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Tracing seismic surface waves induced by road traffic in urban environment: example of st. Catherine's church hill in Warsaw

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This paper concerns the problem of ground vibrations induced by road traffic and its influence on nearby historical monuments. The influence of vibrations induced by road traffic on buildings of St. Catherine's church was studied, this church lying in Warsaw, near a heavily used street. The measurements of vibrations of soil and walls of the church were executed using standard, 10 Hz, seismic, three-component geophone stations. Measuring points were established along chosen profiles between the street and the church. Interpretation of the obtained vibration records permitted to trace road-traffic-induced vibrations to the church wall with a velocity in the range characteristic of surface seismic waves and to quantify the range of the frequency and acceleration of the vibrations of soils and walls of the church. These results were compared to the Polish construction norm PN-85/B -02170 (title: "Evaluation of the harmfulness of building vibrations due to ground motion"). In effect, the recorded and traced vibrations exceeded the norms tolerable for such constructions.

Key words: geophones, surface waves, seismic measurements, vibration frequency

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INTRODUCTION

Urban environment is becoming increasingly influenced by a range of highly energetic phenomena related to environmental changes produced by rising human activity. One of such phenomena is acoustic and ground vibrations produced by the increasing volume of road traffic, including heavy trucks. This is particularly true for locations in which buildings are positioned near urban highways on which, due to urbanistic solutions, traffic may be strongly increased. In particular, older buildings and especially centuryies-old monuments, constructed often on weak foundations and with fragile materials, may be damaged by the influence of vibrations. A major factor for potential damages is the amplitude and frequency of vibrations, but also a summary effectiveness of vibrations repeated over long periods of time should not be neglected.

In this paper, we present results of a study on the influence of vibrations induced by nearby road on St. Catherine's church in Warsaw. St. Catherine's church was built in the 12th century. The church is located near the edge of the slope of the Vistula river valley. There is a street with a very high traffic intensity at a distance of about 100 meters from the church. Fractures appeared several years ego on the walls of the church. Geotechnical investigations showed the bad quality of its foundations. In spite of strengthening the foundations (e. g., using micro piles), fractures on the walls of the church appeared again.

The measurements show the influence of vibrations induced by road traffic on the walls of the church. In Warsaw, there are numerous places where old monuments and heritage objects are close to streets with a heavy traffic. The investigations reported here provoked a project to launch a major research into similar measurements in other areas of Warsaw.

REVIEW OF LITERATURE RELATING THE VIBRATIONS INDUCED BY ROAD TRAFFIC

Investigations of vibrations induced by road traffic are described in detail in (Crispino, D'apuzzo, 2001). The first researches connected with the influence of vibrations on soil behaviour were executed in the early sixties of the 20th century by the Road Research Laboratory (now Transport Research Laboratory) in Great Britain.

The investigations included measurements of the vibration amplitude of highway A1 surface in Huntingdonshire, related to the passage of heavy vehicles. It was found that the size and range of depth measured vibrations increased proportionally to the speed and to the weight of vehicles, and the majority of vibrations had a frequency below 30 Hz.

Martin (Martin, 1978) and Watts (Watts, 1987, 1988, 1989) describe the influence of vibrations induced by road traffic on various residential and office buildings. They estimated the parameters of the vibrations as well as the duration of their influence. In Poland, there is little information published on the measurement of ground vibration induced by road traffic and especially on its influence on constructions.

The first scientific centre at which such investigations were performed was the Institute of Structural Mechanics (Faculty of Civil Engineering in Cracow). The studies were directed by Prof. R. Ciesielski (Ciesielski et al., 1961, 1963, 1997).

