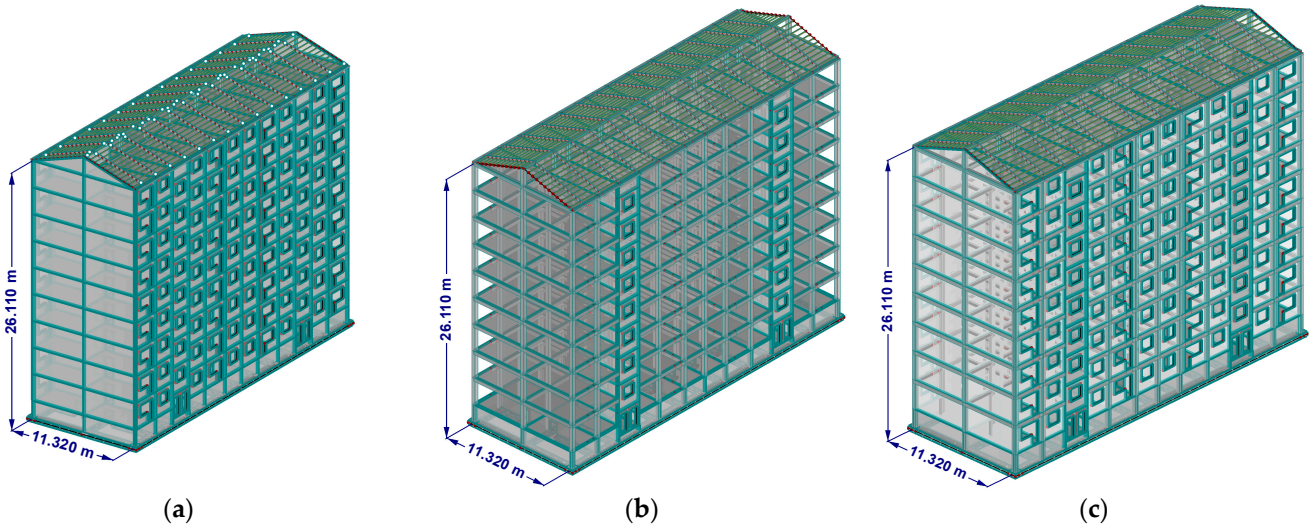
2. Materials and Methods

In SHM it is important to separate changes caused by structural damage from changes caused by varying operational and environmental conditions. Data acquisition and normalisation in measurements under varying conditions are very important in the identification of structural damage.

Changes in modal parameters caused by operational and environmental conditions, such as temperature or humidity, can vary depending on climate characteristics, exact time of the day, and other factors. Many researchers have studied the soil impact and assessment

in SHM measurements. In these studies, it was presumed that the soil impact is static, and it does not change within a certain amount of time. As mentioned above, soil parameters can be changed during short-time or long-time periods depending on various factors.

This paper investigates variable soil effect impact on modal parameters of the buildings due to groundwater level fluctuation. Ninety finite element model (FEM) cases were performed to determine the impact of the groundwater level fluctuation on the modal parameters of the medium-rise buildings. Three different structural system type finite element (FE) models of nine-storey RC buildings with shallow foundations were developed and calculated using the structural FE analysis software Dlubal RFEM and RF-SOILIN add-on module. Numerical simulations have been developed using linear elastic analysis. FE model type A is RC cellular structure building, FE model type B is RC beam and column structural system with two rigidity cores, and FE model type C is a framed RC beam and column structural system building with lightweight shear infill walls and two rigidity cores. These three types of building are common structural systems for mass housing, especially in Eastern Europe. The structural column cross-section is square 350 × 350 mm^2, bearing wall thickness is 300 mm, slab thickness is 100 mm and lightweight shear wall thickness is 200 mm. Building types are shown in Figure 3.



(**a**) (**b**) (**c**)

Figure 3. Finite element (FE) model types: (**a**) FE model type A; (**b**) FE model type B; (**c**) FE model type C.

