Civil Engineering Beyond Limits 2 (2024) 1922
Civil Engineering Beyond Limits
journal home: www.acapublishing.com/journals/1/cebel

Research Article

Determination of the Modal Parameters of the Historical Elevated Water Tank Using Experimental and Numerical Methods

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Keywords

Finite element method, Operational modal, Analysis, Ambient vibration, Modal parameters, Historic structures.

Abstract

Determining the modal parameters of historical buildings is crucial for understanding their dynamic behavior, which is essential for their preservation and safety for future generations. Experimental and numerical studies are commonly used to characterize modal properties such as natural frequencies and mode shapes. Experimental studies typically employ the operational modal analysis method, while numerical studies employ the finite element method. Vibration measurements of the structure under various environmental conditions, including wind and traffic, were used to determine the modal parameters. However, discrepancies often arise between modal parameters obtained from experimental research and those assessed by finite element models, primarily due to unknown factors like boundary conditions and material properties. The purpose of this study was to measure the vibrations of a historic elevated water tank a 150-year history under ambient conditions to determine its modal characteristics. Comparing the modal parameters obtained from numerical and experimental investigations revealed that the water tank's finite element model requires updating to align with the findings of the experimental modal study. Using the updated finite element model in future evaluations or assessments of the structure can lead to a better understanding of the behavior of the structure.

1. Introduction

Mathematical or numerical models are usually created in every engineering domain to understand how real systems operate. Among them, the finite element (FE) method is often chosen due to its effectiveness and affordability in generating numerical models of structures and assessing their behavior. FE models are commonly used in civil engineering to evaluate how structures respond under dynamic loads. Understanding the behavior of individual structures or entire structures under such situations requires an understanding of these models [1-4].

In civil engineering, the operational modal analysis (OMA) method has recently become more popular in assessing structural systems exposed to random or naturally occurring vibrations under current conditions. This method is also extensively applied in other engineering disciplines, such as mechanical engineering, due to its practical advantages [5-9]. The OMA test examines vibrations originating from natural (random) sources, where the amplitude and time-dependent variations are unknown, to determine the modal characteristics of a structure. These natural sources of vibrations include traffic loads, human activities, wind effects, wave effects, and ground motions, all of which are analyzed to evaluate the structure's modal parameters.

Elevated water tanks are significant civil engineering structures built at considerable heights to apply sufficient pressure for supplying water from available sources to surrounding areas, based on their capacity. Due to their height and shape, effects such as earthquakes, wind, and traffic loads passing at close distances cause lateral displacement of these tanks, making them critical load components when analyzing and designing the water tank. Studies exploring the static and dynamic behaviors of these kinds of structures, which are essential in many regions worldwide, particularly in large cities, are increasing due to these impacts.

Three elevated concrete water tanks, each made of reinforced concrete with a capacity of 900 cubic meters and heights of 25, 32, and 39 meters, were studied by Shakib et al. (2010) [13] using a series of seismic recordings. They utilized nonlinear time history analysis to calculate the seismic demands for the elevated water tanks under three scenarios: empty, half-full, and full. An elevated water tank's structural identification was the subject of a case study by Norris and Grimmelsman (2014) [14]. A structural identification program was used in their investigation to generate an FE model that was precisely calibrated to pinpoint the source of any damage. They explored the impact of various operational variables, such as wind speeds and water levels, on the tank's behavior and used these conditions to calibrate the FE model. Ambient vibration testing was performed under these circumstances. An experimental study on the structural investigation of a water tank by applying dynamic and static pressure loading was conducted by Wang et al. (2015) [15]. This investigation revealed the failure modes and maximum resistance of the specimens, and the findings were compared to numerical values. They verified the accuracy of the numerical models by contrasting the predicted displacement responses with the experimental results as they analyzed the behavior of the water tank using nonlinear finite element analysis.

