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The application of Digital Twins and the Internet of Things to assess the metro dynamic effects on historical buildings

L'application des jumeaux numériques et de l'Internet des objets pour évaluer les effets dynamiques du métro sur les bâtiments historiques

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ABSTRACT: The Hostynnyi Dvir two-storey building erected in Kyiv at the beginning of the 19th century is complicated in plan and consists of two U-shaped parts. Under the building the metro tunnels pass with trains running on a normal (non-vibration-isolated) track every 2 minutes. The nature of the foundation structures damage indicates that the main cause of its occurrence is an uneven deformation of the foundations base due to the additional soil compaction under dynamic effects. The damage analysis shows that in fact the building is divided into several blocks and has experienced the spatial rigidity reduction. According to the results of the vibrodynamic tests carried out with the use of the Internet of Things during the metro trains movement, the additional vertical dynamic loads on the building foundations up to 1%, on the soil near the building up to 7%, and on the building floor up to 5% from the object own weight were determined. Modelling of the stress-strain state of the "base – foundation – metro" system is performed using the Midas GTS NX software package. The constructed Digital Twin is a three-dimensional model reflecting the actual soils layering and including the subway tunnels structures, foundations and superstructure parts. The building superstructure parts are included in the model for obtaining a more accurate initial stress-strain state for the base taking into account the building spatial rigidity. The obtained calculated acceleration values coincide with the results of vibrodynamic studies at the IoT sensors installation points.

RÉSUMÉ: Le bâtiment à deux étages Hostynnyi Dvir érigé à Kiev au début du XIXe siècle est de plan compliqué et se compose de deux parties en forme de U. Les tunnels du métro passent sous le bâtiment avec des trains circulant sur une voie normale (non isolée des vibrations) toutes les 2 minutes. La nature des dommages aux structures de fondation indique que la principale cause de leur apparition est une déformation inégale de la base des fondations due au compactage supplémentaire du sol sous les effets dynamiques. L'analyse des dommages montre que le bâtiment est en fait divisé en plusieurs blocs et a subi une réduction de la rigidité spatiale. Selon les résultats des tests vibrodynamiques effectués sur la base de l'Internet des objets, les charges dynamiques verticales supplémentaires sur les fondations du bâtiment jusqu'à 1%, sur le sol à proximité du bâtiment jusqu'à 7% et sur le sol du bâtiment jusqu'à à 5% du poids propre de l'objet ont été déterminés lors du mouvement des rames de métro. La modélisation de l'état contrainte-déformation du système "socle – fondation – métro" est réalisée à l'aide du progiciel Midas GTS NX. Le Digital Twin construit est un modèle tridimensionnel reflétant la stratification réelle des sols et comprenant les structures, les fondations et les parties de superstructure des tunnels de métro. Les valeurs d'accélération de conception obtenues coïncident avec les résultats des études vibrodynamiques aux points d'installation des capteurs IoT.

Keywords: Dynamic loading; metro; compacted urban development; finite element method; experiment.

1 INTRODUCTION

Hostynnyi Dvir is the main and central element of 'The Buildings Complex on Kontraktova Ploshcha (Contract Square), the 10th – the end of the 19th centuries' Architecture and Urban Planning Monument of Local Importance, which comprises a monumental trading store on Kontraktova Ploshcha in the historical neighborhood of Podil. It had partially been constructed in 1809–1813 under the project of Luigi Rusca and was then rebuilt in 1828–1833 according to the project of Andrii Melenskyi. The Hostynnyi Dvir two-storey building (HDB) with a basement has a complicated plan as it consists of two U-shaped parts forming a closed internal area with the axial dimensions 122.2 m x 65.5 m (Figure 1).

Figure 1. Hostynnyi Dvir, photo of 1930s.

High traffic volumes are observed on the motor vehicle and tram routes located nearby. The metro tunnels pass under the HDB, and the metro trains run on the normal (non-vibration-isolated) tracks every two minutes (Figure 2).

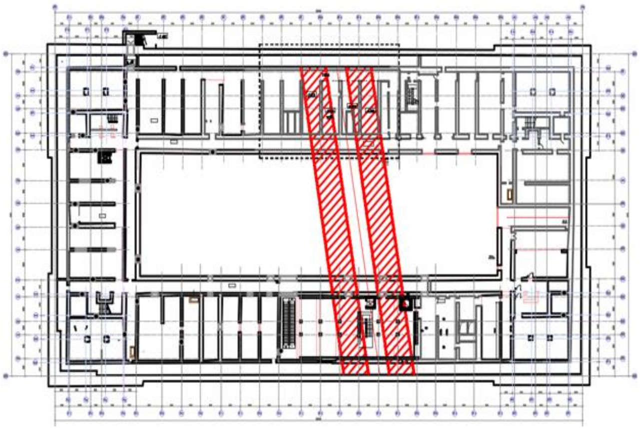

Figure 2. The layout of the Hostynnyi Dvir building. Two red stripes are the subway lines.