The stiffness and damping properties of the soil are modelled using vertical and horizontal springs. Springs are calculated for each soil type using RFEM soil-structure interaction analysis. The program determines the spring coefficients in each finite element. For FE model type C (framed RC beam and column structural system building with lightweight shear wall infill and two rigidity cores), masonry infill has been included in the appropriate manner in the finite element model [15]. For the calculation, it was considered that the foundation base vertical spring values are variable due to soil parameter changes, but horizontal foundation base springs are 70% of the vertical spring value. The value of the applied load was equal for all FEM model simulations. Groundwater level fluctuation caused stiffness changes on the foundation base.

The range of soil parameters was chosen based on typical characteristics of soil reported in the literature [16,17]. Soil type 1 is dense sand layers soil structure, Soil type 2 is clay and sand layers soil structure and Soil type 3 is dense sand layers soil structure with an attenuation peat layer. Input parameters for FEM calculation are presented in Tables 1–3.

Table 1. Description of soil type 1.

Soil Description	Soil Layer Parameters					
	Specific Weight		Modulus of Elasticity, [MN/m^2]	Poisson's Ratio ν	Thickness, m	Ordinate from Ground Level, m
	γ, kN/m^3	γ_{sat}, kN/m^3				
Sand, closely graded	17.0	19.0	30.0	0.30	0.80	0.80
Sand	19.0	21.0	30.0	0.30	2.50	3.30
Dusty sand	18.0	20.3	18.0	0.30	3.50	6.80
Sand, gravelly sand	18.0	20.0	20.0	0.30	7.20	14.0

Table 2. Description of soil type 2.

Soil Description	Soil Layer Parameters					
	Specific Weight		Modulus of Elasticity, [MN/m^2]	Poisson's Ratio ν	Thickness, m	Ordinate from Ground Level, m
	γ, kN/m^3	γ_{sat}, kN/m^3				
Sand, closely graded	17.0	19.0	30.0	0.30	0.80	0.80
Sand	19.0	21.0	30.0	0.30	2.50	3.30
Clay, low plasticity	19.0	19.5	2.50	0.42	3.50	6.80
Sand-clay mixture	18.0	19.0	10.0	0.35	7.20	14.0

Table 3. Description of soil type 3.

Soil Description	Soil Layer Parameters					
	Specific Weight		Modulus of Elasticity, [MN/m^2]	Poisson's Ratio ν	Thickness, m	Ordinate from Ground Level, m
	γ, kN/m^3	γ_{sat}, kN/m^3				
Sand, closely graded	17.0	19.0	30.0	0.30	0.80	0.80
Sand	19.0	21.0	30.0	0.30	2.50	3.30
Peat	10.40	10.40	1.0	0.40	0.30	3.60
Dusty sand	18.0	20.3	18.0	0.30	3.2	6.80
Sand, gravelly sand	18.0	20.0	20.0	0.30	7.2	14.0

The groundwater level of the reference FE model was chosen −2.1 m from the building ground level, and the fluctuation step of the groundwater level was 20 centimetres. The impact of the groundwater level change on modal parameters for each soil type and FE model type was calculated as a difference between the reference FEM natural frequency and the calculated FEM natural frequency value of the next fluctuation step of groundwater level:

$$\Delta f_i = f_{1i} - f_{2i} \quad (4)$$

Δf_i—natural frequency difference for mode i,
f_{1i}—natural frequency of reference FEM groundwater level for mode i,
f_{2i}—natural frequency of FEM of next fluctuation step of groundwater level for mode i.

3. Results

Calculations were undertaken for each groundwater level depth for three types of soil structure and three types of building structural system in order to investigate the groundwater level impact on the first natural frequencies of the reinforced concrete buildings.