Kangda (2021) [16] provided a brief synopsis of the underlying assumptions and relevant modeling components for ANSYS software modeling of circular and rectangular liquid storage tanks. The study also investigates the benefits and drawbacks of various analysis techniques offered in the finite element program to determine sloshing parameters. A probabilistic method based on Monte Carlo simulations was employed by Hammoum et al. (2021) [17] to assess the dependability of raised water tanks subjected to seismic loads caused by hazards. Fragility curves, which depend on soil types and seismic zones, were created using a probabilistic method. The main failure mechanisms that might lead to structural collapse in the tank container are depicted in these curves about different seismic

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Received 13 Jun 2024; Revised 22 Jun 2024; Accepted 22 Jun 2024
https://doi.org/10.36937/cebel.2024.1922

intensities, soil types, and water height levels. Baghban et al. (2022) [18] evaluated the relative effectiveness of circular and horizontal baffles on the dynamic response of elevated water tanks. The analytical results were contrasted with baffle-free raised storage tanks. Here, we look at the flexible and stiff storage tank analysis, when liquid fills half of the tank height.

Considering this information, within the scope of this study, the Historical Water Tank, with a 150-year history, was repaired by the Samsun İlkadım Municipality and is now transformed into the "Circassian Ethnography Museum." To ensure the continued functionality of this structure, which holds historical and cultural value, it is crucial to examine its performance under seismic loads. One of the main issues that can cause such structures to collapse is earthquakes. Therefore, to ensure the safe continuation of the function of elevated water tanks, their analysis under dynamic loads must be carried out carefully. In this case, vibration recordings were made under normal environmental conditions, and the operational modal analysis (OMA) approach was used to determine the experimental modal characteristics, such as natural frequency and natural mode shape. The structure's FE models were created, and the analytical modal parameters were determined. Next, discrepancies between the frequency values and mode shapes were identified by comparing the experimental and analytical modal characteristics.

2. Material and method

2.1. Operational modal analysis technique

The Discrete Fourier transform is used in the FDD approach [19] to transform time-domain data into frequency-domain data. By using this technique, the system's responses are converted into several single-degree-of-freedom systems. One of the most significant advantages of this method is that it allows for the rapid acquisition of modal parameters. The process of identifying mode shapes and frequencies from the obtained peak points is simplified. However, the damping ratios of the system cannot be calculated with this method. Therefore, a more advanced version, the EFDD technique, which can also calculate damping ratios, was developed. Using the EFDD technique, the study's structural mode shapes and natural frequency values were determined.

2.2. Enhanced Frequency Domain Decomposition Technique

Since the EFDD method is completely non-parametric, the estimations of the modes are only obtained from the results of signal processing. Using Brincker et al. (2000) [19], the relationship between the input and output signals in the EFDD approach can be stated as follows:

$$\left[G_{yy}(\omega)\right] = [H(\omega)]^{*}[G_{xx}(\omega)][H(\omega)]^{T} \quad (1)$$

The output Power Spectral Density matrix (PSD) can be converted to a pole/residue form as follows a few mathematical operations:

$$\left[G_{yy}(\omega)\right] = \sum_{k=1}^{m}\left(\frac{[A_k]}{j\omega-\lambda_k}+\frac{[A_k]^{*}}{j\omega-\lambda_k^{*}}+\frac{[B_k]}{-j\omega-\lambda_k}+\frac{[B_k]^{*}}{-j\omega-\lambda_k^{*}}\right) \quad (2)$$

With a lightly damped system in mind, the response spectral density matrix can be expressed in the below form as follows:

$$\left[G_{yy}(\omega)\right] = \sum_{k=Sub(\omega)}\left(\frac{d_k\psi_k\psi_k^{T}}{j\omega-\lambda_k}+\frac{d_k^{*}\psi_k^{*}\psi_k^{T}}{j\omega-\lambda_k^{*}}\right) \quad (3)$$

Consequently, by carrying out the output PSD matrix's singular value decomposition, which is known at discrete frequencies, one obtains:

$$\hat{G}_{yy}(j\omega_i) = U_i S_i U_i^{H} \quad (4)$$

Only the mode is dominant near a peak in the spectrum that corresponds to it, and the PSD matrix generally represents a rank one matrix as follows:

$$\hat{G}_{yy}(j\omega_i) = s_i u_{i1} u_{i1}^{H}, \quad \omega_i \rightarrow \omega_k \quad (5)$$

The first singular vector at the resonance is an estimate of the mode shape:

$$\hat{\varphi}_r = u_{r1} \quad (6)$$

2.3. Analytical determination of modal parameters

Theoretically determining modal parameters begins with creating a simplified model that accurately represents the actual system and can be analyzed more easily mathematically. This simplified model is referred to as the analytical model. After creating the analytical model, the equations of motion for this model are formulated, which constitute the mathematical model of the structural system. These equations of motion, which are usually written as differential equations, characterize the dynamic behavior of the structure. Modal parameters such as natural frequencies, mode shapes, and damping ratios are then determined using these equations of motion, with the modal parameters being derived from the solutions of these equations.