International concerns over cultural and natural heritage were reflected in the World Heritage Convention which was adopted by UNESCO in 1972 (World Heritage Convention, 2023). It aims at encouraging national governments to give greater protection to the sites of importance for nature conservation, to conduct research that allows gaining a deeper understanding of their cultural and natural heritage sites and the existing threats to them. The State Parties to this Convention are called on to integrate the protection of their cultural and natural heritage into regional planning programmes, to set up special services with an appropriate staff within their territories, to undertake scientific and technical conservation research, and to take measures giving their heritage a function in the day-to-day life of the community. The issues of dynamic effects on buildings and structures; transport vibration influence on the stress-strain state (SSS) of existing buildings, further deformations of their bases and foundations, their uneven settlements and other negative phenomena were considered in numerous works of such national and foreign researchers as Huston, 2011; Kaliukh et al., 2018; Lollino et al., 2006; Sedin et al., 2019.

2 METHODS FOR ASSESSING THE HDB BASE SSS CHANGES UNDER THE DYNAMIC EFFECTS

Assessment of the „base – structure“ system SSS change is generally made via comparing its specific technical parameters. The number and types of controlled parameters shall be determined according to the preliminary survey results, the regulatory and project documents requirements, and the conditions for maintaining the object operational characteristics throughout its lifecycle. The SSS technical parameters shall be identified pursuant to the results of the object technical conditions complex study including the following activities: visual inspection (defects, damage, assessment of compliance with the project etc.); instrumental studies of the materials strength; geodetic measurements of deformations (settlements, deflections, structures positions etc.); engineering geological and hydrogeological surveys; dynamic vibration tests of soils and structures; numerical 2llowance of the „base – foundation“ system SSS with an2llowancee for the parameters obtained from the investigations mentioned above. Reactions to changes in the structural components technical state are recorded by the monitoring system sensors, which allow receiving data on the object responses to the external and internal effects including the object and its individual components spatial displacements taking place in the form of deflections, settlements, rolls etc.; deformations in building structures; changes in dynamic characteristics of the building structures and building as a whole; and changes in the environment surrounding the object. The above information analysis and numerous examples of new construction activities under conditions of urban density in the city of Kyiv show an urgent need to elaborate a hybrid theoretical and methodological approach using the Internet of Things (IoT) as the logical continuation and development of the scientific and technical construction objects support for avoiding and preventing soil accidents in the future. The IoT sensors allow to carry out the tensometric measurements and the following physical quantities measurements: angles of buildings and structures inclination; levels of crack opening (closure), object components shifts and expansion joints; vibrations; temperature; humidity; pressure etc. (Figure 3). The IoT basic elements in the sphere of geotechnics are as follows: procedures of sequential analysis when choosing the diagnostic criteria; means of technical diagnostics and methods for processing the obtained information; reference approximation models for the monitoring system testing by the in real time (online) comparison method; multilevel functions and means for monitoring research; diagnostic information concentration in the form of an appropriate database.

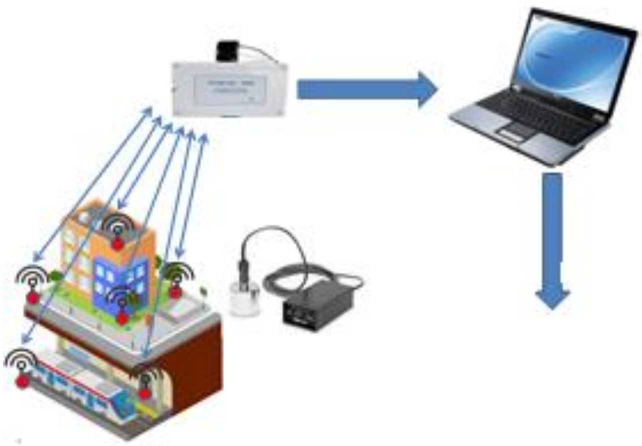

Figure 3. System for on-line monitoring of the object vibration characteristics using the IoT.

Numerical modelling of the HDB SSS under static and dynamic loads was carried out considering the results of checking the HDB mathematical model for its relevance to the real object. That allowed to take decisions on the possibility of using the data obtained after conducting computer experiments on the object mathematical model for setting up and clarifying the composition and placement of sensitive elements of the monitoring system determining the HDB load-bearing structures state. In this case, the relevance of the HDB computer model means that the HDB civil structures integral characteristics obtained from measurements during the field surveys and by means of modelling are almost identical; the discrepancy is within the acceptable range of permissible error.

3 EXPERIMENTAL STUDIES OF THE HDB USING THE IOT TECHNOLOGIES

The above-mentioned studies included the following elements: the visual inspection and instrumental studies of the structures materials strength; checking calculations to assess the "base – foundation – structure" system SSS for HDB; the vibrodynamic tests of soil, foundation and load-bearing structures under the effects of the metro trains, trams and motor vehicles traffic and construction equipment operation. The damage nature indicates that the building structures destruction is mainly caused by the uneven deformation of the HDB foundation bases due to the additional soil compaction under the dynamic effects. The damage analysis shows that in fact the building is divided into several blocks and has experienced the spatial stiffness reduction. According to the results of HDB vibrodynamic tests, the dominant frequencies of soil vibrations were determined as 15 Hz during the land transport movement and 55 Hz during the metro trains movement. The maximum vibration acceleration amplitudes determined with the values of 64 cm/s² in the horizontal direction and 42 cm/s² in the vertical direction under the simultaneous action of all possible dynamic effects were recorded for the soil near the building above the metro tunnels. During the metro trains movement, the HDB own weight caused additional vertical dynamic loads up to 1% on the building foundation, up to 7% on the soil near the building, and up to 5% on the building floor structures. The obtained calculation accelerograms serve as the initial conditions for the SSS modeling of HDB "base – construction – metro" system using the direct dynamic method.