It was found that groundwater level rise has an impact on modal parameters of the buildings, such as natural frequencies. Impact on modal parameters differs from building mode and soil structure. Various soil structures have a different impact on the natural frequencies of the buildings in a specific mode. For FE model type A and model type C, for

comparison, we took natural frequencies in first transverse mode, first longitudinal mode and first torsional mode. However, for FE model type B we took natural frequencies in the first longitudinal mode, first torsional mode and second torsional mode.

Groundwater level change has an impact on first natural frequencies in first transverse mode and first longitudinal mode for FE model type A, reached 2.5% difference in Soil type 2 (Figures 4 and 5). However, in the first torsional mode difference between reference groundwater level and fluctuation step, FE model natural frequencies reached 0.05%. Groundwater level rise decreases natural frequencies values to 1.1 m level where frequencies value increases. A groundwater level at −1.3 m reached foundation base level and in graphs the change of natural frequencies had a peak value here. After the level −1.1 m, natural frequencies values continued to decrease (Table 4).

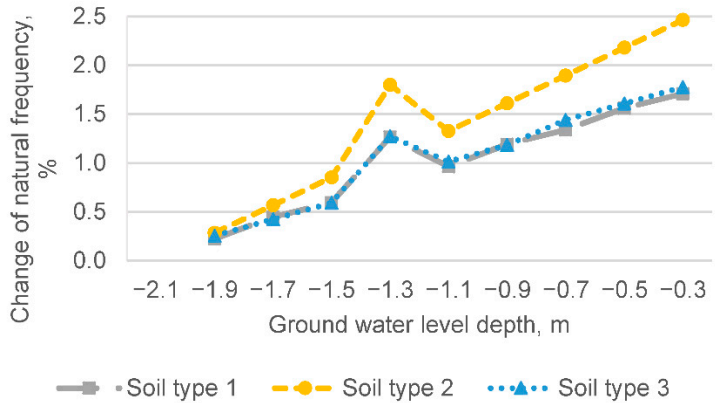


Figure 4. Difference of the natural frequencies of FE model type A in the first transverse mode for three different soil types.

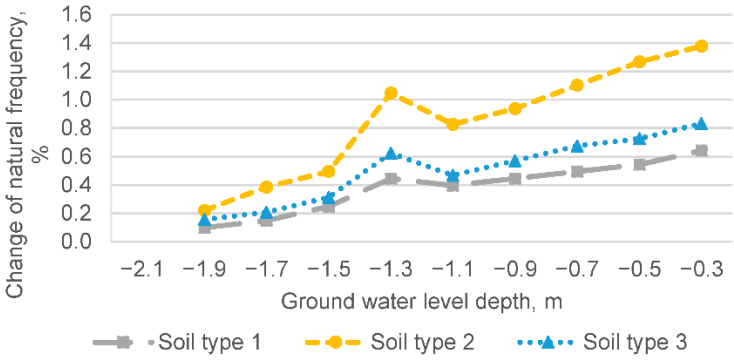


Figure 5. Difference of the natural frequencies of FE model type A in the first longitudinal mode for three different soil types.

Table 4. Difference of the natural frequencies due to groundwater level depth fluctuation for FE model type A.

Soil Type No.	Vibration Mode of FEM of Reference Groundwater Level, (Natural Frequency, Hz)	Groundwater Level Depth from Ground Level, m								
		−1.9	−1.7	−1.5	−1.3	−1.1	−0.9	−0.7	−0.5	−0.3
		Difference of the Natural Frequency Δf_i, %								
1	1st transverse mode (1.348 Hz)	0.22	0.45	0.59	1.26	0.96	1.19	1.34	1.56	1.71
	1st longitudinal mode (2.023 Hz)	0.10	0.15	0.25	0.44	0.40	0.44	0.49	0.54	0.64
	1st torsional mode (2.174 Hz)	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table 4. *Cont.*