Real-world structures are multi-degree-of-freedom (MDOF) systems. The generic equation of motion for a system with multiple degrees of freedom can be written as follows:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \quad (7)$$

When there is no damping and no external force, a structural system is in its undamped free vibration state. In this situation, the damping matrix [C]=0 and the force vector{F(t)} is also set to zero, the equation of motion then becomes:

$$[M]\{\ddot{x}\} + [K]\{x\} = \{0\} \quad (8)$$

Free vibration motion is a simple harmonic motion and displacement:

$$\{x\} = \{A\}sin\omega t \quad (9)$$

Here, {A} is a vector that does not depend on time and represents the amplitude vector of the movement and w represents the angular frequency, If the second order derivative of {x} and {x} is substituted into the equation of motion,

$$-\omega^2\,[M]\{A\} + [K]\{A\} = \{0\} \quad (10)$$

For this equation to have a non-zero solution,

$$|[K] - \omega^2\,[M]| = 0 \quad (11)$$

By expanding this determinant, a polynomial of degree n is obtained. The roots of this polynomial are the eigenvalues, and these eigenvalues give the squares of the angular frequencies (ω2). After the roots are found, the corresponding angular frequencies are obtained for each root value (ω2). As a result, angular frequency (ω_1, ω_2, ω_3, ...,ω_n) and with n degrees of freedom, the matching mode shape is obtained. The shape that the structure assumes in response to the smallest frequency, known as the fundamental frequency, is known as the fundamental model shape.

2.4. Accelerations

Transducers are instruments that convert responses such as displacement, velocity, and acceleration within a structural system into proportional electrical signals which can be transmitted to a data acquisition unit for signal processing. Because of their large dynamic range and broad frequency response, accelerometers are the most often used form of transducer, given their relatively small and lightweight nature. In the study mentioned, high-sensitivity field-type accelerometers were utilized, specifically the Sensebox 7021 single-axis and three-axis accelerometers (Fig. 1). These accelerometers are designed to accurately measure accelerations in various directions and are suitable for field measurements requiring high sensitivity and precision.

Figure 1. Accelerometers used in the experimental study

2.5. Data acquisition system and signal processing

Devices that transform analog data into digital data at predetermined intervals are known as data acquisition devices. A data acquisition system typically comprises a data acquisition unit, a computer, and specialized software. The data acquisition unit is responsible for transferring vibration signals from sensors such as accelerometers to the computer program. Specialized software acts as the interface for collecting, processing, and analyzing the vibration signals stored in the computer.

Data collection for the experimental measurements was done using a TESTBOX2010. The dynamic data acquisition device TESTBOX2010 can handle signals from various voltage output sensors, including displacement, strain gauges, acceleration, and load cells, at high rates and high resolution. The TESTBOX2010 device used in the study is a 4-channel unit, allowing for simultaneous sampling across all channels. The setup of the data acquisition system is depicted in Fig. 2.

For data acquisition and processing, the TestLab_V2 software was employed. This software works with the dynamic data acquisition system and facilitates tasks such as connecting accelerometers to the data acquisition unit, collecting vibration signals, processing signals, and transferring information to computer-based signal processing applications.

Figure 2. Dynamic data acquisition device and acceleration recording system

3. Application and Results

3.1. Experimental modal identification of the structure

This research aims to investigate the dynamic behavior of a historic water tank, a structure with a 150-year history. It has been repaired by Samsun İlkadım Municipality and transformed into the "Circassian Ethnography Museum," as shown in Fig. 3a. Some damages on the structure, resulting from factors such as earthquake loads over time, wind loads, and traffic loads from the nearby heavy rail railway and the Samsun-Trabzon Highway passing within 10m-15m of the structure, are also shown in Fig. 3b. Due to its historical and cultural value, it is crucial to examine the structure to ensure its continued functionality.