As a result of these studies, the norm PN-85/B-02170 "Evaluation of the harmfulness of buildings vibrations due to ground motion" (PN-85/B02170) was released. In this norm, presented are the graphs of dependence of frequency vibrations of soil on the acceleration of particles in the soil, which permit to estimate the influence of vibrations of soil on buildings. The team guided by Prof. R. Ciesielski investigated the influence of soil vibrations induced by road traffic on St. Catherine's church in 1997 (Ciesielski et al., 1997). They applied geophones which recorded vibrations in the range 1–30 Hz. It was confirmed that vibrations are perceptible through a building and, though harmless to the construction, may cause an accelerated deterioration of a building. Another article that deserves attention is the paper of P. Clemente and D. Rinaldis (Clemente, Rinaldis, 1998). The authors studied the effectiveness of antivibration screens in the vicinity of objects of cultural heritage in Rome, Italy.

At present, in professional literature it is possible to find a lot of papers treating the problem of influence of soil vibrations from road and railway traffic on building objects. Articles in this field are printed in *Journal of Sound and Vibration, Soil Dynamics and Earthquake Engineering, Journal of Geotechnic Geoenvironmental Engineering,* and others.

The "*International Symposium on Environmental Impact of Road*" is a special conference dedicated to soil vibrations caused by road traffic.

GEOLOGICAL SETTINGS

The area of the study is located on the edge of a postglacial moraine neighboring the Vistula valley. It is a kem hill rising to 22 m above the level of the river. The eastern side of the hill is divided into two sharply rising (up to 45°) slopes. The relative height of the hill is here up to 12 m. The western side of the hill is markedly different, as the slope was here denivelated to reduce its height.

The hill is mostly built of sandy loams or clayish sands (Fig. 1) in a semi-consistent to firm state. These sediments are strongly consolidated, with a tendency to horizontal fracturing. The appearing fractures break the sediment into irregular horizontal layers not exceeding 5 cm in thickness. Under these clays appear fluvioglacial sands, in part saturated with water. Just under the surface, a large proportion of soil consists of anthropogenic rubble.

DATA ACQUISITION

Vibration measurements were performed employing 10 Hz geophones using a combination of vertical and horizontal sensors to provide three-component records (Fig. 2). The measurements stations therefore were composed of one vertical (Z) and two horizontal (X and Y) sensors, and using a 40-channel recording set (Summit DMT) it was possible to set up a system of 13 stations. They were disposed along a roughly L-shaped profile, with four stations parallel to the street and four stations along the line from the street to the church. The further four stations were set along the church close to its foundations, and the last station was set on the church wall (Fig. 3). The aim of the study was to detect and measure vibrations produced by the traffic on the street, their pattern in the ground and vibrations of the church structure.

During a day of measurements, recording was done in batches of 8 seconds with the sampling frequency of 0.5 ms, when a heavy

