Investigation of the diaphragm wall isolation of vibrations' transferred through the subsoil

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Abstract Diaphragm walls are deep extended walls through granular or cohesive soils in shallow water table areas. This paper focus problems involved in excavating diaphragm walls including dynamic impact on the environment. Construction of diaphragm wall involves extracting a soil trench while simultaneously keeping heavy viscous slurry (bentonite) filling the excavation to provide lateral pressure that must be at least equal or greater than lateral soil pressure. Extraction of soil with machinery causes vibrations to be transmitted to the adjacent buildings. The research presented in the paper is also to assess the effectiveness of the concrete diaphragm wall in damping vibrations transmitted to the surrounding buildings. The first execution phase of the technology when a vertical finite-length trench element is excavated under a hydrostatic support from inside of a bentonite slurry is under consideration.

1. Introduction
The main advantage of diaphragm wall technique is to avoid a huge excavations in place where excavation is difficult or impossible to be performed. Terzaghi and Peck [1] defined “deep excavation” as those excavations that exceed a depth of 6 or 7 m. The deep excavations are required by needs of underground parking places (especially in the big cities), protection of existing objects in the excavation vicinities etc. The concept of vertical reinforced-concrete panels is both technically effective and economically justified also in order to reduce large loadings transmitted through the ground [2]. Diaphragm wall is also applicable construction in places where dewatering cannot be performed. This solutions are remedy solutions in granular soils with high ground water table, when low permeability layer underlies granular soil. Diaphragm walls are ended in underlying low permeability layer which consist of soil/rock keying into low permeability layer reduce ground water seepage below wall.

However, the construction of the diaphragm walls is always accompanied with a lot of difficulties and problems which are based mainly on how to estimate the deformation of the trench sides in the deepening phase. In the construction of such kind of deep excavation protection is the most serious problem encountered. Designing a retaining structure should be consistent with standards [e.g. 3, 4]. It is particularly important when the support works as a permanent structure. Estimating the predicted displacements at the design stage is essential for ensuring safety. The excavation protections are inspected by geodetic monitoring, which consists, first of all, in measuring displacements at points located in the adjacent engineering structures and in the excavation support top. These measurements enable evaluation of the size and range of excavation impact on surrounding structures, as well as displacements of excavation supporting system – usually its top [5, 6]. During the excavated trench
execution, dynamic load on the surrounding buildings also occur and these dynamic impact should be carefully analysed.

2. Site preparation and excavation
First stage before starting the excavation a bentonite slurry plant must be prepared for mixing and providing bentonite to the trench or panels under excavation through a net of steel pipes. During excavation bentonite has to be provided to the trench while excavated soil mixed with bentonite are pumped again to the bentonite plant for recycling i.e. separation of soil particles and fractions mixed with bentonite during the process of excavation [7].

In the first phase of the technology when a vertical finite-length trench element is excavated under a hydrostatic support from inside of a bentonite slurry. During the trench excavation some dangerous effects can result from the variations of the groundwater table, the pore pressure, the soil collapse, the slurry level, weak soil lenses, suction forces, etc. [2, 8].

Figure 1. Cutter - excavation machine.  
Figure 2. Monitored building.

At this stage it must be decided what kind of excavation machines must be used in order to achieve the basic requirements for a minimum disturbance of the soil around or surrounding the trench. [7]. Special clamshell also known as grabs/buckets/cutter are rectangular shaped and used to excavate vertical slots called panels/trench. Loose sand and gravels can be excavated by using grab while excavation of hard strata can be performed by using cutter. Digging mechanism may be cable or hydraulic operated. In practical geotechnical engineering many problems are caused by the response of soil subjected to the vibrations [9], so the more interest should be paid to the dynamic impact of excavation machine on adjacent buildings.
3. Monitoring process
Attempts to measure the influence of geotechnical works on existing infrastructure have been reported in the course of large pile driving, sheet pile driving or rapid impulse compaction [10]. Structural damage caused by vibrations can be limited by the use of construction and connections resistant to excitation based on passive, active or semi-active techniques of vibration reduction [11] and the use of barriers in the ground to prevent surface wave energy transfer [11]. Vibrations caused by civil works, vehicle traffic, etc. are monitored according to respective guidelines and standards which specify admissible levels of vibrations depending on their frequency and the type of civil structure. The basis for the result analysis and the assessment of safe vibration levels is typically constituted by the following codes of practice: [12, 13, 14]. Signals generated during geotechnical works are of variable nature, which means that these vibrations require individual approach and detailed analyses to get as much information as possible. In most cases vibrations can be described as non-stationary stochastic process, i.e., the average value, variance and autocorrelation function varies along time [15].

Concrete trench counterparts or a row of piles is solution for vibration screening, this type of barrier is studied in the paper. The majority of the energy that affects nearby structures is carried by Rayleigh wave travelling on ground surface, away from source of vibration. This energy comprises approximately 67 per cent of the total energy [16]. A ground discontinuity makes wave propagation impeded. After incidence on an obstacle, the majority of the energy of the Rayleigh wave is reflected, with partial transmission through the barrier, and new body radiate outwards.