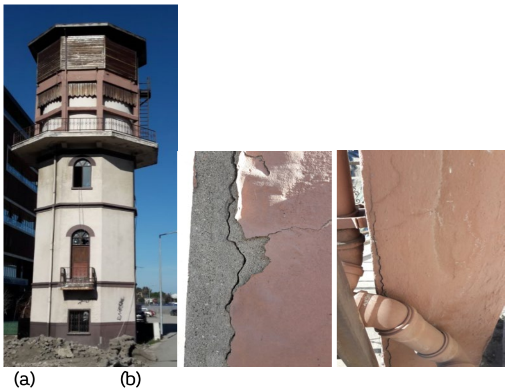


Figure 3. Historic Elevated Water Tank

The structure has an octagonal geometry. It consists of 3 regular floors, a floor with a water tank, and an attic floor. The heights of the regular floors are 3.95 meters, 4.5 meters, and 3.95 meters respectively. The floor with the water tank is 4.6 meters high, and the attic floor is 4 meters high. The building is 21 meters tall overall. The specifications of the beams are 25 by 33 cm, the brick walls are 25 cm thick, and the columns on the normal floors are 25 by 40 cm. On the floor with the water tank, the columns are 26x33 cm and the beams are 20x33 cm. With an exterior diameter of 2.7 meters, an inner diameter of 2.45 meters, and a height of 4.4 meters, the water tank is a vertical circular cylinder.

The natural frequency and mode shape of the historic structure were determined using the OMA technique. Vibration measurements were taken at a column-beam joints throughout the building. Reference accelerometers were positioned at a column-beam joint on the first level of the building, capturing vibrations in both horizontal directions. For the vibration measurements, single and tri-axial accelerometers with a frequency range of 0.1-120 Hz were employed. In total, 9 single-axis and 4 tri-axial accelerometers were placed at different 20 joints on the structure to collect measurements. On the first floor, 4 tri-axial and 8 single-axis accelerometers were placed at 8 joint points; on the second floor, 4 tri-axial and 7 single-axis accelerometers were placed at 8 joint points; and on the third floor, 2 tri-axial and 4 single-axis accelerometers were placed at 4 joint points to capture the vibration signals caused by environmental effects on the structure. The experimental setup is shown in Fig. 4.

Figure 4. The experimental setup of the structure

Fig. 5 illustrates the acceleration configuration at each floor level. The frequency range of 0 to 100 Hz and the measurement duration of 20 minutes were selected as the measurement parameters. TestLab_V2 software was used to record the vibration signals that the accelerometers acquired via the data acquisition device. The ARTeMIS Modal 1.5 program [20] was used to analyze the experimental modal parameters of the historic structure. This software aids in identifying the inherent frequencies and mode shapes of structures and is specifically designed for modal analysis. The EFDD approach was used to characterize the structure's natural frequencies and mode shapes, as shown in Fig. 6. The identified mode shapes include torsional and translational modes. The experimentally obtained mode shapes of the structure, along with their corresponding evaluated natural frequency values, are illustrated in Fig. 7.