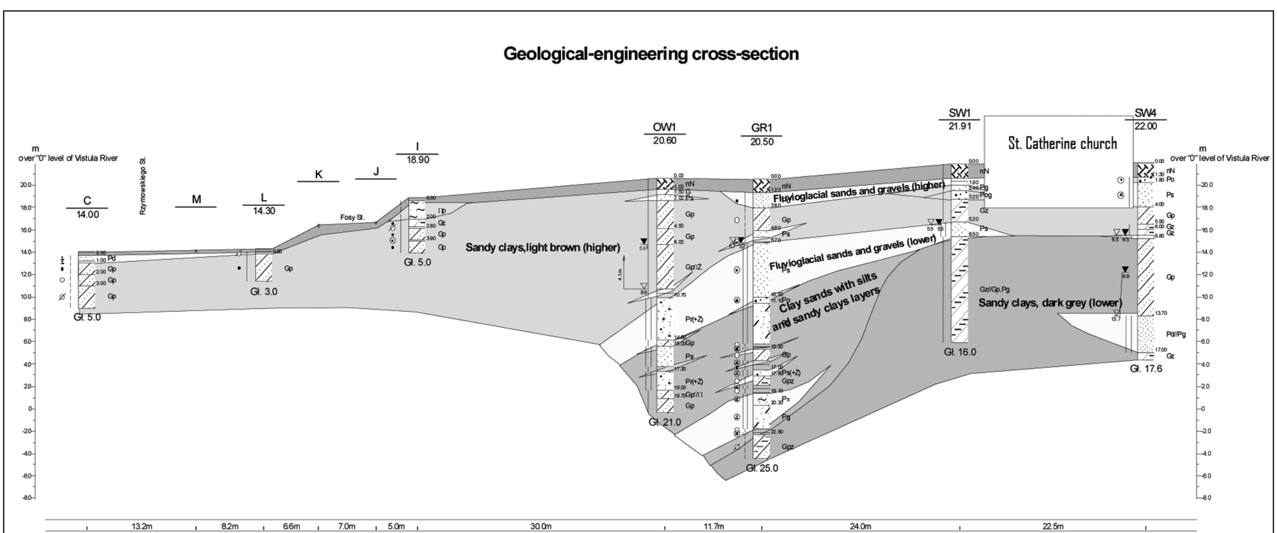

Fig. 1. Geological-engineering cross-section through the southern part of St. Catherine church hill

vehicle was spotted on the street. Thirty five such batches were recorded. An example of record is given in Fig. 4. It is clear that the passage of a vehicle corresponds to a vibration wave distinctly identifiable in the first eight stations positioned between the street and the church, less clearly pronounced in the four stations along the church, and again visible on the record of the last station on the wall of the church. Moreover, records of the wave allow identifying two wave bursts produced by the passage of the front and rear axles of the vehicle with the time gap of about 1 second.

RESULTS

In this first preliminary presentation, we show an assessment of the velocity of the ground wave propagation and the analysis of vibrations of the church wall to indicate the possible damages of this monument due to the traffic-induced motion of the ground.