Soil Type No.	Vibration Mode of FEM of Reference Groundwater Level, (Natural Frequency, Hz)	Groundwater Level Depth from Ground Level, m								
		−1.9	−1.7	−1.5	−1.3	−1.1	−0.9	−0.7	−0.5	−0.3
		Difference of the Natural Frequency Δf_i, %								
2	1st transverse mode (1.056 Hz)	0.28	0.57	0.85	1.80	1.33	1.61	1.89	2.18	2.46
	1st longitudinal mode (1.816 Hz)	0.22	0.39	0.50	1.05	0.83	0.94	1.10	1.27	1.38
	1st torsional mode (2.167 Hz)	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05
3	1st transverse mode (1.184 Hz)	0.25	0.42	0.59	1.27	1.01	1.18	1.44	1.60	1.77
	1st longitudinal mode (1.925 Hz)	0.16	0.21	0.31	0.62	0.47	0.57	0.68	0.73	0.83
	1st torsional mode (2.169 Hz)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

For FE model type B, groundwater level change has an impact on natural frequencies in the first longitudinal mode, first torsional mode, and second torsional mode that reached a 1.5% difference in Soil type 2 (Figures 6–8). Groundwater level rise decreases natural frequency values as non-linearly related features (Table 5).

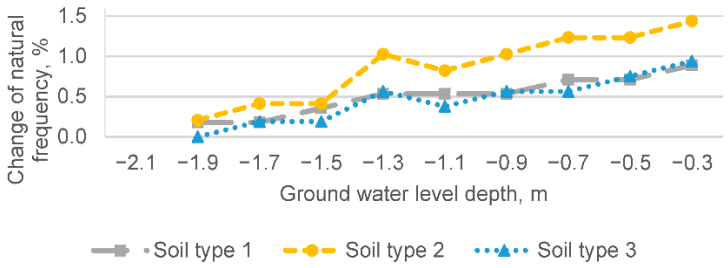


Figure 6. Difference of the natural frequencies of FE model type B in the first longitudinal mode for three different soil types.

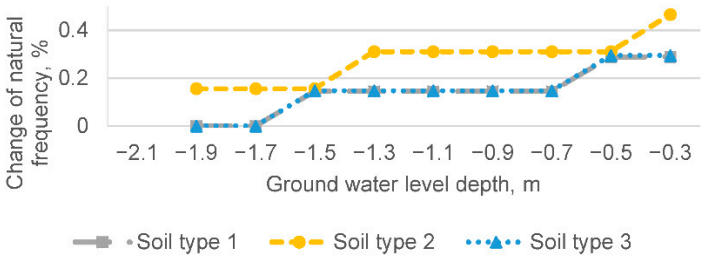


Figure 7. Difference of the natural frequencies of FE model type B in the first torsional mode for three different soil types.

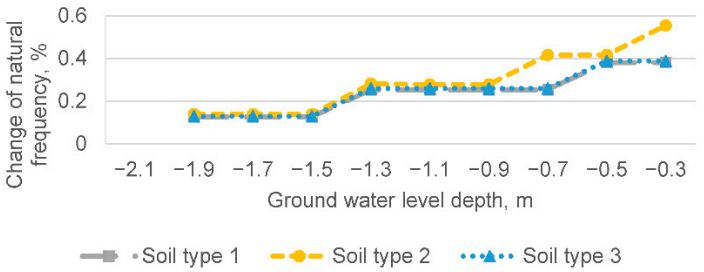


Figure 8. Difference of the natural frequencies of FE model type B in the second torsional mode for three different soil types.

Table 5. Difference of the natural frequencies due to groundwater level depth fluctuation for FE model type B.