4 SSS NUMERICAL MODELING FOR THE HDB BASE UNDER DYNAMIC EFFECTS USING THE DOUBLE TWINS METHOD

The existing methods do not allow to comprehensively solve the complicated task of forecasting the SSS changes in the "base – structure" system under the dynamic influences including the metro trains effects. The difficulty lies in the necessity of taking into account such important factors as urban density, which is often combined with a developed underground component, and complex engineering and geological conditions of the site with various soils layers. The modern software packages that implement the finite element method (FEM) allow taking into account all the above-mentioned features of real objects with sufficient accuracy. The Midas GTS NX is one of such software packages (Midas, 2018). To perform the numerical modeling, in this paper the Linear Time History is applied. In the GTS NX an implicit integration method for the direct time integration for the linear assignments is used. The GTS NX uses the HHT-α method proposed by Hilber, Hughes, and Taylor for the implicit direct integration. The proposed Digital Twins is a three-dimensional model presenting the actual soil layering, metro tunnel structure, and HDB foundations and superstructure components. The superstructures are included in the model for obtaining a more accurate initial base SSS taking into account the building spatial rigidity. When solving FEM problems, the calculation area is considered as a collection of a finite number of elements. The main advantage of the SSS numerical calculations is that all components of stresses σ_{ij} (x, y, z), of deformations ε_{ij} (x, y, z) and of displacements u (x, y, z), v (x, y, z), and w (x, y, z) necessary for the SSS assessment and analysis for the entire soil massif are obtained at the output. As a result of the calculations, both the qualitative and quantitative pictures of the SSS parameters changes in the HDB foundations base under the dynamic impacts were obtained. The calculated values of the accelerations coincide with the results of vibrodynamic studies at the sensors installation points. Figure 4 present the assessment of the maximum zone of the dynamic impact during the movement of two trains.

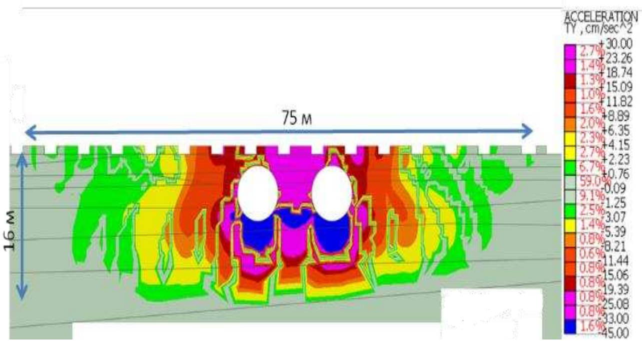

Figure 4. The maximum zone of the dynamic impact during two trains movement (acceleration). During the passage of metro trains, the maximum values of accelerations in the HDB foundation soil base reach 45 cm/s^2 (dark blue color) in the space between the tunnels and under the tunnels, more than 30 cm/s^2 is observed directly under the tunnels (pink and dark red colors), and approximately 20 cm/s^2 is recorded at a distance of 4 m from the nearest tunnel (pink color).

The influence zone of the metro is determined based on the analysis of changes in the parameters of the SSS system during static and dynamic calculations at characteristic points at a certain distance from the source of influence (metro tunnel). According to numerical calculations, it was found that vertical stresses at the base directly under the tunnel increase up to 35.8%. At a distance of 2 to 4 meters, the increase is in the range of [8.2; 11.3]%, at a distance of 8.5 meters, it is up to 2.5%, and at a distance of 13 meters, it is less than 1%. Horizontal stresses at the base directly under the tunnel increase up to 50.6%. At a distance of 2 to 4 meters, the increase is in the range of [8.1; 33.2]%, at a distance of 8.5 meters, it is up to 2.3%, and at a distance of 13 meters, it is less than 1%.

5 CONCLUSIONS

1. Based on the results of the SSS parameters analysis for the "base – foundation – building" system under static and dynamic influences, the qualitative and quantitative pictures of the HDB SSS parameters changes, as well as an idea of the actual vibrations distribution in the soil massif taking into account the real layering of soils, hydrological conditions, underground structures etc. were obtained.
2. The soil vibrations predominant frequencies of 15 Hz during the land transport movement and 55 Hz during the metro trains movement were experimentally determined. Considering the simultaneous action of all types of dynamic influence, the maximum values of vibration acceleration amplitudes of 64 cm/s^2 in the horizontal direction and 42 cm/s^2 in the vertical direction were recorded for the soil near the building above the metro lines.
3. In certain zones of the HDB soil base the excessive pore pressure occurs. The additional soil compaction is possible due to the vibrocompression.

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