Fig. 2. Seismic station and XYZ three-component geophone set

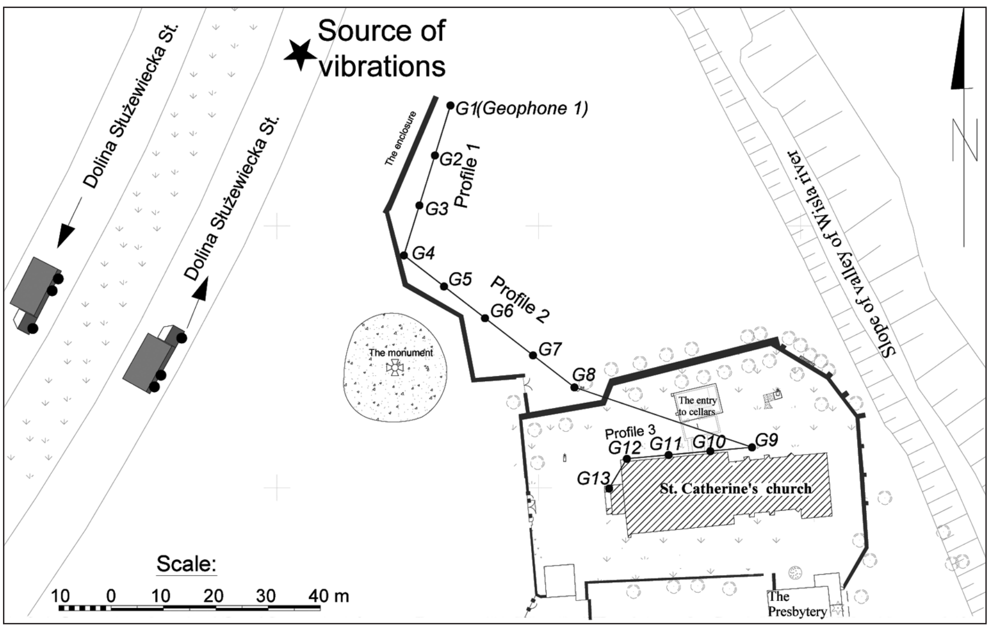

Fig. 3. Plan of location of the recording stations

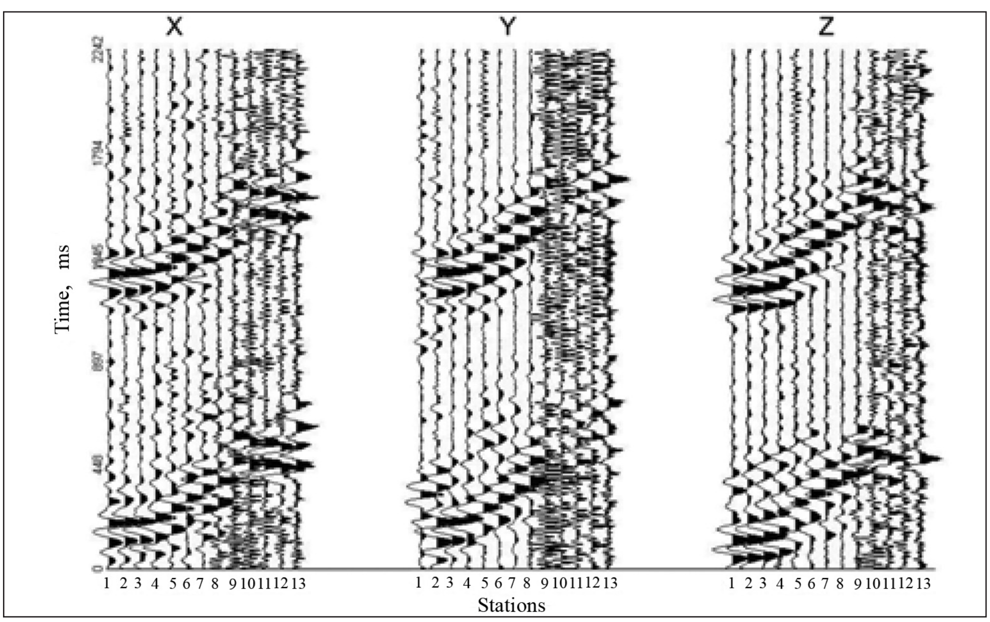

Fig. 4. Seismic signal recorded when a heavy vehicle runs along the road

Wave propagation velocity

An example of a record is given in Fig. 4. To obtain the velocity, the cross-correlation was used to calculate the shift of the phase between the records. This corresponds to, e. g., a clearly visible phase shift as shown in Fig. 5 for the first eight stations along the profile and on the record from the church wall. Records from the stations 9–13 show a high noise and were not interpreted in this preliminary analysis.

The stations are located on the map in Fig. 3, and their Cartesian coordinates allow to calculate the distances from the road and in particular from a pothole on the road. The plot of the time vs. distance is shown in Fig. 6.

The pattern of time arrivals shows two different velocities: 275 m/s corresponding to the first eight stations lying on the slope between the street and the inner terrace wall, and a much lower 128 m/s velocity for the segment close to the church. This deceleration of wave propagation may be explained by the rubble material around the church.

Frequency analysis

Measurements performed in this study were supposed to answer two questions: (1) do the vibrations resulting from the road traffic affect the historic church? (2) is the increasing traffic harmful for the church? To compare the influence of vibrations on the church with measurements from 1997 (Ciesielski et al., 1997) it was useful to use the same norm (PN-85/B02170) mentioned above. This norm introduced the scale of harmful vibrations of the construction objects SWD II (Fig. 7). However, this scale is directly adapted to measurements in narrow frequency bands, while our records were obtained in a wide range of the frequency spectrum. Therefore, it was necessary to process the data through filters which permitted to separate the narrow bands of frequencies required by the scale in the norm. An elliptical numeric filter (1) was used as it has a steep slope in the intermediate band. This filter is based on the elliptical Jacobian function and has a constant amplitude both in the pass band and in the stop band.