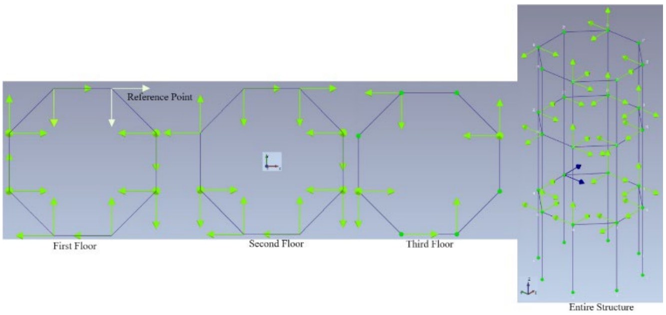


Figure 5. Location and direction of accelerometers

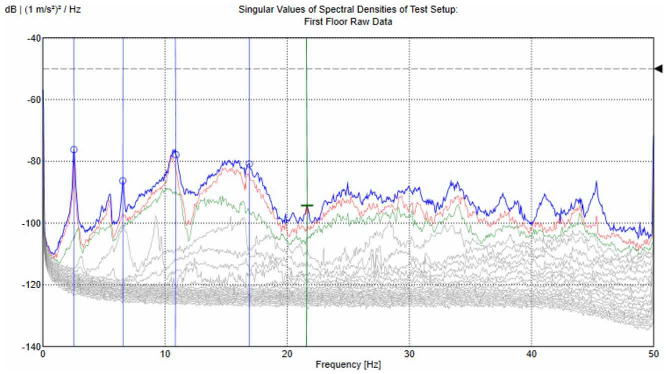


Figure 6. Average of normalized singular values of spectral density matrices of all test setups

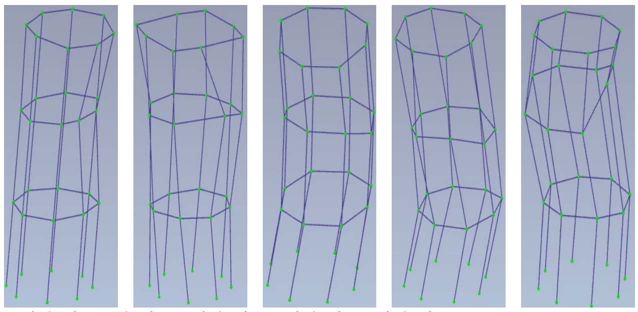
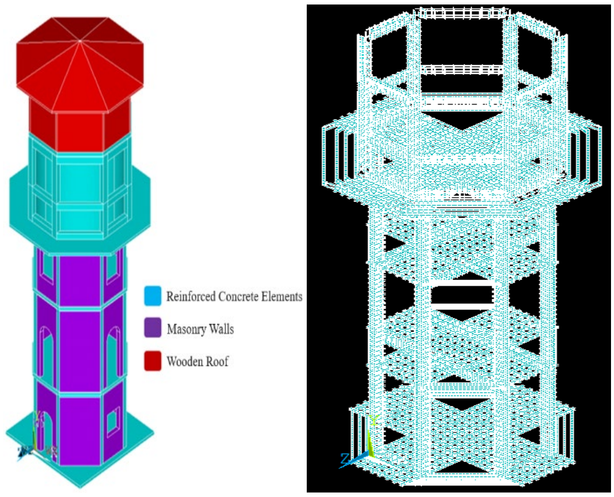


Figure 7. Experimentally obtained mode shapes and natural frequency values

3.2. Finite Element Model of the Structure

The finite element model (FEM) of the structure in this investigation was created using the ANSYS Workbench software [22]. Analytical modal parameters such as modal shapes and natural frequencies, were determined based on the FE model. SOLID186 elements, which consist of 20 nodes with three translational degrees of freedom at each node (u_x, u_y, and u_z), were used in the FE model. Plasticity, creep, swelling, stress stiffening, significant deformation, and strain are all possible with these constituents. On the other hand, the FE model was predicated on the material's linear elastic behavior. Fixed supports were specified as boundary conditions in the structural model, indicating that certain parts of the structure were constrained from movement or deformation, typically representing fixed connections to the ground or other structural elements.

In the FE modeling of the historical structure, the load-bearing and non-load-bearing elements were modeled separately. The modeling of the historical structure's masonry walls, timber roof, and reinforced concrete beams, columns, and slabs is shown in Fig. 8(a). A smeared modeling approach was used for reinforcing the concrete column, beam, and slab elements as demonstrated in Fig. 8(b). In the smeared modeling, the reinforcements were defined spatially on the respective meshes.



(a) Structural Elements(b)Smeared Reinforcing Model

Figure 8. FE model of the historical structure

Because of the historical significance of the structure, no experimental studies could be conducted to determine its material properties. Therefore, in this study, material properties obtained from similar studies in the literature [22, 23] were carried out to classify the material characteristics. The material properties of the reinforced concrete structural elements, masonry walls, and wooden roofs are presented in Table 1.