Soil Type No.	Vibration Mode of FEM of Reference Groundwater Level (Natural Frequency, Hz)	Groundwater Level Depth from Ground Level, m								
		−1.9	−1.7	−1.5	−1.3	−1.1	−0.9	−0.7	−0.5	−0.3
		Difference of the Natural Frequency Δf_i, %								
1	1st longitudinal mode (0.563 Hz)	0.18	0.18	0.36	0.53	0.53	0.53	0.71	0.71	0.89
	1st torsional mode (0.691 Hz)	0.00	0.00	0.14	0.14	0.14	0.14	0.14	0.29	0.29
	2nd torsional mode (0.789 Hz)	0.13	0.13	0.13	0.25	0.25	0.25	0.25	0.38	0.38
2	1st longitudinal mode (0.487 Hz)	0.21	0.41	0.41	1.03	0.82	1.03	1.23	1.23	1.44
	1st torsional mode (0.643 Hz)	0.16	0.16	0.16	0.31	0.31	0.31	0.31	0.31	0.47
	2nd torsional mode (0.722 Hz)	0.14	0.14	0.14	0.28	0.28	0.28	0.42	0.42	0.55
3	1st longitudinal mode (0.532 Hz)	0.00	0.19	0.19	0.56	0.38	0.56	0.56	0.75	0.94
	1st torsional mode (0.678 Hz)	0.00	0.00	0.15	0.15	0.15	0.15	0.15	0.29	0.29
	2nd torsional mode (0.773 Hz)	0.13	0.13	0.13	0.26	0.26	0.26	0.26	0.39	0.39

Building model types have different stiffness and different mass values. Therefore, also groundwater level change impact on natural frequencies of the building has considerable disparity. For example, the global bending stiffness value difference for cellular structure and frame structure is around 85%. This explains the difference of 1st natural frequency for model type A and model type B.

For FE model type C, groundwater level change impact is similar to FE model A simulation. Changes are observed on the first natural frequencies in the first transverse mode and first longitudinal mode, reaching a 2.5% difference in soil type 2 (Figures 9 and 10). Also, in the first torsional mode, the difference between the natural frequencies of the FE model of reference groundwater level and FE model of the next groundwater level fluctuation step reached 0.05% and groundwater level rise decreased natural frequencies values until the 1.1 m level where frequencies value increased. After 1.1 m, natural frequencies values continued to decrease (Table 6).

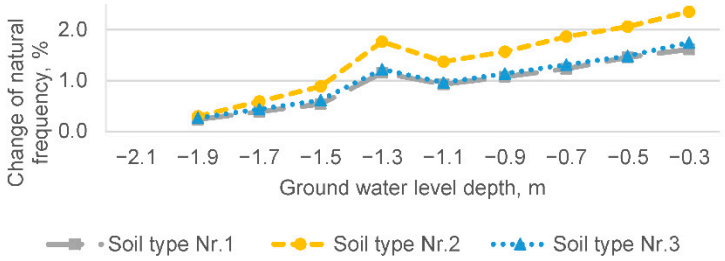


Figure 9. Difference of the natural frequencies of FE model type C in the first transverse mode for three different soil types.

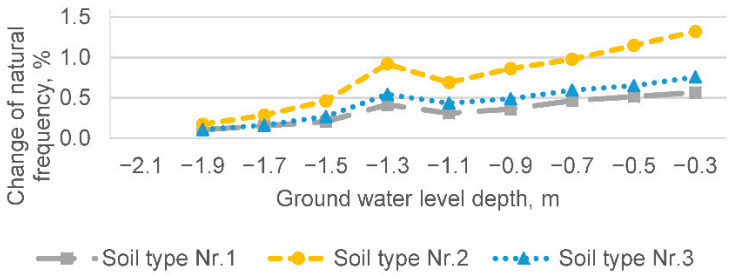


Figure 10. Difference of the natural frequencies of FE model type C in the first longitudinal mode for three different soil types.

Table 6. Difference of the natural frequencies due to groundwater level depth fluctuation for FE model type C.