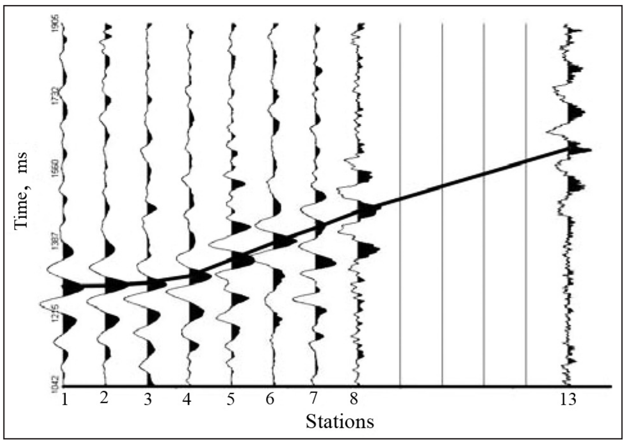

Fig. 5. (Subset of Fig. 4). Fragment of record for component X. The third maximum of the wave was picked to calculate the velocity. Records for Stations 9–12 along the church wall were muted

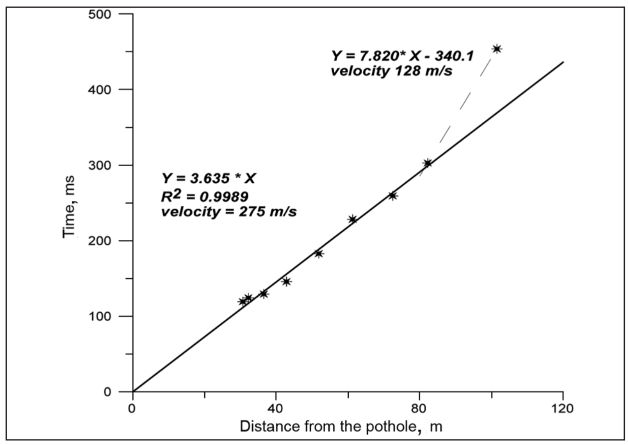

Fig. 6. Time of arrival vs. distance for the wave burst from Fig. 5. Regression lines are for the first eight stations and for the passage from Station 8 to the church wall

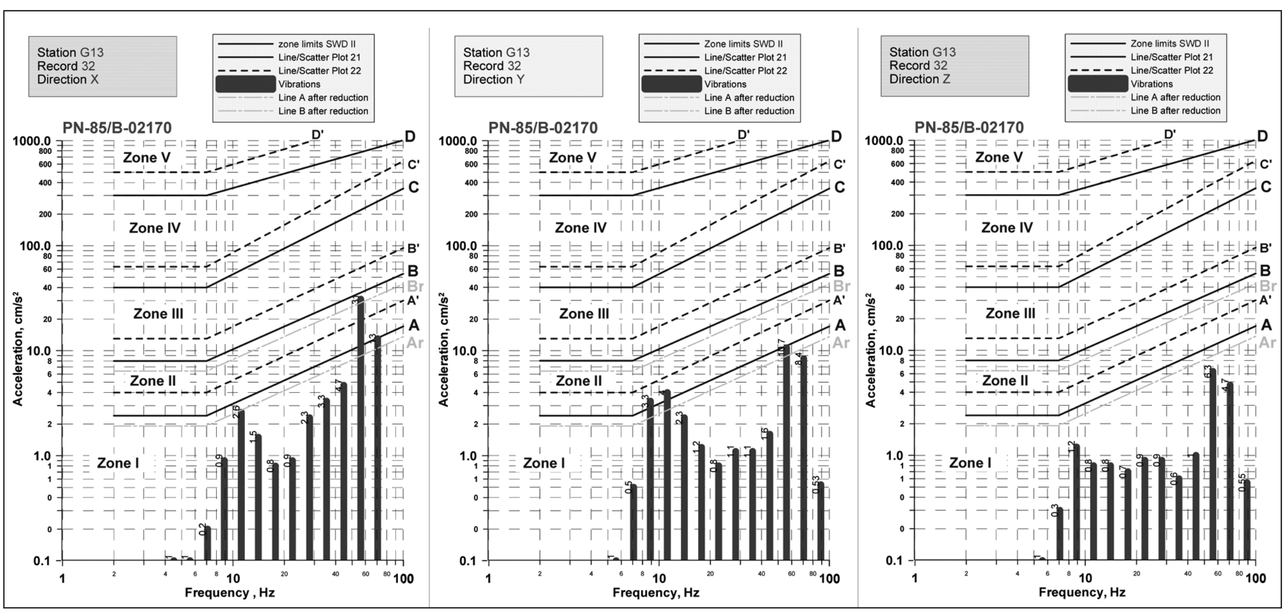

Fig. 7. Acceleration of vibrations recorded on the church wall in three (X, Y, Z) components on the scale of potential damage introduced in the norm (PN-85/B02170)