The ANSYS software program was used to conduct a modal analysis of the historical water tank's FE model, enabling determination of its modal parameters. Mode shapes computed in the numerical analysis were compared with those obtained in experimental studies, and the corresponding natural frequencies are presented in Fig. 9. Additionally, a comparison was made between the natural frequency values from the FE model and the experimental study's values, and the results are shown in Table 2. The variations in these natural frequency values were also examined and shown in Table 2, provide insights into the accuracy and consistency of the FE model in capturing the water tank's dynamic behavior.

Table 1. Material characteristics for the historical structural elements' FE model

Structural Elements	Unit Weight (kg/m3)	Modulus of Elasticity (MPa)	Poisson Ratio
Columns	2400	28000	0.2
Beams	2400	28000	0.2
Slaps	2400	28000	0.2
Concrete	2400	28000	0.2
Masonry Walls	1800	1000	0.2
Wooden Roof	450	9000	0.2
Reinforcement	7850	200000	0.3

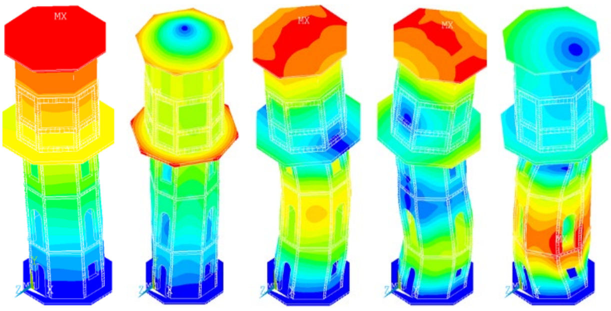


Figure 9. Numerically obtained mode shapes and natural frequency values

Table 2. Comparison in numerically and experimentally obtained natural frequency values

Mode	FE Model (Hz)	OMA (Hz)	Residuals (%)
First Translational Mode	2.51	2.53	0.8
First Torsional Mode	4.10	6.56	37.5
Second Translational Mode	9.94	10.84	8.30
Third Translational Mode	16.59	16.89	1.78
Forth Translational Mode	21.59	21.53	-0.27

When comparing the modal parameters of the historical water reservoir obtained through theoretical and experimental methods, the mode shapes align well with each other. However, Table 2's comparative analysis shows discrepancies between the analytically and experimentally determined frequency values. It is vital to update the original finite element model of the structure based on the findings of the experimental measurements to lessen or completely eradicate these differences in natural frequencies. Using this method makes it possible to create a finite element model that more accurately captures the structural behavior of the water tank.

4. Conclusion

Historical structures, which have typically stood for many years or even centuries, are subjected to external influences such as earthquakes, floods, and wind over long periods, resulting in some structural damage. The current state of these historic structures must be regularly monitored to implement appropriate remedial procedures against any possible issues.

Under environmental vibrations, the OMA approach was used to determine the modal characteristics—natural frequencies and mode shapes—of the historical water tank. The mode shapes of the historical water tank and the corresponding natural frequency values were determined using the frequency domain-based EFDD method. Comparing the natural frequency values obtained from experimental and FE models revealed differences of approximately 0% to 10% for translational modes and around 40% for the torsional mode.

Based on this data, it has been determined that the developed FE model needs to be calibrated because the analytical model of the historical water tank is insufficient to accurately represent the dynamic behavior of the real structure.

Nomenclature

H : The Frequency Response Function (FRF) matrix
G_{yy} : The Power Spectral Density matrix of the output signal
G_{xx} : The Power Spectral Density matrix of the input signal
* : Complex conjugate
T : Transpose
λ_k : The pole
A_k,B_k : The kth residue matrices of the output Power Spectral Density
Ψ_k : The kth mode shape vector
d_k : A scalar constant
S_i : A diagonal matrix holding the scalar singular values s_{ij}
U_i : A unitary matrix holding the singular vector u_{ij}
[M] : Mass matrix
[K] : Stiffness matrix
[C] : Damping matrix
$\{\ddot{x}\}$: Acceleration vector
$\{\dot{x}\}$: Velocity vector
$\{x\}$: Displacement vector
{F} : Force vector

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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How to Cite This Article

Yazıksız, E. and Alpaslan, E., Determination of the Modal Parameters of the Historical Elevated Water Tank Using Experimental and Numerical Methods, Civil Engineering Beyond Limits, 2(2024), 1922. https://doi.org/10.36937/cebel.2024. 1922