The research presented is to assess the effectiveness of the concrete diaphragm wall in damping vibrations transmitted to the surrounding sensitive buildings. In the studied case, a 18 m deep concrete trench was constructed. Excavation of hard strata was performed by using cutter. The work of the machine consists in short lowering the grab weighing 21.5 tons freely. This part of trench deepening is the source of highest vibrations amplitudes. Occurrence of big, hard and smooth surface stones that keep rolling under cutter wheels or stacking of these stones between the teeth of the cutter extends the process of the trench lowering. Crushing the boulders and stones causes also high vibration values.

The monitored structure was a sensitive building made in traditional technology (figure 2). The figure 3 shows the location of diaphragm wall section, building and measurement point. Vibration of the point at the corner of the buildings wall was monitored.

![Figure 3. a) Scheme of diaphragm wall sections and location of the sensor, b)Trench cross section, extreme grab position.](image)

In the first stage, the corner trench (Section A) of the excavation protection was made. The second stage of diaphragm wall (Section B) was completed after obtaining concrete strength of the corner
trench. The building wall was monitored during these phases and the distance from the source of vibrations (from a running cutter) to the sensor varied from 2.3 m to 19.7 m. According to the standard [12] the monitored building falls into first or second category, and as such requires dynamical monitoring.

4. Results of vibration measurements

The vibration parameters of the building during the execution of the closest to the building corner Section A were collected on the first day of monitoring (Section A). During the selected monitored time interval (6:00 – 7:52), the sensors recorded the highest amplitude $V_x = 10$ mm/s of observation from the whole working day (where $x$ – direction parallel to the building front, $y$ – direction perpendicular). During the second day of diaphragm wall execution the sensors recorded the highest amplitude $V_y = 2.50$ mm/s. The graph showing velocity in time domain is presented in figure 4 and figure 5, where red lines represent $V_x$ and blue lines represent $V_y$ (see figure 3a).

The data for the two sections is set in the table 1. It is practical to count the time when the amplitude limit value is exceeded.

| Parameter                | Section A | Section B |
|--------------------------|-----------|-----------|
| $V_x$ (mm/s)             | 0.41      | 0.20      |
| $V_y$ (mm/s)             | 0.32      | 0.24      |
| average value            |           |           |
| median                   | 0.22      | 0.03      |
| skewness                 | 5.37      | 2.72      |
| maximum                  | 9.92      | 3.96      |
| number of occurrence     |           |           |
| $V_x$ or $V_y > 1$ mm/s  | 645       | 8         |
| $V_x$ or $V_y > 2$ mm/s  | 331       | 0         |
| $V_x$ or $V_y > 3$ mm/s  | 210       | 74        |
| $V_x$ or $V_y > 4$ mm/s  | 115       | 22        |
| $V_x$ or $V_y > 5$ mm/s  | 48        | 3         |
| $V_x$ or $V_y > 6$ mm/s  | 21        | 2         |
| $V_x$ or $V_y > 7$ mm/s  | 3         | 2         |

Diagrams 6 and 7 show vibration parameters $V_x$, $V_y$ for Section A and Section B. For the first section the most common vibration velocities are 0.0-1.0 mm/s, and the frequencies are in the range of 2–40
Hz. For the Section B the most common vibration velocities are 0-0.2 mm/s, and the frequencies are in the range of 2–30 Hz.

\[
\begin{align*}
\text{Peak velocity [mm/s]} & \quad \text{Peak velocity [mm/s]} \\
\text{Number of occurrence [•]} & \quad \text{Number of occurrence [•]}
\end{align*}
\]

**Figure 6.** Histogram – frequency of occurrence of the vibration velocity for Section A.

\[
\begin{align*}
\text{Peak velocity [mm/s]} & \quad \text{Peak velocity [mm/s]} \\
\text{Number of occurrence [•]} & \quad \text{Number of occurrence [•]}
\end{align*}
\]

**Figure 7.** Histogram – frequency of occurrence of the vibration velocity for Section B.

5. **Conclusions**

It is evident that the results are highly dependent on the ground conditions and vibration energy at the source.

The nature of vibrations generated by trench deepening has two sources: harmonic excitation, e.g. movement of heavy machine or low frequency cutter. Therefore conducted investigating provide varied results of vibration parameters in terms of each section of diaphragm wall.

The frequencies of individual peak particle velocity values presented in figures 6 and 7 show that data collected for Section A and Section B are divergent from one another. Both data sets are positively skewed. The mean value of the sample is raised by a few relatively high scores at the right-hand end of the distribution, and the most values are concentrated in the left-hand end of the distribution. This is
more expressive for the measurements for Section A. This can be explained by the diverse distance sensor location from both trench section. The figure 3b shows the extreme position of the vibration source during trench deepening. The ratio of these distances for Section A and Section B is approximately equal 0.40 for initial grab position on the ground surface and 0.90 for deepest grab position at the trench bottom. It is assumed that the relationship between the amplitude of the source $A_o$ and that measured $A_r$ at the distance $r$ is $A_r = A_o r$.

During the measurements for Section B, no velocity amplitudes greater than 3.0 mm/s were observed, while several hundred were recorded for the Section A.

The vibration attenuation effectiveness of fixed concrete trench is especially visible for the maximum amplitudes (AMF – amplitude mitigation factor)

$$\text{AMF} = \frac{V_{BX}}{V_{AX}} = 0.13 \quad \text{and} \quad \text{AMF} = \frac{V_{BY}}{V_{AY}} = 0.30$$

The previously formed Section A gains function passive technique of vibration reduction as the barrier in the ground to prevent wave energy transfer while deepening further part Section B.

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