$$\left|H_a(j\omega_a)\right|^2 = \frac{1}{1+\varepsilon^2 U_N^2(\omega_a)}, \quad (1)$$

where $U_N^{\,2}(\omega_a)$ is a Jacobian function.

The signal was filtered in several different frequency bands to determine the maximum values of oscillation velocities. Only after this processing it was possible to put the results on the scale from the norm.

The norm (WATTS, 1988) determines the potential damage of vibrations in frequency bands in categories specifying the degree of risk on a scale rising from minor or negligible (Zone I), through not dangerous to the construction, but potentially damaging to frescos and mortar (Zone II) up to a total destruction of the structure in zone V. For large, old buildings, the norm has obviously limits of the zones lowered to provide for ancient and possibly altered building materials and nonstandard construction techniques. In Fig. 7, one can see that the recorded vibrations exceeded in several cases the lower limit of Zone II, both for lower and higher frequency bands in horizontal components X and Y, and for the high frequency vibrations in the Y component they clearly exceeded the lower limit of Zone III (vibrations harmful to the building construction inducing fractures and breaks).

The results from 1997 (Ciesielski et al., 1997) are shown in Fig. 8. The major difference between these results and the results of this work is the different frequency range of the spectra. The 1997 results cover the frequencies from 2 to 16 Hz, while our data cover the range from 10 to 100 Hz. A slight comparable increase of intensity is observed in our data (Fig. 7) in the range 10–16 Hz.

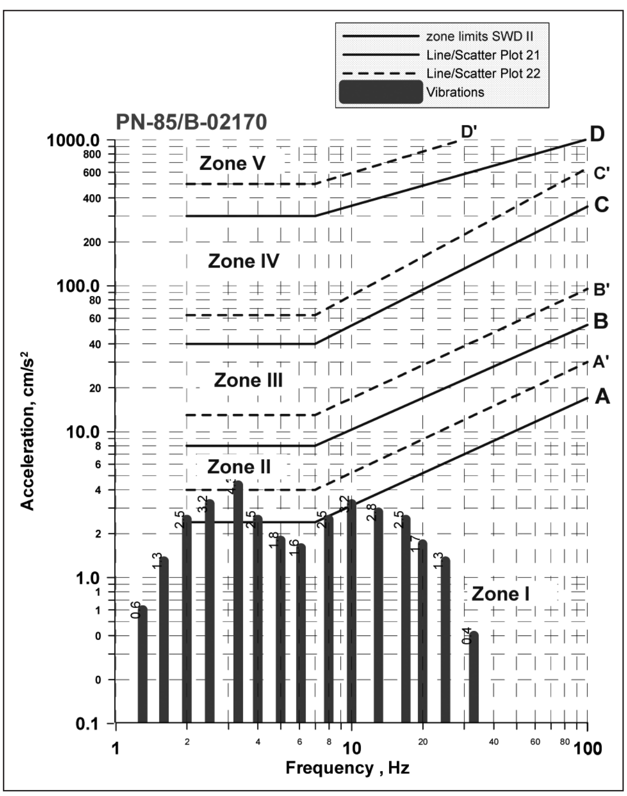

Fig. 8. Results of investigations executed in 1997 under direction of R. Ciesielski (Ciesielski et al., 1997)

CONCLUDING REMARKS

The results reported here show that road traffic may have a significant damaging effect on church buildings. The source of vibrations is evidently related to potholes and fractures on the road surface. However, this paper concerns only a preliminary investigation in a relatively high (> 10 Hz) frequency range and should be completed by further measurements and analysis.