Soil Type No.	Vibration Mode of FEM of Reference Groundwater Level, (Natural Frequency, Hz)	Groundwater Level Depth from Ground Level, m								
		−1.9	−1.7	−1.5	−1.3	−1.1	−0.9	−0.7	−0.5	−0.3
		Difference of the Natural Frequency Δf_i, %								
1	1st transverse mode (1.303 Hz)	0.23	0.38	0.54	1.15	0.92	1.07	1.23	1.46	1.61
	1st longitudinal mode (1.942 Hz)	0.10	0.15	0.21	0.41	0.31	0.36	0.46	0.51	0.57
	1st torsional mode (2.134 Hz)	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05
2	1st transverse mode (1.02 Hz)	0.29	0.59	0.88	1.76	1.37	1.57	1.86	2.06	2.35
	1st longitudinal mode (1.743 Hz)	0.17	0.29	0.46	0.92	0.69	0.86	0.98	1.15	1.32
	1st torsional mode (2.119 Hz)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1st transverse mode (1.146 Hz)	0.26	0.44	0.61	1.22	0.96	1.13	1.31	1.48	1.75
	1st longitudinal mode (1.851 Hz)	0.11	0.16	0.27	0.54	0.43	0.49	0.59	0.65	0.76
	1st torsional mode (2.125 Hz)	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05

4. Discussion

The collected data show that the groundwater level fluctuation in the soil with clayey layers impacts the natural frequencies of the buildings.

The research results coincided with the study [18] in which the authors investigate the modal parameters of a frame structure, including dynamic soil–structure interaction effects. In that study, it was also found that the soil–structure interaction affects all of the structural modes in the case of soft soil foundation.

According to formula (3) of the article, the fundamental frequency is roughly proportional to the square root of the building foundation stiffness. However, this stiffness also is influenced by foundation settlement changes due to the water ground-level fluctuations. A traditional way to take into account this effect is to use the correction factor Cw as a multiplier to the settlement in dry condition [12]. According to the field investigations reported in the literature, e.g., [19,20], settlement has maximum value when the water table reaches the footing level. In Figure 4, where the peak value of the natural frequencies is reached, groundwater level (−1.3 m) is precisely at the foundation base level. Furthermore, when water are above the footing base, the settlement due to water level rise increases at a slower rate [21]. This explains the peak value of fundamental frequency in the results obtained. Nevertheless, it is straightforwardly connected to the adopted methodology of settlement calculations.

However, the groundwater level fluctuation in sandy soil layers has less impact on the features, even including the peat layer as a stiffness attenuation layer.

Natural frequencies of different building structural system-type changes under variable environmental conditions such as groundwater level show that to avoid faulty results in SHM it is very important to include and consider operational and environmental effects in measurements.

To assess all environmental factors in SHM and introduce automatic damage detection in practice long monitoring and many FEM simulations are needed. Operational and environmental effects may affect each structure individually. It can take a lot of time and effort to develop each structure's behaviour separately under varying operational and environmental conditions. Due to changing effects, only part of the measurements from similar conditions can be used [22].

For SHM, in order to minimise false structural damage identifications, it is important to obtain simulation data in a wide range of environmental and operations conditions [23].

Reynders et al. [24] present the SHM approach consisting of three steps:

1. Reducing data by identifying damage sensitive features such as modal parameters in short periods;
2. Determination of non-linear environmental model using the damage sensitive features as outputs from the previous stage;

3. Monitoring the forecasting error of the global model.

However, this approach has limited applicability of SHM measurements in practice. It was found that the values of the parameters involved should be selected very carefully to obtain useful results.

Several studies present data normalisation or elimination. For a linear relationship between the features and the unknown latent variables, factor analysis can be used for measurements [22].

Cross et al. [25] describe cointegration as a new method to deal with change in structural response induced by the environment. The main idea is response variables that are integrated to create a stationary performance whose stationarity reflects the normal state of the structure could be linearly combined. Nevertheless, the method only works for linearly related variables.

However, not all environmental or operational effects have a linear impact on the features. Results show a non-linear correlation between groundwater level fluctuation and changes of the natural frequencies of the buildings. Kullaa in [22] describes a mixture of factor analyses model to compensate for the non-linear effects. This research shows that using non-linear models in SHM, structural damage is more clearly detected. However, at the same time, it results in more false identifications of damage.