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PAVIRŠINIŲ BANGŲ, SUKELTŲ GATVĖS TRANSPORTO URBANIZUOTOSE TERITORIJOSE, SKLIDIMAS

Santrauka

Straipsnyje nagrinėjamas gatvės transporto sukeltų žemės paviršiaus virpesių poveikis Šv. Kotrynos bažnyčiai (Varšuva), stovinčiai šalia judrios automagistralės. Matuojant žemės paviršiaus virpesius 10 Hz geofonais, buvo užregistruotos trys bangos komponentės. Matavimo taškai buvo išdėstyti išilgai gatvės ir bažnyčios. Tyrimų duomenų analizė ir interpretacija padėjo nustatyti paviršinės bangos spindulio kelią, bangos greitį bei dažnį, taip pat grunto ir bažnyčios sienų dalelių pagreitį. Gauti rezultatai buvo palyginti su „PN-85/B-02170: kenksmingų virpesių, perduodamų statiniams per gruntą, įvertinimas" leistinais dydžiais. Nustatyta, kad užregistruoti virpesiai viršija leistinas vertes.

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ANALIZA FAL POWIERZCHNIOWYCH WZBUDZONYCH RUCHEM KOŁOWYM W TERENIE ZURBANIZOWANYM NA PRZYKŁADZIE WZGÓRZA PRZY KOŚCIELE ŚW. KATARZYNY W WARSZAWIE

Streszczenie

Niniejszy artykuł dotyczy zagadnień drgań ośrodka gruntowego wywołanych ruchem drogowym oraz ich wpływu na obiekty dziedzictwa kulturowego. Szczegółowo zbadano wpływ drgań wywołanych przez ruch samochodowy na kościół Św. Katarzyny w Warszawie, który jest położony blisko trasy o dużym natężeniu ruchu. Pomiary sejsmiczne drgań powierzchni ziemi oraz ścian kościoła wykonano przy użyciu geofonów 10 Hz, umożliwiających rejestrację trzech składowych drgań. Punkty pomiarowe zostały zlokalizowane wzdłuż założonych profili, poprowadzonych pomiędzy ulicą a kościołem. Interpretacja otrzymanych danych pozwoliła określić drogę fali powierzchniowej, jej prędkość, częstotliwość oraz przyśpieszenie drgań cząstek gruntu i ścian kościoła, wywołanych drganiami wzbudzonymi przez ruch kołowy. Otrzymane wyniki interpretacji zostały odniesione do normy PN-85/B-02170 (tytuł: Ocena szkodliwości drgań przekazywanych przez podłoże na budynki). Wyniki interpretacji wskazują, iż zarejestrowane drgania przewyższają normy założone dla tego typu konstrukcji.

Павел Тухолка, Камиль Келбасиньски, Радослав Миешковски

РАСПРОСТРАНЕНИЕ ПОВЕРХНОСТНЫХ ВОЛН, ВОЗБУЖДЕННЫХ УЛИЧНЫМ ТРАНСПОРТОМ НА УРБАНИЗИРОВАННЫХ ТЕРРИТОРИЯХ

Резюме

Оценено влияние колебаний поверхностных волн, возбужденных уличным транспортом, на сооружения – объекты культурного наследия. Детально исследовано влияние таких колебаний на костел Св. Екатерины (Варшава), который расположен возле сильно загруженной автомагистрали. Колебания поверхностных волн измеряли геофонами 10 Hz вдоль профиля улица–костел, регистрируя три компоненты волны. Анализ и интерпретация полученных результатов позволили установить направление радиуса поверхностной волны, скорость волны, частоту колебаний, а также ускорение частиц грунта и материала стен костела. Полученные результаты сопоставлены с требованиями польских норм „PN-85/B-02170. Оценка вредных колебаний, передаваемых сооружениям через грунтовое основание". Установлено, что зафиксированные колебания превышают допустимые нормы.