Erazo et al.et al. [26] presents Kalman filtering for a variable environmental and operational condition induced noise reduction in data.

In research [27], which present natural frequencies variations of the Consoli Palace due to changes in ambient temperature, authors considered that correlation between natural frequencies and temperatures are often non-linear. Also, the groundwater level fluctuation impact on natural frequencies of buildings shows a non-linear correlation and reached a maximum difference of 2.5%, which can negatively influence measurement results. Tjirkallis in [28] accentuates that changes in natural frequency can reach 10% from environmental and operational variations and means that changes can be larger than those caused by significant damage.

In SHM, measured data will depend not only on the condition of damage but also on the environmental and operational variability. Several methods were presented in the research mentioned above, but almost all of them faced false identification of structural damage. Many methods are restricted to use only on the structures for which the model was created [29]. To accurately identify structural damage, it is recommended to choose features that are susceptible to structural damage but not to environmental and operational changes [30].

It is found that groundwater level change impacts the natural frequencies of the buildings when strong soil–structure interaction (SSI) occurs. That is because in this case changes in soil parameters significantly affect the natural frequencies of the buildings. Strong structural and soil interaction is, therefore, important for low and mid-rise buildings on week soil. Future work is to investigate groundwater level change impact on natural frequencies of buildings with other types of building foundation, structural scheme, and irregularly shaped buildings. In future, it is necessary to perform more experimental studies and compare them with the numerical simulation results.

5. Conclusions

In this research, the modal properties of 90 FEM models were analysed to investigate the variable soil effect impact on the buildings' modal parameters due to fluctuation of groundwater level. Three different structural type FE models of nine-storey RC buildings with shallow foundations were developed. FE model types included a wall-bearing RC structural system building, RC beam and column structural system building with two rigidity cores, and a RC beam and column structural system building with lightweight shear walls and two rigidity cores. The groundwater level of the reference FE model was chosen to be −2.1 m from the building ground level, and the fluctuation step of the groundwater level was 20 centimetres. The impact of the groundwater level change on

modal parameters for each soil type and FE model type was calculated as the difference between the reference FEM natural frequency and the calculated FEM natural frequency value of the next fluctuation step of the groundwater level.

This research determined that groundwater level change affects all modes of analysed types of building structural systems. Natural frequency value decreases due to the rise in groundwater level.

Maximum natural frequencies difference reached 2.5% for the RC building with bearing walls and for the RC frame building with lightweight shear walls and two rigidity cores in the case of a clayey soil type. This frequency fluctuation is in the first transverse vibration mode. Natural frequencies of the buildings in torsional mode reached only 0.5% of the frequency difference for all types of buildings and all soil types. Therefore, it is concluded that torsional mode is less sensitive to water ground level changes.

Groundwater level change can influence SHM measurements and cause faulty structural damage identification. The seasonal changes in groundwater level are approximately 1 m. As indicated in the graphs, the buildings' natural frequencies and groundwater level fluctuation have a linear correlation up to 1.2 m. Data normalisation using linear correlation methods can be used for SHM measurements in analysing short-term data. It was observed that groundwater level influence on building natural frequencies could change abruptly, and there is a non-linear correlation between the features in the long term measurements.

This research proposed a new environmental condition that needs to be considered in SHM for the vibration-based method. In practice, structural engineers should be aware of this effect on the modal parameters of the buildings to identify structural damage using vibration-based methods. To approach the precise structural damage identification in the long-term SHM measurements, features that are sensitive to structural damage, not environmental or operational changes, including groundwater level fluctuations, need to be chosen, or those effects should be filtered out from data.

Further experimental investigations are planned to identify structural damage using the vibration-based method for real structures under variable operational and environmental conditions, including groundwater level changes.

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